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INTERNATIONAL SMART GRID ACTION NETWORK

Power Transmission &
Distribution Systems

Modelling storage operation for markets participation and supply of advanced system services

Discussion paper

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Disclaimer

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List of Acronyms

AC/DC	Alternate Current/Direct Current
ACE	Area Control Error
AF	Availability Factor (for Enhanced Frequency Response)
aFRR	Automated Frequency Restoration Reserve
ARERA	Autorità di Regolazione per Energia Reti e Ambiente (Italian Regulatory Authority for Energy, Networks and Environment)
AS	Ancillary Service
ASPM	Annual Service Performance Measure (for Enhanced Frequency Response)
ASM	Ancillary Service Market
BESS	Battery Energy Storage System(s)
BM	Balancing Market
BS	Balancing Service
BSP	Balancing Service Provider
CDF	Cumulative Distribution Function
CE	Continental Europe
DAM	Day-Ahead Market
DER	Distributed Energy Resource
DG	Distributed Generator
DoD	Depth of Discharge
DSO	Distribution System Operator
DSR	Demand Side Response
DW	DoWnward bid
EFR	Enhanced Frequency Response
EPEX	European Power Exchange SPOT SE
ESS	Energy Storage System
FaReS	Fast Reserve Service
FCR	Frequency Containment Reserve
FRSs	Frequency Response Services
FRU	Fast Reserve Unit
GB	Great Britain
GSP	Grid Supply Point

HB	Half-Band
HV	High-Voltage
KPI	Key Performance Indicator
LV	Low-Voltage
mFRR	Manual Frequency Restoration Reserve
MILP	Mixed Integer Linear Programming
MUSST	Multi-purpose Storage stochastic Sizing Tool
NEMO	Nominated Electricity Market Operator
NP-RES	Non-Programmable Renewable Energy Source
O&M	Operation and Maintenance
PBP	PayBack Period
PF	Primary Frequency
PFR	Primary Frequency Regulation
PI	Proportional Integral
PU	Production Unit
PV	PhotoVoltaic
RES	Renewable Energy Source
ROCOF	Rate Of Change Of Frequency
RR	Replacement Reserve
SBSPM	Second By Second Service Performance Measure (for Enhanced Frequency Response)
SF	Secondary Frequency
SFR	Secondary Frequency Regulation
SO GL	System Operation GuideLine
SoC	State of Charge
SPM	Service Performance Measure (for Enhanced Frequency Response)
STOR	Short-Term Operating Reserve
TSO	Transmission System Operator
UP	Upward bid
VPP	Virtual Power Plant

Executive Summary

Power system operation and control are being deeply affected by the increasing spread of generation from Non-Programmable Renewable Energy Sources (NP-RES). For instance, critical issues like congestion or power flow reversal phenomena have increased over the last years, while resources participating in frequency and voltage regulation and in system balancing support are decreasing. Since the operating hours of large synchronous generators are decreasing, so is the system mechanical inertia, which is so important to mitigate frequency transients at their beginning. Battery Energy Storage Systems (BESS), which are endowed with high response speed, modularity and flexibility of use, could be part of a mix of solutions to face such issues. In particular, they could contribute to the supply of ancillary services, not only in a stand-alone configuration, but also in support of NP-RES plants or of conventional power plants. This way, the former could participate in service delivery while preserving RES exploitation, the latter could offer more, or even their whole capacity on the energy market or increase their bids on the ancillary service market. In other words, the flexibility of operation of both renewable and conventional technologies would thus be improved and, at the same time, the system could benefit from more resources for security. Besides, BESS are potentially able to contribute both to traditional services, originally tailored to conventional power plants, and to newly-defined ones, which are gradually being introduced by Transmission System Operators (TSOs) to meet the new needs for a rapid intervention after the onset of a perturbation. However, a careful analysis is necessary, because the former services, despite being characterized by rather slow response times and comparatively small power gradients (which are not an issue for a BESS), may require large energy contributions which could be hard or impossible to be attained with a finite energy content, and the latter, despite requiring smaller energy contributions, still lack consolidated regulatory frameworks and remuneration mechanisms and may also be questionable in terms of their true benefits for the power system and for the market prices.

In this report, a techno-economic point of view is adopted to analyse how, and with what profitability, one or more ancillary services, and also additional functionalities in support of NP-RES plants, could be supplied by a BESS. In most cases, analyses refer to the Italian energy system and market; however, some of the lessons learnt can be generalized.

First of all, for each service considered, simulations have been carried out to inquire the capability of a BESS to respond, e.g. in terms of power exchanges with the grid, to the service requests, and then the related remuneration has been computed, to assess service profitability for the BESS itself, i.e. for its owner/Balancing Service Provider (BSP); the impact on battery aging due to the charge-discharge cycles related to service supply, and also to a simple strategy for state of charge management, has been evaluated too. The considered services include Primary Frequency Regulation (PFR) and Secondary Frequency Regulation (SFR) in Italy, both for a stand-alone BESS and for a BESS supporting an NP-RES plant. For a stand-alone BESS, “fast” primary frequency regulation is also covered, with reference to the so-called Enhanced Frequency Response (EFR) service already implemented in Great Britain by the TSO National Grid ESO. One can recall that, in Italy, a similar service called “Fast Reserve” has recently been introduced as a pilot project by the TSO (Terna).

To inquire tertiary frequency regulation, in particular in the form of real-time balancing on the Italian Ancillary Service Market (ASM), a simplified optimization approach has been adopted, again for a stand-alone BESS. More precisely, by assuming a known bid price profile and a known bid acceptance profile over a year, the energy bids to maximize the profit from the service have been computed, with the necessary constraints, e.g. on the finite energy content of the BESS. The impact of service supply in terms of cycling aging has been analysed as well.

Finally, the optimal profit which could be achieved from a whole set of services/functionalities (to be supplied together) has been targeted, for a BESS coupled to an NP-RES plant. More precisely, by assuming, again, known price profiles (and known bid acceptance status for services bid on the markets), a stochastic constrained optimization problem has been solved to obtain the most profitable (in terms of the income over investment cost ratio) partition of BESS nominal power among the services, while ensuring that the energy exchange requests from the services are satisfied. The considered services are participation in the energy (i.e. day-ahead) market, the supply of PFR, of SFR and of tertiary reserve, the reduction of the imbalances of the coupled NP-RES plant. The algorithm is run iteratively to find the best sizing for the BESS, in terms of nominal power and energy. Again, numerical computations have been carried out with reference to the current Italian market rules and Grid Code specifications.

Starting from the technical and economic results obtained in the case studies described above, useful considerations can be drawn about service profitability, also versus battery aging. For instance, investing in a BESS to supply one or more services could be deemed to be profitable if the computed PayBack Period (PBP) is smaller not only than a number of years acceptable for the BESS owner/BSP, but also than the estimated battery cycling life and/or the expected calendar life. According to this criterion, one can e.g. observe that in Italy SFR, tertiary reserve supply and balancing can be considered as potentially profitable. However, deeper analyses of feasible and effective bidding strategies are needed, since acceptance of the bids for these services does not depend on economic merit order only.

Table of Content

1. Introduction

This report is prepared within the framework of ISGAN Annex 6 (**http://www.iea-isgan.org/our-work/annex-6/**). The work of Annex 6 on Battery Energy Storage Systems (BESS) for Ancillary Service (AS) provision promotes solutions to contribute to maintaining and improving the security, reliability and quality of electric power supply, in view of an increasing spread of non-programmable renewable generation. This report is based on the outcome of Activity 2020.01 within Focus Area *Transmission and Distribution System Interaction*. The main objective of this activity is to conduct studies on how profitable AS provision could be for the BESS owner or for its Balancing Service Provider (BSP), with particular care for the Italian power system. Figure 1-1 positions this work in the ISGAN context.

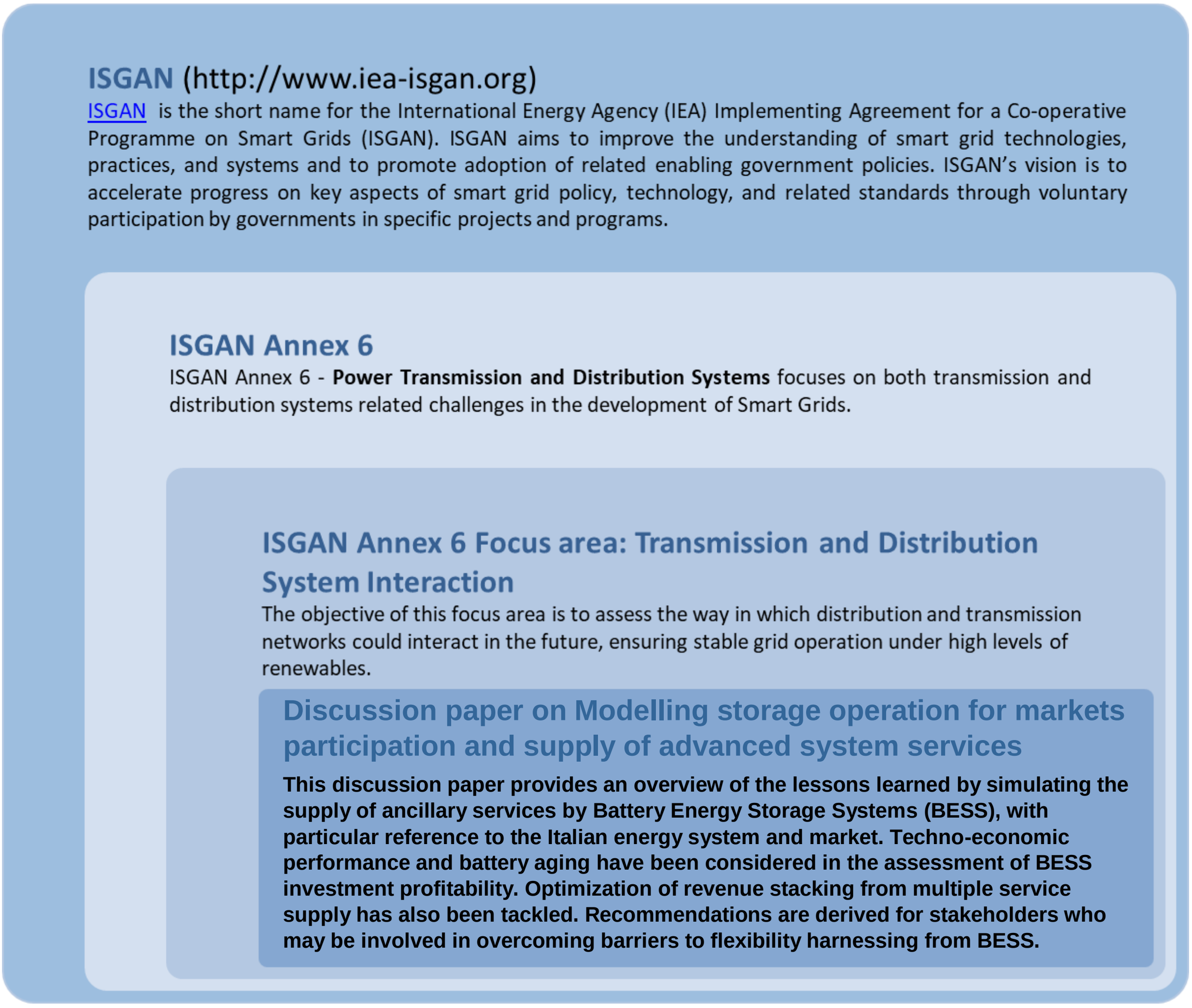


Figure 1-1 Position of this discussion paper within the context of ISGAN

1.1. Background and motivation: need for flexibility in the power system

The traditional structure of the power system is based on large dispatchable power generators (in thermal units and hydro units) connected to the high-voltage transmission grid in order to supply the end consumers mainly connected to the medium-/low-voltage distribution grid; the large generation units are often located very far from the consumption areas. In particular, the AS to control the power system (e.g. operating reserves such as active and reactive power reserves to control the frequency and the voltage) are usually provided only by dispatchable generation units, with no participation of generation units fed with Non-Programmable Renewable Energy Sources (NP-RES) and of flexible load units, except for large consumption units available for the load shedding action.

In recent years the traditional power system operation and planning have been impacted by the significant increase of generators based on NP-RES, in particular of wind and solar PhotoVoltaic (PV) generators; this new generation capacity increases the existing NP-RES capacity composed of hydro (e.g. run-of-river), biomass and geothermal generation; wind generators are mainly connected to the high-voltage transmission grid, while PV ones are mainly connected to the medium-/low-voltage distribution grid. Such new generators, often characterized by high production variability and forecast uncertainty and by low or null mechanical inertia [1], are displacing large conventional power plants which have always supplied power reserves for AS. So, the power system has transitioned into a bi-directional power flow system, with the distribution system able to inject into the transmission system, thus causing power reversal phenomena and increasing congestions in the transmission system again; in addition, frequency deviations in case of imbalances are becoming wider and/or faster and voltage drops combined with lack of short circuit power are becoming more extensive and/or deeper. Besides, NP-RES generators are not usually required to supply AS, as already hinted at, while just more resources for AS supply are needed, to support power system security and reliability.

Therefore, in the presence of high NP-RES penetration there is a need for

- increased flexibility requirements for existing/new dispatchable conventional power units;
- the introduction of AS requirements for NP-RES units;
- the introduction of new providers of AS;
- the introduction of innovative AS (with the related technical requirements).

This report is focused on new providers of AS and on innovative AS. New providers can include, apart from NP-RES, devices/solutions which can support the AS provision by NP-RES, e.g. the integration of Demand Side Response (DSR) with NP-RES themselves, or new flexible devices. Innovative AS represent new AS which are not required now but which could be required tomorrow (e.g. inertial response, ramping services). These new AS can be exchanged on the Ancillary Service Market (ASM) by BSPs/aggregators.

Distributed Energy Resources (DER), such as DSR and Distributed Generators (DG), are already selling energy on wholesale markets, and in some countries they are already providing AS to Transmission System Operators (TSOs) and Distribution System Operators (DSOs). As to DSR in particular, thanks to grid "smartization", the consumer can become an active prosumer who, by using localized generation and/or electric vehicles and/or by controlling domestic load units (think, e.g., of demand side management with smart home technologies), can participate in AS supply, thus contributing to an increase of flexibility in power system control.

AS could also be supplied by new kinds of flexible resources able to store/restore electric energy directly or indirectly (via AC/DC converter interfaces), i.e. by new kinds of Energy Storage Systems (ESS) [2]. The ESS classification includes mechanical ESS (pumped hydro, compressed air energy storage, flywheels), electro-chemical ESS (rechargeable batteries, flow batteries, fuel cells), electrical ESS (supercapacitors), thermal ESS and hybrid ESS.

Starting from the main interest in ESS declared by the Italian TSO (Terna) in its 2012-2015 Defence Plan [3], presented to the national Regulatory Authority for Energy, Networks and Environment (in Italian Autorità di Regolazione per Energia Reti e Ambiente - ARERA), and in its 2011 Development Plan [4], in this report the main focus is on commercial ESS technologies such as rechargeable Battery ESS (BESS), devices that can be integrated into generation power plants/demand facilities or operate as stand-alone systems. In particular, the BESS technologies here selected are based on lithium ions, sodium-sulphur and sodium-nickel chloride; they will be referred to in the following with these labels respectively: Li, NaS and $NaNiCl_2$.

In order to deploy a smart grid concept where the integration of flexibility into the transmission/distribution system is essential for TSOs/DSOs and the active participation of new providers of AS in the ASM is wanted, the economic evaluation of both existing and new AS from BESS is fundamental from the point of view of different stakeholders, e.g. grid operators and market operators. In fact, a profitable AS provision can increase the interactions between TSOs/DSOs and DERs/market operators so that all the stakeholders can maximize the potential benefits of these interactions: e.g., the TSO could avoid network reinforcements, and also save AS costs (thanks to higher market liquidity for balancing services), while the AS provider could increase his/her net revenues or could save costs in the final energy consumption in case he/she is an end consumer. These economic results can support the policy makers in order to direct towards new market rules overcoming technological, economic and regulatory barriers to a widespread, active and rewarding access of new participants to the ASM.

1.2. Scope and objectives

This report aims to identify one or more AS that could be provided by BESS in a profitable way for the BESS owner/BSP.

Starting from the current Italian Grid Code [5], we consider the provision of balancing services such as regulation services (e.g. Primary Frequency Response[1], Secondary Frequency Response[2]) and/or reserve services (spinning reserve, replacement reserve)[3]. The first frequency response simulations are meant to show the ability of the BESS to participate in primary and secondary frequency regulation (frequency error correction, secondary frequency regulation set-point tracking) while trying to keep the battery State of Charge (SoC) under control; battery cycling aging is also estimated. The energy exchanges related to each service and to SoC control are evaluated economically based on the current Italian Day-Ahead Market (DAM) and ASM rules, by referring to historical results about prices on the Italian market platform. Simulations about the provision of tertiary reserve in the form of balancing services exchanged on the Balancing Market (BM), the real-time stage of the Italian ASM, are carried out by optimizing the energy bids for the services, for simplicity at pre-set bid prices and pre-set bid acceptance/rejection status; the optimal energy bids

[1] This AS refers to the activation of the primary reserve specified within the Italian Grid Code; this Primary Reserve is equivalent to the Frequency Containment Reserve (FCR) defined within the System Operation GuideLine (SO GL) enforced in 14 September 2017 via Commission Regulation (EU) 2017/1485 [60].

[2] This AS refers to the activation of the secondary reserve specified within the Italian Grid Code; the Secondary Reserve is equivalent to the (automatic) Frequency Restoration Reserve (aFRR) defined within the mentioned SO GL.

[3] These AS refer to the tertiary reserves specified within the Italian Grid Code: upward ready tertiary reserve (equivalent to manual FRR-mFRR defined within the mentioned SO GL), upward/downward spinning tertiary reserve and upward/downward replacement tertiary reserve (equivalent to Replacement Reserve-RR defined within the SO GL).

maximize the annual profit from the services. Again, the adopted prices and acceptance/rejection status values are derived from BM historical results.

Possible new AS to supply a frequency response faster than primary frequency regulation are also taken into consideration: in particular, attention is focused on the so-called Enhanced Frequency Response (EFR) service introduced in Great Britain few years ago. Starting from the service requirements and the power response performance index formulated by the British TSO, simulations are carried out to show the ability of the BESS to participate in this regulation, also with a simple SoC management strategy. The related battery cycling aging is estimated as well. Some considerations are drawn about a possible sizing of the service for the Continental Europe (CE) synchronous system too.

In the last group of simulations, the aim is to find the optimal partition of the BESS nominal power into power bands to carry out a set of services/functionalities, and also to find out the optimal size of the BESS, in terms of nominal power and nominal energy, to maximize the net revenues from such a set (i.e. to maximize the revenue stacking). Here the response to primary and secondary frequency regulation requests is optimized together with the participation of the BESS owner/BSP in the DAM, the participation in the ASM for tertiary reserve and BESS management for the reduction of the imbalances of an NP-RES plant to which the BESS is coupled. Again these simulations are based on the current Italian DAM and ASM rules, and both frequency response and DAM/ASM participation are evaluated economically by referring to the historical results about bid prices on the Italian market platform.

Profitable results from all the simulations performed can help to detect the economic potential for AS provision by BESS, especially within the existing Italian ASM, and so the possible barriers to overcome, in the next future, in terms of ASM rules, new requirements for AS supply, new BESS control strategies, new bidding strategies, etc., in order to support policy makers decisions.

2. Methodology

In order to achieve the declared objectives, firstly it is necessary to define the main stages and data to simulate BESS participation in AS provision.

Stage 1. A suitable **BESS model** is needed, to capture the involved dynamics and to take into account the main features of the considered BESS technology, e.g. in terms of aging. For the considered applications, the SoC dynamics will be the main concern.

Stage 2. The simulation needs suitable **AS input signals** in order to simulate the BESS response to them. In case of frequency response simulation, the input signal will be the network frequency error (expressed in Hz) for the primary frequency response, the output signal of the centralised network Proportional-Integral (PI) controller (expressed in p.u. of the secondary reserve band) for the secondary frequency response; in case of reserve services simulation, the input signal will be the time series of the accepted bid prices, on the ASM, of the BESS owner/BSP along the simulated time interval.

Stage 3. The AS supply simulation needs, as its **output evaluation**, the evaluation of the BESS response in terms of the exchanged power (expressed in MW) or energy (expressed in MWh), the related SoC time profile, battery aging due to charge-discharge cycles at least, and the net revenue associated to the energy exchanged or not exchanged. This evaluation could then yield one or more Key Performance Indicators (KPIs) for BESS capability in AS provision or could support the detection of an optimal bidding strategy or of the optimal BESS sizing for the provision of a chosen set of AS.

These stages are here combined together into different simulation approaches.

Approach 1. Pure simulation of service supply, without any optimization, in order to analyse/understand the main technical issues about BESS charge-discharge management and the possible profitability of the considered service/services.

Approach 2. BESS optimization, in terms of charge-discharge management and also of sizing. The optimization has to lead to the maximum profit from the examined services.

These two approaches allow to derive overall results, based on which main recommendations can be obtained for stakeholders like investors or decision makers.

2.1. BESS model for Frequency Response Services

In Europe, the Frequency Response Services (FRSs) for frequency containment and frequency restoration aim, after imbalance events (in particular after severe perturbations), at containing system frequency deviations and, respectively, at restoring the system frequency to its set-point value and the power interchanges with adjacent control areas to their programmed scheduled values. More precisely, as to the Continental Europe (CE) [6] power system, FCRs have 30 s of full activation time and aim at keeping the maximum frequency deviation quasi-steady-state value at the predefined value of ±200 mHz, while FRRs have 15 minutes of full activation time.

Here we describe how the BESS technologies can participate to FRSs [7], starting from the rules for the traditional provision by conventional generation units and inquiring if BESS' performance can overcome the conventional units' one.

We preliminarily recall that the actual contribution to Primary Frequency Regulation (PFR) and the actual contribution to Secondary Frequency Regulation (SFR) depend on the interaction of the individual regulation unit with the rest of the power system dynamics (closed-loop regulation). Since the energy exchanged by a BESS is here considered to be negligible if compared to the overall energy injected into the power system by the large plants, the Primary Frequency (PF) response and the Secondary Frequency (SF) response by the BESS can be simplified by considering it in open loop.

Besides, the BESS response is faster than the dynamics involved in PFR and SFR, so an electro-mechanical model of the BESS is not required, but it is enough to account for the SoC dynamics only, related to the power exchanges with the grid.

2.1.1. Primary Frequency Regulation support

The provision of PFR is referred to a power output variation set-point value in response to a network signal, namely frequency deviation (i.e. error) with respect to the frequency set-point value[4], as locally measured. The contribution to PFR depends mainly on the primary reserve of the regulation unit concerned (mainly generation units) and on the slope (droop) of the power-frequency characteristic that the regulation unit has to follow to accomplish the regulation; the droop requirements for conventional technologies are specified, in Italy, in the TSO Grid Code [5].

Also for the BESS the PF regulator is assumed as purely proportional, as in conventional power plants. Its frequency-power characteristic curve is characterized by

- the maximum frequency deviation (quasi-steady-state value), called Δf_{max}, around the nominal frequency ($f_0 = 50\,Hz$), for which the maximum power variation, in absorption or injection, is requested;
- the maximum power variation itself, in absorption or injection, available from the BESS for PFR, i.e. the so-called Primary Reserve (PR_{max}); this is assumed to be supplied for Δf_{max};
- the deadband around nominal frequency f_0.

Thus, the curve slope, i.e. droop σ_{BESS}, is determined, as

$$\sigma_{BESS} = \frac{P_n}{PR_{max}} \frac{\Delta f_{max}}{f_0}$$

and the quasi-steady-state contribution to PFR requested to the BESS, with the load convention for the sign, is

$$\Delta P_{BESS,req,PFR}(t) = \frac{P_{n,BESS}}{\sigma_{BESS} \cdot f_0} \Delta f(t),$$

Here, $\Delta f = f - f_0$ and $\Delta P_{BESS,PR}$ is the power variation with respect to the BESS default power set-point, called P_0 and here assumed to be zero, for simplicity; P_n is the BESS nominal power, assumed to be symmetrical, i.e. equal in charge and in discharge, for simplicity.

2.1.2. Secondary Frequency Regulation support

The provision of SFR is referred to a power output variation set-point value in response to a network signal which is the output signal of the centralised network PI controller. The network signal, called “level” signal $L(t)$, reflects, in a PI way indeed, the amplitude of the Area Control Error (ACE), which is the sum of a term proportional to frequency deviation and a term proportional to the error in the scheduled power exchanges with the neighbouring control areas. The TSO control action via signal $L(t)$ is meant to zero the ACE, in order to

[4] The set-point value can be the nominal frequency or a value close to it. Here we assume it to be equal to the nominal frequency, for simplicity.

balance the considered control area. The centralised network PI controller computes $L(t)$ for a set of selected regulation sets (mainly generation sets) and transmits this signal to them in order to compensate for the ACE value; for each of these regulation sets, the signal is translated into an update of its power set-point value. According to the Italian TSO Grid Code, $L(t)$ is expressed as a percentage ($0\% \le L(t) \le 100\%$) computed with respect to the total secondary reserve provided by all the participating units within the control area, with the 50% value corresponding to the request for no power variation. The power contribution, to SFR, of the single regulation unit concerned is derived by rescaling $L(t)$ on the secondary reserve of the unit itself. By adopting these rules for a BESS as well, one can implement the SFR response requested to the BESS as this power output variation in response to $L(t)$:

$$\Delta P_{BESS,req,SFR}(t) = -2 \cdot SR_{max} \cdot \frac{L(t) - 50\%}{100\%},$$

which is indeed limited by the amount of maximum secondary reserve (SR_{max}) available from the BESS.

2.1.3. BESS sizing

Of course, a BESS has a limited power output available, namely its nominal power P_n.

In case of PFR and SFR response by a BESS, the maximum power output has to take into account both the primary and secondary reserves, which can be chosen in different ways also according to the BESS operating configuration, namely whether the BESS is stand-alone or supporting another plant.

In particular, for stand-alone operation for a BESS assumed to be completely devoted to the two frequency regulations, the sum of the primary reserve and of the secondary reserve is equal to the maximum power output, and each reserve contribution can be chosen as a fixed fraction of the maximum power output. Otherwise, if other services, e.g. participation in the DAM or tertiary reserve supply on the ASM, are considered as well, it is necessary to have a residual power capacity to be used for them.

For a BESS supporting an NP-RES plant or a conventional power plant, instead, the maximum power output can be composed of two parts: a part to carry out the regulations for the BESS itself and a part to carry out the regulations on behalf of the supported power plant. If the BESS is assumed to be completely devoted to the two frequency regulations, one has that, as in the stand-alone configuration, each of the two parts is in turn divided into a primary and a secondary reserve; otherwise, namely if the BESS is not fully devoted to the two frequency regulations, it can have a residual power capacity that can be used for other services, e.g. participation in the DAM or tertiary reserve supply.

Finally, as to the battery nominal energy, here called E_n, its choice depends on the technology and on the considered service/s.

2.1.4. State of Charge

The BESS is characterized by limited energy capacity and affected by internal dissipation effects both in the power electronic converter and in the battery of cells itself.

For each time instant t, the battery SoC can be defined, for simplicity, as the state of energy:

$$SoC(t) = \frac{E(t)}{E_n},$$

where $E(t)$ is the battery energy content at time instant t and E_n the battery nominal energy, so that, for each time instant, 0 ≤ SoC ≤ 1. SoC dynamics

$$\frac{dSoC(t)}{dt} = \frac{1}{E_n}\frac{dE(t)}{dt}$$

are determined by the BESS power output, in absorption and in injection. More precisely, the power exchanges with the grid ($P_{BESS,output}(t)$) are converted into inner power exchanges via the charging/discharging efficiency coefficients (both between 0 and 1), accounting for dissipation effects both in the inverter and in the battery of cells (self-discharge is here neglected, for simplicity): during the "load" (i.e. charge) operation the amount of energy stored into the BESS is smaller than the energy absorbed from the grid, and during the "generator" (i.e. discharge) operation the amount of energy leaving the BESS is larger than the energy delivered to the grid. In other words, the SoC dynamics can be described as follows:

$$E_n \frac{dSoC(t)}{dt} = \begin{cases} \eta_{charge} \cdot P_{BESS,output}(t), & if\ P_{BESS,output}(t) \geq 0\ (BESS\ absorption) \\ \dfrac{1}{\eta_{discharge}} \cdot P_{BESS,output}(t), & if\ P_{BESS,output}(t) \leq 0\ (BESS\ injection) \end{cases}$$

The power exchanges with the grid ($P_{BESS,output}(t)$), in turn, depend on

- a default setpoint $P_0(t)$, if present;
- the power output requests from the PF and SF regulators;
- the current SoC;
- the adopted SoC management strategy [8], if present; this aims at keeping the SoC under control against too large deviations, which may be caused by the regulations in this case.

2.1.5. SoC management strategy

When the considered BESS is devoted to PFR and SFR, the power variation requests due to the two regulations may lead to a sustained increase or decrease of the SoC, so that SoC limits are approached or reached, thus running in the risk of no longer being able to absorb or inject further energy from or into the grid to fulfill the regulation requests (especially in case the TSO requires the ability to keep regulating for a minimal amount of time, namely to ensure a minimal energy availability for a service). Therefore, it is useful to introduce a SoC management strategy to better control the energy exchange.

Here the adopted SoC management strategy [8] aims at restoring the SoC towards a target interval $[\mathrm{SoC}_{\mathrm{tgt,min}}, \mathrm{SoC}_{\mathrm{tgt,max}}]$, between a minimum SoC target value and a maximum SoC target value. When no PFR+SFR requests are present, if the SoC is outside the target interval the BESS tries to restore the SoC to that interval, by absorbing or injecting a specified amount of power. In short, the BESS power output is given by

$$P_{BESS,output}(t) = P_{BESS,PFR\ and\ SFR}(t) + P_{BESS,SoC\ restoration}(t)$$

"No regulation requests are present" means that system frequency is within the deadband range and the ACE is zero, or that the algebraic sum of the requests due to PFR and SFR is zero. This way, the two terms on the right-hand side are never nonzero at the same time.

If the SoC is higher than $SoC_{tgt,max}$, the restoration action is in discharge, i.e. $\mathrm{P}_{\mathrm{BESS,SoC\_restoration}} < 0$; if the SoC is lower than $SoC_{tgt,min}$, the restoration action is in charge, i.e. $\mathrm{P}_{\mathrm{BESS,SoC\_restoration}} > 0$; the absolute value of the charge and discharge power is here chosen to be the same and called P_{rest}.

Finally, we remark that, in case the BESS is not in a stand-alone configuration, but in support of an NP-RES plant, when the plant is generating less than a threshold power $P_{RES,min}$ the two regulations are assumed to be switched off, so this is another occasion on which no regulation requests are present.

2.1.6. Battery aging

Battery aging causes the actual energy storage capacity (and, although to a smaller extent, the actual maximum power output capacity) to decrease with the passing of time. In general the degradation rate is related in a nonlinear way to different stress factors, like cell temperature, charging/discharging rate, time, and also of the current state of life itself [9] [10]. While recalling that battery life limitations due to calendar aging always have to be taken into consideration, we now focus on cycling aging, in this case due to the accomplishment of the FRSs, and of the SoC restoration process if present.

Cycling aging [9] depends, on the whole, on the charging/discharging rate, the average SoC, cell temperature and Depth of Discharge (DoD) in each cycle (the DoD is computed with respect to nominal energy capacity). Here, anyway, we neglect the effects, on energy exchange capacity fade, of the charging/discharging rate, because they are only few per cent if a battery is not operated at full power regimes, and of temperature, since, in the presence of an effective air temperature conditioning system, nearly constant cell temperature can be assumed. By neglecting, for simplicity, also the effects of the average SoC on battery life, we analyse here DoD effects only in order to evaluate the maximum number of cycles and lifetime. We adopt two approaches to the purpose: a standard approach, referring to a unitary DoD assumption, and a still approximated, but more refined approach, referring to the actual DoD values showing up during the BESS simulated operation.

For each battery technology, curves are available in the literature relating the maximum number of cycles which can be achieved to the DoD of the cycles themselves during the operation time [11]: $n_{\max} = f(DoD)$, i.e. $n_{\max} = n_{\max}(DoD)$, with 0 ≤ DoD ≤ 1 (or, in per cent values, 0% ≤ DoD ≤ 100%). An example of such characteristic curves is reported in **Figure 2-1** for the NaS, Li and $NaNiCl_2$ technologies. We recall that the former approach relies only on the $n_{\max} = f(1)$ point (i.e. the maximum number of cycles at DoD = 1) or on an estimate of it, the latter on the whole curve. The curves depicted in **Figure 2-1** are adopted in this work for cycling life estimation carried out according to the latter approach.

2.1.6.1. Standard approach

Let E_n be the BESS nominal energy, T the considered time interval, expressed in years, and E_d the total energy discharged in T due to the BESS operation (in the present case, this includes AS accomplishment and, if present, SoC restoration). If the DoD were always equal to 1, then the number of equivalent whole half-cycles done in T would be

$$nc_{eq} = \frac{E_d}{1 \cdot E_n} = \frac{E_d}{E_n}$$

and the BESS would last n_{y} years:

$$n_{\mathrm{y}} = n_{\max}(1)T/nc_{\mathrm{eq}}.$$

2.1.6.2. Refined approach

The average DoD of the actual cycles done, of course, is not always equal to 1 in general. Let us consider the overall time interval for operation, namely T, again, and focus on each partial cycle carried out during T. Let DoD_i be the DoD associated to the *i-th* partial half-cycle, in discharge or charge, i.e. associated to the SoC monotonic variation due to the *i-th* continuous injection or absorption of energy by the BESS. When the injection or absorption re-starts (after the *i-th* partial half-cycle in absorption or injection respectively), the next, *(i+1)-th* partial discharge or charge half-cycle begins, to which DoD_{i+1} is associated. Therefore, according to the $n_{max} = f(DoD)$ characteristic curve, the maximum number of partial cycles which can be done at DoD_i and, similarly, at $DoD_{i+1}$is $n_{max,i} = n_{max}(DoD_i)$ and, similarly,

$n_{max,i+1} = n_{max}(DoD_{i+1})$. Let N be the number of partial half-cycles carried out over T. Then, the expected maximum number of cycles which can be done is here estimated as the following weighted average:

$$n_{max,exp} = \frac{\sum_{i=1}^{N} n_{max,i} \cdot DoD_i}{\sum_{i=1}^{N} DoD_i}.$$

The "expected average DoD" (DoD_{avg}) is the DoD corresponding to $n_{max,exp}$ on the $n_{max} = f(DoD)$ characteristic curve:

$$DoD_{avg} = arg(n_{max,exp}).$$

The equivalent number of discharge cycles done at such DoD along time *T* is

$$nc_{eq,avg} = \frac{E_d}{DoD_{avg} \cdot E_n}.$$

Therefore, the BESS is expected to last $n_{\mathrm{y,avg}}$ years:

$$n_{\mathrm{y,avg}} = n_{max,exp} T / nc_{\mathrm{eq,avg}}.$$

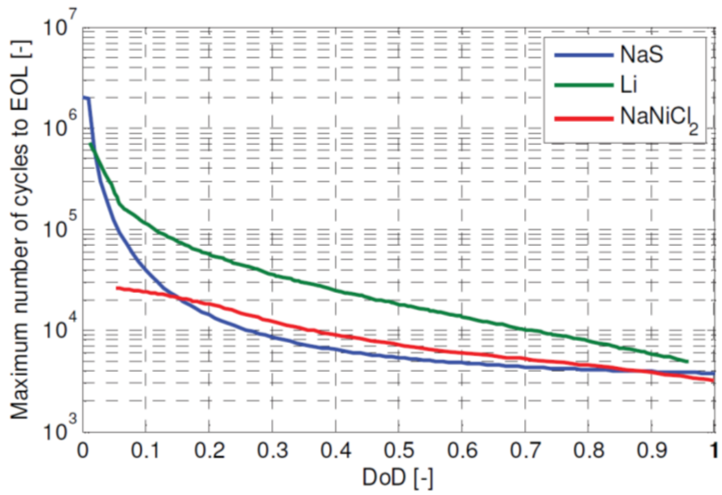


Figure 2-1 Maximum number of cycles versus DoD curves adopted

2.1.7. Input signals

In order to simulate the PFR response the input signal is the network frequency error, i.e. the difference between the current value of the frequency and the frequency set-point value. As to the former, real measured frequency data are adopted here.

In order to simulate the SFR response, the input signal is the output signal of the centralised network PI controller provided by the TSO. Again, real data are adopted here.

In case of an NP-RES plant coupled with the BESS for PFR and SFR, the hourly production data of a wind power plant or of a PV plant are considered here. Such data come from real plants and are scaled, if necessary, to the simulated plant size.

To carry out economic evaluations after the simulation of BESS response to PFR and SFR requests, additional input signals are needed in terms of market prices, as described in Section 2.1.8.3. These inputs are not adopted in the response simulation themselves, since attention is first of all focused on the BESS technical performance in supplying the services, so the BESS is assumed simply to be trying to track the frequency error and the level signal, independently of the market participation rules and of the remuneration mechanisms; these mechanisms are therefore taken into account as a second step, to give an economic value to the BESS energy exchanges thus computed.

2.1.8. Output evaluation

The main simulation outputs in case of the FRSs include the exchanged energy (expressed in MWh), the SoC response behaviour, battery aging, net revenues and the BESS investment PayBack Period (PBP).

2.1.8.1. Power/energy exchanges and battery SoC

For each simulation, absorption and injection power exchanges with the grid are computed:

- regulation requests by the PF and SF controllers; these are labelled as "ideal requests", as explained below;
- regulation requests actually accomplished by the BESS;
- regulation requests which cannot be accomplished, due to SoC saturation to 1 or 0, and so which are completely or partially "lost" for regulation purposes;
- in case the BESS supports an NP-RES plant, the power exchanges requested to the plant itself if the BESS cannot accomplish the regulation requests completely;
- power exchanges for SoC restoration.

In case the BESS supports an NP-RES plant, a minimal threshold on NP-RES power production has been considered to start contributing to the frequency regulations: PFR and SFR are activated only when the actual generation is greater than 10% the rated power of the NP-RES plant. If the BESS cannot accomplish a downward request (i.e. for a reduction of the plant injection into the grid) completely, then a request is sent to the plant to supply the power variation left which the BESS cannot carry out (this is why the threshold has been introduced); upward requests (i.e. for injection increase), instead, are assumed not to be allowed for the NP-RES plant. The presence of the minimal threshold on the plant power production implies that the requests for regulation actually sent to the BESS (and eventually to the NP-RES plant) are less, and smaller in absolute value, than the original requests coming from the PF and SF controllers, which are therefore called "ideal requests". For a stand-alone BESS, instead, the "ideal requests" are sent to the BESS unaltered.

The power exchange profiles are computed with reference to the minimum sampling time between the frequency and level signals; integration of absorption and injection power exchanges with the grid in each 15-minute or 1-hour settlement period yields energy exchanges to be considered for economic evaluations.

From the power output time profile the SoC time profile is also obtained, with the same time granularity.

2.1.8.2. Battery aging

Battery cycling aging is analysed both with the standard approach and with the refined one. As to this latter, in particular, from the obtained SoC time profile the "average DoD" time profile throughout time period T is computed, so the equivalent number of (partial) discharge cycles done over T (i.e. $nc_{eq,avg}$) is determined, together with the number of years that the BESS is expected to last ($n_{y,avg}$). Then, $nc_{eq,avg}$ and $n_{y,avg}$ can be compared to the number of equivalent full cycles (nc_{eq}) and to the related life (n_y) which are obtained as if the DoD were always 1.

2.1.8.3. Economic evaluations

The profitability of FRSs for the BESS is evaluated based on a simplified PBP approach: the PBP is defined as the number of years necessary to recover the BESS investment costs thanks to the net revenues obtained from the FRSs themselves, taking into account the SoC restoration if present.

Here the BESS investment costs are composed of

- costs per MW, including the costs of the power conversion system, the power control system and the balance-of-plant equipment;
- costs per MWh, including the costs of the battery and the installation (fixed O&M costs are neglected here, for simplicity).

Such unit costs have been derived by elaborating the values reported in [12] and [13].

Net revenues from FRSs are computed, as described in [7], by applying to the BESS the present Italian PFR remuneration scheme for conventional power plants, market rules for SFR for conventional power plants again, imbalance rules for non-eligible units as to SoC restoration energy exchanges.

As to PFR remuneration, the unit price is defined for each hour, taking into account the DAM zonal selling price and the unit price and energy quantity of the SFR upward/downward accepted bids [14] [15]:

- for under-frequency (i.e. upward) regulation in each hour, the DAM zonal price is increased by $(p_1 – p_2)/2$, where p_1 is the weighted average price, with reference to the previous year, of the bids for upward SFR accepted in the Italian BM, while p_2 is the average of the DAM zonal selling prices, with reference to the previous year, weighted by the quantities accepted for upward SFR in the considered zone;
- similarly, for over-frequency (i.e. downward) regulation, the zonal DAM price is decreased by $(p_3 – p_4)/2$, where p_4 is the weighted average price, with reference to the previous year, of the bids for downward SFR accepted in the BM, while p_3 is the average of the DAM zonal selling prices, with reference to the previous year, weighted by the quantities accepted for downward SFR in the considered zone.

To value energy contributions to SFR, the historical upward/downward accepted zonal bid prices in the BM, which has a 15-minute granularity, have been adopted.

As already mentioned, energy exchanges for SoC restoration have been evaluated according to the imbalance rules of generating units not enabled to provide ancillary services, i.e. the ones with nominal power lower than 10 MW and the non-programmable ones [16] [17]: for each hourly time slot,

- if the sign of the zonal aggregated imbalances is positive, the price is the minimum between
  - the average price of the downward bids accepted on the ASM for real-time balancing, weighted by the related quantities, in the same time slot, in the interested macro-zone;
  - the price of accepted selling bids on the DAM, in the same time slot, in the interested zone;
- if the sign of the zonal aggregated imbalances is negative, the price is the maximum between:
  - the average price of the upward offers accepted on the ASM for real-time balancing, weighted by the related quantities, in the same time slot, in the interested macro-zone;
  - the price of accepted selling bids on the DAM, in the same time slot, in the interested zone.

The sign of the zonal aggregated imbalances is published by the Italian TSO (Terna).

The algebraic sum of costs and revenues from PFR, SFR and SoC restoration (if present) along a year yields the income which, divided by the BESS investment costs, yields the PBP of the considered combination of services, which is finally compared to the estimated battery life in order to assess the service profitability.

2.2. BESS model for Fast Frequency Response services

An innovative application of the BESS technology is the supply of a fast frequency response, in order to contribute to contain frequency deviations on smaller times scales than the ones typical of PFR (even smaller time scales are tackled by services for the containment of the Rate Of Change Of Frequency - ROCOF at the very beginning of frequency transients due to perturbations on the network). An example of a fast frequency response service is the so-called Enhanced Frequency Response (EFR) [18], recently introduced by the British TSO, National Grid ESO, just in order to *"improve management of system frequency pre-fault, i.e. to maintain the system frequency closer to 50 Hz under normal operation, however as a dynamic service there will also be a benefit in post-fault frequency containment"* [18].

The same approach adopted for PFR and SFR is adopted here for the EFR service simulation [19], so the reader is referred to Section 2.1; in particular, the adopted SoC dynamic model, the SoC restoration strategy and the methodologies for aging assessment are the same. The main difference is that the BESS is now employed for one service only, to which the whole BESS nominal power is devoted, and a stand-alone BESS only is considered. The differences in terms of power-frequency behaviour requested and in terms of performance indicators are illustrated below.

Of course, in order to simulate the EFR response the input signal is the network frequency error, i.e. the difference between the current value of the frequency and the frequency set-point value. As to the former, real measured frequency data are adopted here as well.

2.2.1. Power-frequency characteristics, envelope region and activation requirements

According to the rules defined by the British TSO, the power output of a device providing the EFR service in Great Britain (GB) [18] [20] has to be within the region defined by the upper and lower power-frequency characteristic curves reported in **Figure 2-2**, at all times. The region bounded by the two curves, and coinciding with part of them where they are superposed, is called the "envelope" region. The values of the coordinates of the main points defining the envelope region are tuned by the TSO in order to obtain a service with milder or stronger requests. The capacity of the upward and downward response must be symmetrical. The centre curve has been conceived to be the reference one for devices without finite energy capacity, i.e. the ones which do not need to manage a finite SoC.

The EFR service must be fully activated by a regulation unit within 1 s, i.e. much faster than the PFR contribution. We recall, for comparison, that the typical deployment times of PFR by conventional generation units in Italy are 15 s for 50% of the reserve, 30 s for the whole reserve [5], and, similarly, in the CE synchronous system the contribution to PFR, more precisely to frequency containment, has to reach its steady state within 30 s [6]; in GB, the contribution to PFR has to be a ramp for the first 10 s and then it must be kept for 30 s [21].

Besides, a regulation unit eligible for EFR provision must be able to deliver the maximum power contracted for up to 15 minutes, both in injection and in absorption.

The British TSO also specifies ramp rate limits in the different parts of the power-frequency plane; however, these limits are neglected here, also due to the fast response capabilities typical of batteries.

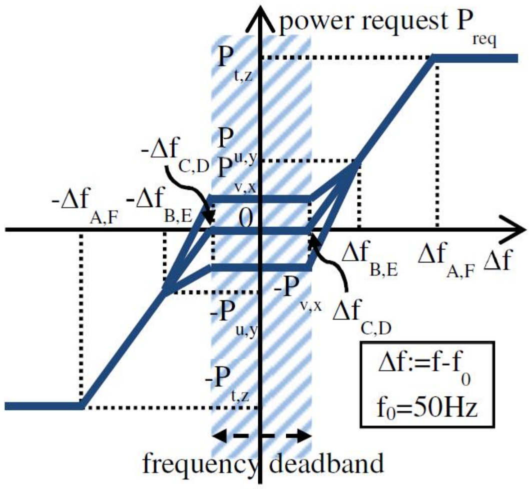


Figure 2-2 The feasible region, i.e. the envelope, for the EFR service (load convention for the sign of power), and its parameters

2.2.2. Service performance indicators

Resources for the EFR service are procured by the British TSO in the form of power capacity. To measure performance in service supply and to pay for the resource availability to do the service, the TSO computes suitable performance indicators. In such computations, reference is made to the contracted half-hourly settlement periods.

In each settlement period, a Service Performance Measure (SPM) index is computed, which is defined as the average of a Second By Second Performance Measure (SBSPM) index. The SBSPM, in turn, is defined in each second as

$$SBSPM = \max(0, 1 - \text{abs}(R - C)),$$

where

- R is the actual response to EFR normalised with respect to the operational capacity, i.e. to the tendered power;
- C is the point on the envelope closest to R.

If R is within the envelope, then SBSPM = 1, i.e. 100%. Over-delivery against the operational capacity, instead, is not remunerated.

In case of a reduction of the MW capacity for the service or in case of operation outside the envelope, the availability payment is reduced, for any affected settlement period, via an Availability Factor (AF): the actual payment is equal to the product of the AF and of the original availability payment. The AF is related to the SPM via a set of threshold values: e.g., if SPM ≥ 95%, then AF = 100%, so no penalty is applied, while if SPM < 50% then AF = 0%, so no payment is received by the service supplier. Settlement periods during planned maintenance have AF = 0%, so they yield no payment.

There is also an Annual Service Performance Measure (ASPM), which is defined as the average of all SPMs over a rolling 12 month period; the calculation of the ASPM includes also settlement periods during planned maintenance. If ASPM < 95%, the TSO tries to identify with the provider the causes of the underperformance and possible mitigation measures. If ASPM < 50%, this process could result in contract termination.

If frequency ≤ 49.5 Hz or frequency ≥ 50.5 Hz for 15 consecutive minutes, the time period immediately following this period and lasting until the frequency has returned to the deadband plus 30 minutes is called an “extended frequency event”. Within such an event, EFR assets may continue to deliver EFR but the event itself is not taken into account in the calculation of the SPM, so assets stopping the EFR service supply in this period are not penalised. In this work, however, this rule is not considered, for simplicity (besides, the data adopted in the simulations do not include extended frequency events).

2.2.3. Output evaluation

Here the BESS time response to the EFR requests is simulated, with the same sampling time as the one of the available frequency data, with reference to a long enough time interval *T*. The main simulation outputs can be described as follows:

- absorption and injection power exchanges with the grid are computed along *T*, with the frequency sampling time; more precisely, the computed power exchanges include
  - the ideal power exchanges requested by the EFR service;
  - the actual power exchanged by the BESS in order to accomplish the service;
- energy exchanges with the grid in each 1/2-hour settlement period are obtained by integration of absorption and injection power exchanges; more precisely, the computed energy exchanges include
  - the ideal total energy exchanges requested by the EFR service;
  - the actual total energy exchanged by the BESS in order to accomplish the service;
- from the actual power output time profiles mentioned above, the SoC time profile is obtained (thanks to efficiency coefficients), with the same time granularity;
- the SBSPM, the SPM and the AF are computed, each according to the proper time frame;
- battery aging is evaluated according to the two considered methodologies, as already described for PFR and SFR; more precisely, the useful life that the BESS can reach due to the charge/discharge cycles related to the service and, if present, to a SoC restoration strategy is computed.

In this case, the analysis is focused mainly on the BESS technical performance in service supply. The actual remuneration for the service is determined by the AF, which, in turn, depends on such performance. An explicit economic evaluation of the service supply by the BESS is not carried out here: just some preliminary overall considerations are drawn.

2.3. BESS model for Balancing Market participation

A different approach is now adopted to analyse how BESS could supply Balancing Services (BSs) on the Balancing Market (BM), the real-time stage of the Italian ASM, and in particular to assess the profitability achievable for the BESS from such services. More precisely, a stand-alone BESS is assumed to be operating in the BM (the scheduling stage, called “ex ante” ASM, is not dealt with, for simplicity) and to be devoted to the set of active power “step variation” services (“step 1” to “step 4” [22]): these are related to the real-time supply of tertiary frequency regulation, and they are collectively called here “balancing service”. The aim is to optimize the upward (label “*UP*”) and downward (label “*DW*”) energy bids for the service along a year *T*, to maximize the related annual profit; for simplicity, e.g. to keep the problem linear, pre-set bid prices and pre-set bid acceptance/rejection status values are assumed. Since the battery cannot charge and discharge at the same time, a Mixed-Integer Linear Programming (MILP) problem is obtained. Of course, constraints including limitations on power exchanges and on the SoC are taken into account.

2.3.1. Overall methodology

The global computation scheme adopted is composed of three main steps:

- the optimization procedure is run first, so that it computes the minimal cost for the service, together with the related power exchanges and energy profile along *T*;
- then, two computations are carried out in parallel:
  a) the opposite of the minimal cost is the maximal profit from the service, which is employed to compute the BESS investment PBP;
  b) the optimal energy exchange profile yields the SoC profile immediately, which is then elaborated by the battery cycling life estimation procedures (according to the methodologies already described in Section 2.1.6);
- finally, the estimated life and the PBP are examined both individually and in comparison to each other, to evaluate the service profitability.

2.3.2. Optimization procedure

In the Italian BM, each bid for the service consists of an energy quantity (expressed in MWh) and a unit price (expressed in €/MWh). If an upward or downward bid is accepted, an upward or downward (respectively) dispatching order is issued by the TSO and the BESS has to exchange the accepted quantity, which may also be different from the bid quantity. Remuneration for accepted UPs and DWs, more precisely for the accepted quantities, is "pay as bid", i.e. at the bid price. Here, the aim is to detect the best energy quantities to bid on the BM in each time slot throughout a year, in order to maximize the annual profit from service accomplishment. As already hinted at, the bid prices are here chosen "a priori" and their acceptance status is also determined in advance. As to the reference time slot, two alternatives are considered here, yielding two formulations of the optimization problem:

- Formulation 1 features hourly bids, accepted by the TSO on a quarter-of-an-hourly basis, as it happens currently in the BM;
- Formulation 2 features quarter-of-an-hourly bids, accepted, again, on a quarter-of-an-hourly basis: this may be a possible future situation, with BM negotiations closer to real time [23].

In both formulations, power exchanges are assumed, for simplicity, to be constant throughout each quarter of an hour (¼ h), so that the related energy quantity is the product of the power and the ¼ h time interval; thus, by assuming, for simplicity, that, for an accepted bid, the whole related energy in that ¼ h is accepted, the accepted power is assumed to be equal to the bid power. This way, the problem of optimizing *energy bids* is here formulated as optimizing *power bids*, in each time slot over one year.

2.3.2.1. Formulation 1 (bids made on an hourly basis)

Let t be the time interval index, in ¼ h, along the optimization time horizon: thus, $t \epsilon T$ = [1,2,…,35040]. The following optimization variables, $\forall t \epsilon T$, are considered:

- $P_{hlev,ch}(t)$: the optimal charge power level (in MW) to be bid (downwards) in each ¼ h of an hour;
- $P_{hlev,disch}(t)$: the optimal discharge power level (in MW) to be bid (upwards) in each ¼ h of an hour;
- $P_{ch}(t)$: the power (in MW) to be absorbed from the grid in each ¼ h; it is equal, in each ¼ h in which a DW is accepted, to the optimal downward bid power level of the hour to which the ¼ h belongs, i.e. to $P_{hlev,ch}(t)$; in each ¼ h in which a DW is not accepted, it is equal to 0;
- $P_{disch}(t)$: the power (in MW) to be injected into the grid in each ¼ h; it is equal, in each ¼ h in which an UP is accepted, to the optimal upward bid power level of the

hour to which the ¼ h belongs, i.e. to $P_{hlev,disch}(t)$; in each ¼ h in which an UP is not accepted, it is equal to 0;

- $S_{ch}(t)$: the binary variable indicating, in each ¼ h, if charge is carried out or not, namely the "charge or not charge" state variable;
- $S_{disch}(t)$: the binary variable indicating, in each ¼ h, if discharge is carried out or not, namely the "discharge or not discharge" state variable.

To express the fact that DWs and UPs are made on an hourly basis, the amount of energy bid downward or upward, respectively, in an hour is assumed, for simplicity, divided into four equal parts, each of which associated to a ¼ h in that hour. Therefore, the charge power levels $P_{hlev,ch}(t)$ to be bid in the four ¼ h of that hour are set to be equal to each other, so that constant power is bid throughout the hour, and similarly the discharge power levels $P_{hlev,disch}(t)$ to be bid in the four ¼ h of that hour are set to be equal to each other, so that constant power is bid throughout the hour. Of course, the upward and downward bid power levels in the same hour can be different from each other and can also turn out to be zero; indeed, they are the true optimization outputs. The word "level" is adopted here to distinguish them from the values of the power actually absorbed or injected in each ¼ h of the hour, which determine the battery energy content in each ¼ h, called $E(t)$, to which $SoC(t) = E(t)/E_n$ corresponds.

The cost function, called C_T [€], to be optimized, namely minimized, over the considered year is the net cost for the BS, i.e. the algebraic sum of costs related to power absorption for accepted DWs and of revenues related to power injection for accepted UPs; there can also be an additional cost to take into account (i.e. to penalize) cycling aging: thus

$$C_T = \sum\nolimits_{t \epsilon T} \left[P_{ch}(t) p_{acc\,DW}(t) - P_{disch}(t) \left(p_{acc\,UP}(t) - p_{cycl}(t) \right) \right] \cdot \frac{1}{4} h \qquad \textbf{2.1}$$

where

- $p_{acc\,DW}(t)$ and $p_{acc\,UP}(t)$ are the unit prices (both expressed in €/MWh) of the accepted DW and of the accepted UP, respectively, in quarter of an hour *t*; since bids are made on an hourly basis, each of these prices is the same in the four ¼ h of the same hour; as already recalled, they are assumed as problem inputs;
- $p_{cycl}(t)$ is the unit price (again, in €/MWh) for cycling, associated to the discharged energy in ¼ h *t*; it is also assumed as a problem input; for simplicity, it is assumed to be constant, i.e. the same $\forall\ t \ \epsilon\ T$; in particular, by choosing $p_{cycl}(t) = 0$ $\forall\ t \ \epsilon\ T$ one can neglect aging in the optimization.

For simplicity, in each hour, only one pair (bid quantity, bid unit price) is assumed to be bid downwards and only one such pair upwards (since we refer to one overall BS), although in the actual BM exchange platform the formulation of more DW pairs (up to four, since there are four "step" BSs) and of more UP pairs (again up to four, since there are four "step" BSs) is allowed. As already mentioned, the DW and UP prices, here called $p_{DW}(t)$ and $p_{UP}(t)$ respectively, are chosen/computed in advance; since DWs and UPs have to be formulated on an hourly basis, in the four ¼ h of an hour $p_{DW}(t)$ is built as a constant and so is $p_{UP}(t)$. Due to the pay-as-bid acceptance mechanism in the BM, the accepted prices $p_{acc\,DW}(t)$ and $p_{acc\,UP}(t)$ in (2.1) coincide with the bid prices $p_{DW}(t)$ and $p_{UP}(t)$, respectively, in case of acceptance, otherwise they are set to very large values (they would be ideally infinite), to penalize (and thus avoid) charge or discharge, respectively, in the cost function. The acceptance status of bids is also chosen in advance; it is identified by a binary value 1/0 (accepted/not accepted), namely $S_{DW}(t)$ and $S_{UP}(t)$ for the bid prices $p_{DW}(t)$ and $p_{UP}(t)$ respectively. Therefore, $S_{DW}(t)$ and $S_{UP}(t)$, like $p_{DW}(t)$ and $p_{UP}(t)$, are input variables for the optimization problem. Accepted DW prices and accepted UP prices are assumed here to be able to be present together in the same ¼ h, so $S_{DW}(t)$ and $S_{UP}(t)$ can also be both equal to 1 for the same *t* (otherwise, a more refined acceptance criterion should be adopted to simulate the market behaviour, so that one of them at most is 1 in each ¼ h); in that case, since the battery is assumed either to be charged or to be discharged (or to exchange no power) in a ¼ h, the optimization algorithm has to determine whether to charge or discharge the battery in that ¼ h, which implies that the discharge power level $P_{hlev,disch}(t)$ or the charge power level $P_{hlev,ch}(t)$, respectively (or both of them), is zero in that ¼ h and therefore in the whole hour.

As to the battery energy content, namely $E(t)$, constraints in the optimization express its limitations between the empty, zero value (no energy available) and the full value corresponding to the whole nominal energy E_n. A standard discrete-time model of the energy content dynamics due to the power exchanges with the grid is adopted, as already done for frequency regulation services (see Section 2.1.4): to be precise, the power exchanges for the service (namely $P_{ch}(t)$, $P_{disch}(t)$), mentioned above, are with respect to the grid:

$$P_{BESS,output}(t) = \begin{cases} P_{ch}(t), & if\ P_{BESS,output}(t) \geq 0\ (BESS\ absorption) \\ P_{disch}(t), & if\ P_{BESS,output}(t) \leq 0\ (BESS\ injection) \end{cases}$$

while the battery "internal" exchanges, affecting its energy content, account for the impact of charging and discharging efficiency.

The fact that charge and discharge cannot be performed together in the same ¼ h is expressed via the binary variables indicating the "charge or not charge" and the "discharge or not discharge" states in each ¼ h, i.e. $S_{ch}(t)$ and $S_{disch}(t)$ respectively. Either state can be equal to 1 or 0 in the same ¼ h, but they cannot be both equal to 1 in the same ¼ h. The presence of these variables makes the problem a MILP one.

Summing up, by indicating with $mod(t,4)$ the rest of the division by 4, the global optimization problem consists of minimizing C_T while fulfilling the following constraints (some of them are redundant, but they are mentioned explicitly for more clarity):

$$P_{ch}(t) = S_{DW}(t) P_{hlev,ch}(t), \forall t \epsilon T \quad \textbf{2.2}$$

$$P_{disch}(t) = S_{UP}(t) P_{hlev,disch}(t), \forall t \epsilon T \quad \textbf{2.3}$$

$$P_{hlev,ch}(t) = P_{hlev,ch}(t-1), if\ mod(t,4) = 2\ or\ 3\ or\ 0 \quad \textbf{2.4}$$

$$P_{hlev,disch}(t) = P_{hlev,disch}(t-1), if\ mod(t,4) = 2\ or\ 3\ or\ 0 \quad \textbf{2.5}$$

$$0 \leq P_{ch}(t) \leq S_{ch}(t) P_{max,abso}, \forall t \epsilon T \quad \textbf{2.6}$$

$$0 \leq P_{disch}(t) \leq S_{disch}(t) P_{max,erog}, \forall t \epsilon T \quad \textbf{2.7}$$

$$S_{ch}(t) + S_{disch}(t) \leq 1, \forall t \epsilon T \quad \textbf{2.8}$$

$$0 \leq P_{hlev,ch}(t) \leq P_{max,abso}, \forall t \epsilon T \quad \textbf{2.9}$$

$$0 \leq P_{hlev,disch}(t) \leq P_{max,erog}, \forall t \epsilon T \quad \textbf{2.10}$$

$$E(t) = E(t-1) + P_{ch}(t) \eta_{charge} \frac{1}{4} h - P_{disch}(t) \frac{1}{\eta_{discharge}} \frac{1}{4} h, \forall t \epsilon T \quad \textbf{2.11}$$

$$E(t_{ini}) = E_{ini}, t_{ini} = 0 \quad \textbf{2.12}$$

$$E(t_{fin}) = E_{fin}, t_{fin} = 35040 \quad \textbf{2.13}$$

$$0 \leq E(t) \leq E_n, \forall t \epsilon T. \quad \textbf{2.14}$$

2.3.2.2. Formulation 2 (bids made on a quarter-of-an-hourly basis)

If bids are assumed to be made in each ¼ h, in addition to being accepted or not in each ¼ h, the problem formulation can be easily obtained starting from Formulation 1, by discarding variables or conditions referring to the hour. More precisely, it is no longer necessary to introduce power "levels" $P_{hlev,ch}(t)$ and $P_{hlev,disch}(t)$ and binary variables $S_{DW}(t)$ and $S_{UP}(t)$, and the optimization variables to be considered, $\forall t \epsilon T$, reduce to $P_{ch}(t)$, $P_{disch}(t)$, $S_{ch}(t)$, $S_{disch}(t)$. The rest of the problem keeps the same as in Formulation 1.

2.3.3. Input signals

In order to optimize participation in the Italian BM for a BESS devoted to the supply of the BS, the adopted input signals are the time profiles of the BESS bidding prices and of the BESS bid acceptance/rejection status, since the bids are (price, quantity) pairs where the energy quantity is the variable to be optimized. Here, for simplicity, the bid prices and bid acceptance/rejection status are chosen based on the historical accepted prices and quantities on the BM for the BSs [24] [22]; the adopted price schemes are described in detail in Section 3.3.1.1. To simulate bids acceptance in the BM, a simple "ex-post" decision criterion is adopted [24] [22]: in each ¼ h,

- an UP is considered to be accepted (so an upward dispatching order is issued) if its price is ≤ maximum price of the historical accepted UPs in that ¼ h;
- a DW is considered to be accepted (so a downward dispatching order is issued) if its price is ≥ minimum price of the historical accepted DWs in that ¼ h.

2.3.4. Output evaluation

According to the overall methodology described in Section 2.3.1, in this case the core of each simulation consists of running an optimization algorithm for a chosen BESS and the chosen input bid prices with their acceptance/rejection status. The main simulation outputs are, besides the optimal profit (net revenue) over time interval *T* and the related PBP, the time profile of the exchanged energy (expressed in MWh) and of the SoC response and an evaluation of battery aging.

2.3.4.1. Power/energy exchanges and battery SoC

For each simulation, the power, and therefore energy, exchanged (in absorption and injection) with the grid in each 15-minute BM settlement period is computed, along the whole simulation time interval *T*. Notice that here these power and energy values are optimal in that they maximize the profit from the BS over *T*. From the power exchanges, the SoC time profile throughout *T* is computed. For simplicity, power exchanges are assumed to be constant in each 15-minute settlement period, therefore the SoC profile inside each period is linear, and the SoC profile over *T* is piecewise linear.

2.3.4.2. Battery aging

Battery cycling aging is analysed here with the refined approach described in Section 2.1.6, i.e. the one based on the computation of an “average DoD” from all the partial cycles carried out. In other words, the standard method based on the DoD = 1 assumption is not adopted in this case.

2.3.4.3. Economic evaluations

The profitability of the BS is also evaluated based on the simplified PBP approach, i.e. the PBP is defined as the number of years necessary to recover the BESS investment costs thanks to the net revenues obtained from the BS. The BESS investment PBP [y] is computed here simply as the ratio of the BESS total investment cost, IC, and the already mentioned optimal annual profit: $PBP = IC/(-C_T)$. The investment cost, for simplicity, is expressed as $IC = UIC_E \cdot E_n$,where UIC_E [k€/MWh] is an overall unit investment cost taking into account both the battery and the power conversion system.

Here SoC restoration, or more in general an explicit SoC management strategy, is not present, because SoC management is intrinsically taken care of by the profit optimization procedure, which outputs the power, so the energy, to be exchanged for the service to obtain the maximum net revenue from it throughout T, while guaranteeing that imbalances (so the possible related economic penalties) are avoided. Each energy exchange, we recall, is remunerated at its bid price.

2.4. BESS optimization model for the supply of multiple services

This section describes the mathematical formulation of MUSST (Multi-purpose Storage stochastic Sizing Tool), a simulation tool for the optimal sizing of BESS devices dedicated to the provision of multiple simultaneous services to the power system and also to the reduction of the imbalances of an NP-RES plant connected to the BESS itself.

The optimality of the sizing is defined with respect to the estimated profitability of the investment, which is measured by means of the ratio between the incomes (net revenue) coming by the provision of the services considered for a representative year of operation and the total investment costs for the installation of the BESS.

2.4.1. Optimization model

This subsection shows the mathematical formulation of the stochastic optimization model on which the MUSST tool is based. Firstly, the considered stochastic approach is briefly described; then, before entering directly into the model equations, a brief discussion on the adopted time discretization is proposed; finally, the description of the symbols used and the complete set of equations constituting the stochastic formulation are introduced.

We preliminarily recall that the considered ASs/functionalities for a BESS are primary, secondary and tertiary frequency regulation, participation in the DAM, reduction of the imbalances of an NP-RES plant with which the BESS is coupled.

2.4.1.1. Stochastic Optimization

Stochastic optimization is the branch of operation research aiming at taking optimal decisions under uncertainty. In particular it is applied to those situations in which the decisions have to be taken before the actual realization of the uncertain parameters is known; typical examples are investment decisions or sizing decisions.

In this framework, the decision variables of the optimization problem are divided into two groups:

- *first stage variables*, which are referred to the decisions to be taken before the realization of the uncertain parameters (e.g. if a further production facility for a given good should be built or not, depending on the uncertainty on the demand of that good); and
- *second stage variables*, that is those variables whose value is influenced directly by the realization of the uncertain parameters (e.g. the actual amount of the given good sold depends on the demand, which is uncertain).

The uncertainty on the parameters is taken into account by means of a number of *scenarios* each representing one possible realization (or one combination of possible realizations, if many uncertain parameters are considered together) and characterized by a given probability of occurrence. This probability is calculated starting from the mathematical description of the uncertainty of all the parameters considered.

First stage variables values are thus defined within the optimization process so that they are optimal for all the possible realizations of the uncertain parameters; mathematically speaking, this means that this group of variables is independent of the scenarios.

Second stage variables, instead, depend on the scenarios.

The problem that is modelled here is referred to the decision of what the best size of a BESS is in terms of storage capacity (i.e. nominal energy) and maximum power output (i.e. nominal power) and also of the allocation of the nominal power for the different services that the BESS is designed to provide. This decision depends on parameters that are uncertain, in particular the prices at which the provision of the different services is remunerated, that influence the actual absorption/injection of the BESS in each time step. Thus, in this modelling framework the rated storage capacity, the nominal power and its allocation among the considered services are all first stage variables. All the other variables, in particular the one introduced to model the operation of the BESS, are second stage variables, since their values depend in each time step on the actual realization of the uncertain parameters, that is on the scenario considered.

2.4.1.2. Time step definition

The provision of different services may have different reference timescales. For instance, PFR has a reference timescale of the order of seconds, having to cope with the instantaneous frequency deviations from the reference value. SFR, instead, may have a reference timescale of minutes, as it happens in the Italian power system. Going on, tertiary regulation and the accounting for NP-RES imbalances usually have a reference timescale of 15 minutes, while the day-ahead market is referred to hours. Many other examples of different possible timeframes can be given, depending both on the power system considered and on the services considered. Therefore, in order to simulate the provision of multiple ASs together, and also of additional functionalities, a suitable time step has to be carefully chosen.

Here the smallest time reference of the considered services is 1 second. This would be a possible choice as a time step for the optimization of the BESS *daily* operation. However, for the *annual* operation that is considered in MUSST this choice would be impossible, for computational reasons: considering a time step of 1 second would mean having more than 31 million time steps. Also, the time frame of SFR could be too fine too, in particular when many scenarios are considered for the stochastic optimization: a one-minute time step would mean more than 500,000 time steps per scenario.

Choosing a time step width longer than the time frame of some of the services considered introduces approximation issues on the injection/absorption power for these services. One possible solution, used for instance in [25], is to consider the services as provided separately and then use the superposition of effects. Notice that, if one does not account for the *global* BESS power output, violations of the constraints on storage capacity are likely to occur, and, in fact, this approach in [25] is justified by the hypotheses that all the services considered but primary regulation have the same time frame and that primary regulation is a "perturbation" on the operation of the BESS. MUSST is designed to maintain as much generality as possible, thus those very specific hypotheses cannot be applied.

However, the nature of PFR and SFR helps to solve this issue. In fact, as it will be described in the following sections, PFR is set up as an automatic response to deviations of the system frequency from its nominal value, thus the output of the BESS for the provision of this service is driven by this external signal. In a similar way, once the availability of the BESS for the provision of SFR is accepted by the TSO via the Balancing Market (BM) for a quarter of an hour, the actual output as a function of time during that quarter of an hour is imposed by the TSO itself, via the so-called level signal.

This means that, for any given time frame length τ, by knowing these two external signals it is possible to define the instantaneous output of the BESS. Then, it is possible to measure for how much time, in time step t (whose width is τ), the output is positive, negative or null, so to define the width of three sub-intervals $\delta^{up}(t)$, $\delta^{dn}(t)$ and $\delta^{0}(t)$ into which each time step can be divided. For each of these sub-time steps, the average output is considered to be constant. In this way, the bounds on stored energy are accounted for correctly. The process is graphically shown in Figure 2-3. In this work we consider a quarter of an hour as the reference time step width.

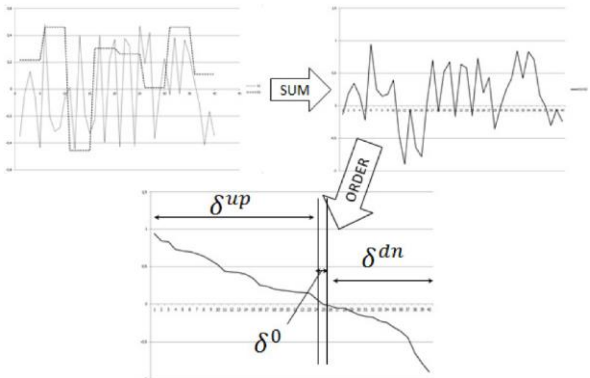


Figure 2-3 – Graphical description of the subdivision of time step *t* into sub intervals $\delta^{up}(t)$, $\delta^{dn}(t)$ and $\delta^{0}(t)$

2.4.1.3. Notation

The symbols adopted in the model are now listed.

Indexes

t	time step
s	scenario
σ	service; in summations, σ = 1, 2, 3, DAM, sbil

First stage variables

C	BESS rated storage capacity [MWh]
$\overline{p}$	BESS nominal power [MW]
β_{σ}	Fraction of the BESS nominal power dedicated to service σ provision

Second stage variables

$p_\sigma(s,t)$	Discharge power for service σ in time step t and scenario s [MW]	$q(s,t)$	Total absorbed power in time step t and scenario s [MW]
$p(s,t)$	Total discharge power in time step t and scenario s [MW]	$E(s,t)$	Energy stored in the BESS in time step t and scenario s [MWh]
$q_\sigma(s,t)$	Absorbed power for service σ in time step t and scenario s [MW]		

Parameters

C_m	Energy capacity of each module composing the BESS [MWh]	$t^*(t)$	Time sub-interval; * stands for up, dn and 0
$\overline{p}_m$	Nominal power of each module composing the BESS [MW]	$\delta^*(t)$	Subinterval width as a fraction of time step t; * stands for up, dn and 0
n	Number of modules composing the BESS	$\delta(t)$	Time step width as a fraction of one hour
η	BESS charge/discharge efficiency	$\Delta f(t)$	Frequency deviation in time step t
K_p	BESS investment cost per unit of nominal power [€/MW]	$\phi_2(t)$	TSO signal for secondary regulation provision, i.e. level signal, in time step t
K_C	BESS investment cost per unit of capacity [€/MWh]		

Stochastic parameters

ψ_s	Scenario s probability	$p_{sbil}^{dn}(s,t)$	Downward NP-RES imbalance in time step t and scenario s
$\pi_\sigma^{sell}(s,t)$	Selling price for service σ provision in time step t and scenario s	$p_{sbil}^{up}(s,t)$	Upward NP-RES imbalance in time step t and scenario s
$\pi_\sigma^{buy}(s,t)$	Purchase price for service σ provision in time step t and scenario s		

2.4.1.4. Objective function

As said in the introduction of this section, the objective of the optimization on which the sizing tool called MUSST is based is the maximization of the ratio between the incomes originating from the provision, by the BESS, of all the considered services during one year of operation and the total investment costs.

Let us call $I^Y\left(\beta_\sigma, p(s,t), q(s,t), p_\sigma(s,t), q_\sigma(s,t), E(s,t) \middle| \pi_\sigma^{sell}(s,t), \pi_\sigma^{buy}(s,t), p_{sbil}^{dn}(s,t), p_{sbil}^{up}(s,t)\right)$ the function indicating the incomes of the one-year operation. Then, the objective function to maximize is

$$\frac{\sum_s \psi_s I^Y\left(\beta_\sigma, p(s,t), q(s,t), p_\sigma(s,t), q_\sigma(s,t), E(s,t) \middle| \pi_\sigma^{sell}(s,t), \pi_\sigma^{buy}(s,t), p_{sbil}^{dn}(s,t), p_{sbil}^{up}(s,t)\right)}{K_p\overline{p} + K_C C} \tag{2.15}$$

Dimensionally, this ratio represents the inverse of a time, with time measured in years; indeed, the inverse of this ratio provides a rough indication on the expected number of years needed to recover the investment for installing the BESS. Thus, by using this objective function and introducing proper constraints to represent both the technical characteristics of the BESS and the technical requirements imposed for the provision of each service considered, it is possible to obtain a technical-economical optimal sizing of the BESS.

We remark that, in expression 2.15, variables can be found both at the numerator and the denominator, making the objective function non-linear. Non-linear optimization problems are very hard to solve and, in many cases, the absolute optimality of the solution cannot be proven. On the contrary, linear optimization problems both are easier to solve and guarantee the absolute optimality of the solution found. Thus, it is necessary to formulate a linear version of objective function 2.15.

To this purpose, we observe, first of all, that function I^Y is already linear, since the incomes for the provision of each service are calculated as the sum of the products of the remuneration prices, which are parameters, for the amounts of energy provided, which are variables. Then, it is possible to approach linearity of expression 2.15 by making the hypothesis that the BESS is made of a number n of modules of given capacity C_m and nominal power $\overline{p}_m$, thus obtaining the following objective function 2.16; there the decision is on how many modules to install, that is on the value of n, which is the new first stage variable and is also an integer:

$$\frac{\sum_s \psi_s \{\sum_{\sigma,t} \delta(t)\delta^*(t^*(t))\left(\pi_\sigma^{sell}(s,t)p_\sigma(s,t) - \pi_\sigma^{buy}(s,t)q_\sigma(s,t)\right)\}}{n\left(K_p\overline{p}_m + K_C C_m\right)} \qquad \textbf{2.16}$$

Being n an integer variable, the model is still non-linear and now also mixed-integer: at first glance the problem is worsened. However, if n were a parameter, objective function 2.16 would be linear. So, the optimal value of n can be found by changing it within a loop, running the optimization of the annual operation for each given value of it and choosing the one for which the optimal value of function 2.16 is maximum.

In this new formulation, the only remaining first stage variables are the fractions of the nominal power dedicated to service σ provision, β_σ.

2.4.1.5. Technical constraints

In this section all the technical constraints considered in the optimization problem will be presented.

Stored energy balance

The energy stored in the BESS for each time interval t and scenario s is given by equation 2.17:

$$E(s,t) = E(s,t-1) - \delta(t) \sum_{*=up,0,dn} \delta^*\left(t^*(t)\right)\left(\frac{p\left(s,t^*(t)\right)}{\eta} - \eta q\left(s,t^*(t)\right)\right) \qquad \textbf{2.17}$$

Parameter $\delta^*\left(t^*(t)\right)$ takes into account the time interval length, as discussed in Paragraph 2.4.1.2. Total injection $p\left(s,t^*(t)\right)$ and total absorption $q\left(s,t^*(t)\right)$ are defined as functions of the injection and absorption for each service as indicated by the following equation 2.18:

$$p\left(s,t^*(t)\right) - q\left(s,t^*(t)\right) = \sum_\sigma \left(p_\sigma\left(s,t^*(t)\right) - q_\sigma\left(s,t^*(t)\right)\right) \qquad \textbf{2.18}$$

Constraints from regulatory requirements

The mathematical model includes a set of constraints to represent the regulatory requirements for the provision of each of the services considered, for instance the requirements included in network codes. This set of constraints obviously can change by changing the set of considered services and/or by changing the power system in which the BESS will be installed. The following constraints represent the present Italian requirements for the provision of primary (inequality 2.19), secondary (inequalities 2.20-2.22) and tertiary frequency regulation (inequalities 2.23-2.24): these hold, traditionally, for large conventional regulating power plants, but they have been applied here to a BESS as well.

$$\beta_1 \geq 0.015 \tag{2.19}$$

$$\beta_2 \geq 0.15 \tag{2.20}$$

$$p_2(s,t) \leq \frac{E(s,t)}{2\ h} \tag{2.21}$$

$$q_2(s,t) \leq \frac{C - E(s,t)}{2\ h} \tag{2.22}$$

$$p_3(s,t) \leq \frac{E(s,t)}{2\ h} \tag{2.23}$$

$$q_3(s,t) \leq \frac{C - E(s,t)}{2\ h} \tag{2.24}$$

In particular, inequality 2.19 states that a symmetric half-band of at least 1.5% of the nominal power of the BESS must be dedicated to the provision of PFR.

Inequality 2.20 imposes a similar requirement for the provision of SFR: at least a symmetric half-band of 15% of the nominal power must be dedicated to it. Presently BESS are not allowed to provide SFR in Italy (except in case of participation in the related pilot project by Terna [26], approved by ARERA in May 2021 [27]) and so no requirement for them is included in the network code; thus, the hypothesis that the same requirement imposed to hydroelectric units apply to BESS has been made.

Inequalities 2.21 and 2.22 impose that the BESS has to be able to maintain the given provision of SFR in time slot t for at least 2 hours. This requirement, again, currently applies to all the devices which are allowed to provide SFR in Italy, but it has been assumed for BESS as well here.

Inequalities 2.23 and 2.24 impose a similar requirement for the provision of tertiary regulation. It is worth noting that the Italian network code considers three kinds of tertiary regulation, namely ready, spinning and replacement tertiary regulation, which require to be able to keep the related power exchanges for at least 120 min, for at least 120 min and with no time limitations respectively. Therefore, the second kind is chosen here, because the time requirement of the third is too strong for a BESS and because the first kind contemplates only the upward direction. Besides, as a marketplace for tertiary regulation reserve procurement, only the ex ante stage of the ASM is considered here, for simplicity.

Primary regulation signal

As introduced in section 2.4.1.2, the power output for PFR is a function of the deviation of the system frequency from its nominal value. This dependency is expressed by a droop function $D(\Delta f(t))$, so the injection and absorption for primary regulation are given by equations 2.25

$$\begin{aligned} p_1(t^*(t)) &= \max\left(D\left(\Delta f(t^*(t))\right)\beta_1\overline{p}, 0\right) \\ q_1(t^*(t)) &= -\min\left(D\left(\Delta f(t^*(t))\right)\beta_1\overline{p}, 0\right) \end{aligned} \tag{2.25}$$

A graphical representation of the droop function considered for the BESS is shown in Figure 2-4.

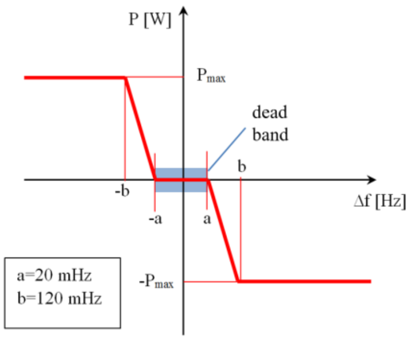


Figure 2-4 – Graphical representation of the droop function

Secondary regulation signal

As said in section 2.4.1.2, also the provision of SFR is driven by an external signal, $\phi_2(t)$, that is sent by the TSO. $\phi_2(t)$ is a discrete signal, whose value goes from 0 (0% more precisely), representing the maximum downward service supply, to 100 (100%), representing the maximum upward service supply; $\phi_2(t)$=50 (50%) indicates zero service supply, so no power output variation for the service.

Then, the output for secondary regulation is given by equations 2.26:

$$p_2\big(t^*(t)\big) = \frac{\max\big[\big(\phi_2\big(t^*(t)\big) - 50\big),0\big]}{50}\beta_2\overline{p}$$
$$q_2\big(t^*(t)\big) = \frac{-\min\big[\big(\phi_2\big(t^*(t)\big) - 50\big),0\big]}{50}\beta_2\overline{p} \qquad \textbf{2.26}$$

Other constraints

Since decision variables β_σ represent the (optimal) fraction of the nominal power dedicated to each service σ, their value is obviously positive and lower than 1 and they must sum up to one, that is

$$\sum_\sigma \beta_\sigma = 1 \qquad \textbf{2.27}$$

Finally the upper bounds on power and energy, given by the nominal power and the installed capacity respectively, together with the maximum available absorption and injection for each service σ have to be included:

$$0 \le p(s,t) \le n\overline{p}$$
$$0 \le q(s,t) \le n\overline{p}$$
$$0 \le p_\sigma(s,t) \le \beta_\sigma n\overline{p} \qquad \textbf{2.28}$$
$$0 \le q_\sigma(s,t) \le \beta_\sigma n\overline{p}$$
$$0 \le E(s,t) \le nC_m$$

Of course, as to NP-RES imbalance reduction functionality by the BESS, these consistency constraints are added:

$$0 \le p_{sbil}(s,t) \le \; p_{sbil}^{dn}(s,t)$$
$$0 \le q_{sbil}(s,t) \le \; p_{sbil}^{up}(s,t) \qquad \textbf{2.29}$$

2.4.2. Input signals

In order to compute the primary regulation signal, the needed input signal is the network frequency error, i.e. the difference between the current value of the frequency and the frequency set-point value (50 Hz here). To this purpose, real measured frequency data are adopted here. In order to compute the secondary regulation signal, the output signal of the centralised network PI controller provided by the TSO is needed. Again, real data are adopted here.

As to the NP-RES plant coupled with the BESS, the hourly imbalance data of an equivalent PV plant, resulting from the aggregation of real small distributed PV plants, are considered here; an imbalance is defined as the difference between the forecast and the actual power production values in each hour.

Additional input signals are needed in terms of market price time profiles, namely the DAM prices, the regulated prices for PFR, the bid prices for SFR on the BM and the bid prices for tertiary frequency regulation on the ex ante ASM, plus the aggregated imbalance sign for imbalance penalisation computation. Of course, the assumed acceptance/rejection status is also specified for the mentioned DAM, ex ante ASM and BM prices, according to acceptance criteria described in Subsection 3.4.1.

2.4.3. Output evaluation

The main simulation outputs are now, in addition to the optimal value of the objective function, the obtained BESS sizing, so its nominal power and energy, and the power bands to be devoted to each service/functionality.

3. Simulation results

This chapter provides a description of the main assumptions and results as to the four applications described in the Methodology chapter:

- the simulation of a BESS providing Frequency Response Services;
- the simulation of a BESS providing the EFR service;
- the optimization of a BESS's bids for the supply of balancing services in the balancing market;
- the optimization of the sizing, in terms of nominal energy and nominal power, and of the management, in terms of power bands, of a BESS for the simultaneous supply of different services/functionalities.

All of them except the EFR provision application take as a reference the Italian electricity market rules, while the EFR application refers to British TSO National Grid ESO's specifications.

3.1. BESS providing primary and secondary frequency response

In this section the combination of PFR and SFR is analysed, with reference to the Italian electricity market.

The study considers a BESS in a stand-alone configuration or coupled with an NP-RES power plant, more specifically a wind or a PV one; in case of coupling, the NP-RES plant may intervene for downward regulations if the BESS is not able to fulfil the requests.

3.1.1. Main assumptions

3.1.1.1. Input signals

In this study the input signals for PFR and SFR response are, respectively, CE system frequency data, more precisely a frequency time series measured at a Low-Voltage (LV) point at RSE premises, and secondary frequency controller data, i.e. the level signal time series, for the Italian continental control area, both for the time interval from 1st June 2015 to 20th December 2015 (about 29 weeks). System frequency data are available with 0.1 s sampling interval whereas the secondary grid controller output with a 1 min sampling interval.

As for the BESS coupled with an NP-RES plant, unit hourly renewable generation curves are available with reference to a wind power plant in central Italy and a PV plant in Sicily (synchronously connected to the continent). The original sizes of both plants have been normalized to 10 MW since this is the minimal plant size required by the Italian TSO to enable to these frequency regulations.

3.1.1.2. Primary Frequency Regulation requests

The power variation request to the BESS from the PF controller ($\Delta P_{BESS,req,PFR}(t)$) is implemented as a proportional control action, as recalled in Section 2.1.1. The droop is chosen by assuming that, according to the recommendations of the Italian TSO Terna, the whole primary reserve ($\pm PR_{max}$) is delivered within $\pm \Delta f_{max} = \pm 100\ mHz$ maximum frequency deviation around f_0. Furthermore, a $\pm \Delta f_{db} = \pm 20\ mHz$ deadband is considered.

The operation of the BESS primary controller model is shown in Figure 3-1.

The PF response by the BESS, in turn, is equal to the request if the SoC allows for this, otherwise only part of the requested power variation can be carried out.

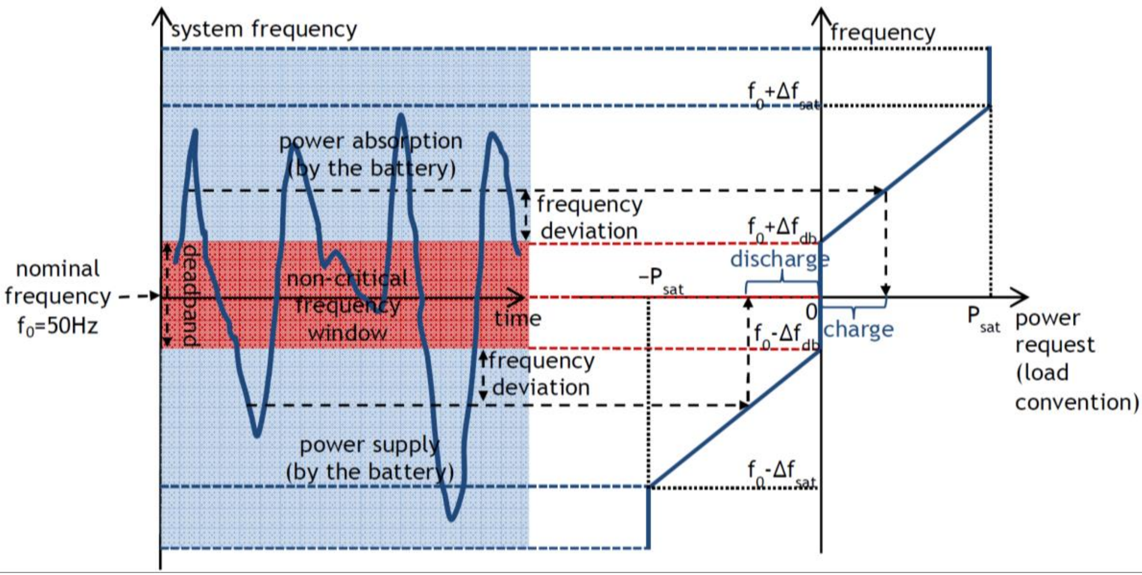


Figure 3-1 BESS controller model for the primary frequency response service

3.1.1.3. Secondary Frequency Regulation requests

In agreement with the Italian TSO Grid Code rules for conventional generation units, the power variation request to the BESS from the SF controller ($\Delta P_{BESS,req,SFR}(t)$) is implemented as described in Section 2.1.2, namely based on the level signal from the centralised network PI controller and with a limitation to the amount of maximum secondary reserve (SR_{max}) available.

The SF response by the BESS, in turn, is equal to the request if the SoC allows for this, otherwise only part of the requested power variation can be carried out.

3.1.1.4. BESS model, SoC management strategy and regulation requests handling

The adopted BESS model consists of the SoC dynamic model described in Section 2.1.4, where $P_{BESS,output}(t)$, namely the BESS power exchange with the grid, is the superposition of the default setpoint (here zero, for simplicity and since the BESS is assumed to be devoted to PFR and SFR), of the contributions to PFR and to SFR and of the SoC restoration power, respectively:

$$P_{BESS,output}(t) = P_0(t) + \Delta P_{BESS,PFR}(t) + \Delta P_{BESS,SFR}(t) + P_{BESS,SoC\_restoration}(t).$$

The BESS model schematic for Primary and Secondary Frequency Response Services is shown in Figure 3-2, also including the SoC restoration strategy.

Of course, due to SoC limitations and dissipation effects impacting on the SoC itself,

$$|\Delta P_{BESS,PFR}(t)| \leq |\Delta P_{BESS,req,PFR}(t)|$$

$$|\Delta P_{BESS,SFR}(t)| \leq |\Delta P_{BESS,req,SFR}(t)|$$

so the aim of the SoC restoration strategy is to increase BESS capability to satisfy regulation requests. In particular, the adopted SoC management strategy, described in Section 2.1.5, aims at restoring the SoC within a target range $[SoC_{tgt,min}, SoC_{tgt,max}]$ by exchanging power $P_{BESS,SoC\_restoration} = \pm P_{rest}$ when the SoC is outside the target range and no regulation requests are present.

In case the BESS is stand alone, the two regulations are always switched on, so “no regulation requests” means that either the frequency is in its deadband and the level signal is 50%, or the superposition of the PFR and SFR requests turns out to be zero. In case the

BESS is in support of an NP-RES plant, instead, when the plant is generating less than or exactly a threshold power $P_{RES,min}$ the two regulations are here assumed to be switched off, so this is another occasion on which no regulation requests are present. Here, $P_{RES,min}$ = 10% $P_{n,RES}$, where $P_{n,RES}$ is the NP-RES plant rated power.

In case an NP-RES plant is present and the overall regulation request is downward, if the BESS cannot accomplish the downward request completely, then a request is sent to the plant to supply the power variation left which the BESS cannot carry out (this is also why the mentioned threshold has been introduced); this is called the "residual" power exchange request. In that case, again, it may happen that the plant can fulfill the request or cannot fulfill the request, completely or in part. Upward regulation requests, instead, are assumed not to be allowed for the NP-RES plant.

As to the management of the superposition of PFR and SFR requests, particular attention has to be devoted to the time instants when the overall power variation request due to the two regulations exceeds the BESS power availability. In fact, the maximal absolute values of the power which can be absorbed or injected by a battery, namely $P_{max,ch}$ and $P_{max,disch}$, are functions of the SoC and decrease to zero as the battery SoC approaches 1 (full battery) or 0 (empty battery); their maximum value is anyway assumed here to be equal to the BESS nominal power (P_n), so no overcharge or overdischarge are allowed. Therefore, when the SoC approaches the 1/0 limits, it may happen that the overall request cannot be accomplished, in part or in total (such an event can also occur with PFR and SFR requests with opposite signs). Simple criteria can be introduced to give priority to one of the two services or to try to satisfy partially both of them at the same time, by taking into account the current SoC, i.e. the current value of the maximum charging power and maximum discharging power, and the direction (upward or downward regulation) of the power output variations requested by PFR and SFR. This way, the missed power variations, and therefore the energy exchanges which are "lost" with respect to the regulation purposes, can be also quantified. The simulation results reported later on have been obtained by adopting a simple criterion: when the overall request exceeds the BESS power availability, the power exchanged by the BESS is divided in a proportional way with respect to the two regulation Half-Bands (HBs).

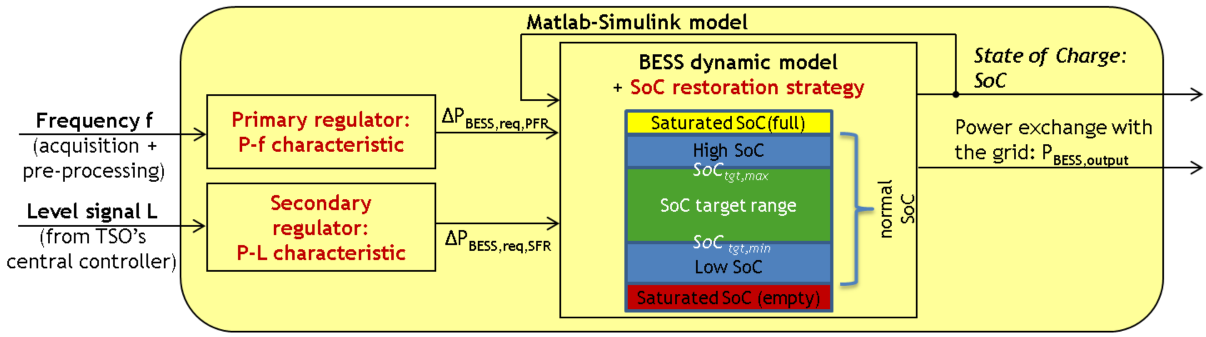


Figure 3-2 BESS model schematic for PFR and SFR

3.1.1.5. BESS parameters and aging estimation

Three BESS technologies are considered in the analyses: the sodium-sulfur (later "NaS") one, the lithium-ion one (later "Li") and the sodium-nickel chloride one (later "$NaNiCl_2$"). Table 3-1 shows the BESS parameters adopted in the simulations, also as far as the SoC restoration strategy is concerned.

The BESS cycling aging estimation is accomplished as described in Section 2.1.6, namely with the standard method based on full equivalent cycles and with a refined method taking into account the partial cycles carried out.

As to the former, the values assumed for the allowed maximum number of cycles are also reported Table 3-1 for the considered NaS, Li and $NaNiCl_2$ technologies; standard cycles both at 100% DoD and at 80% DoD are taken into account.

As to the latter, instead, the adopted $n_{max} = f(DoD)$ characteristic curves are the ones reported in Figure 2-1. They are described in more detail in [28] (see also [11], [9], [29] and [30]). For the DoD values not present in the plotted curves, a linear extrapolation of the curves themselves is assumed.

Table 3-1 – Battery technological parameters and parameters for the SoC restoration strategy

Parameter	NaS	Li	$NaNiCl_2$
E_n/P_n [h]	7.5	2	3
Discharge efficiency $\eta_{discharge}$ [-]	0.866	0.922	0.922
Charge efficiency η_{charge} [-]	0.866	0.922	0.922
Restoration power P_{rest} [$\%P_n$]	20	20	20
$SoC_{tgt,min}$ [-]	0.4	0.4	0.4
$SoC_{tgt,max}$ [-]	0.6	0.6	0.6
Initial SoC in the simulations [-]	0	0	0
Maximum number of cycles to end of life, at 80% DoD [-]	4500	4000	4500
Maximum number of cycles to end of life, at 100% DoD [-]	4000	3000	3000

3.1.1.6. BESS sizing

As already hinted at, we assume that the simulated BESS can modulate its power output between 0 and $P_{max,ch}$ in charge and between $-P_{max,disch}$ and 0 in discharge, where both $P_{max,ch}$ and $P_{max,disch}$ are equal to or lower than its rated active power P_n. Since the BESS is completely devoted to the two frequency response services, we assume

$$P_n = PR_{max} + SR_{max},$$

where the maximum primary reserve and the maximum secondary reserve, PR_{max} and SR_{max} respectively, are taken as the PFR and the SFR HB respectively. For a BESS supporting an NP-RES plant with rated power $P_{n,RES}$, the rated power of the BESS is assumed to be composed of two parts: a part to carry out the regulations for the BESS itself (Part 1) and a part to carry out the regulations on behalf of the NP-RES power plant (Part 2):

$$P_n = \left(PR_{max,1} + SR_{max,1}\right) + \left(PR_{max,2} + SR_{max,2}\right),$$

so that the maximum primary and secondary reserve, or HB here, can be defined as $\left(PR_{max,1} + PR_{max,2}\right)$ and $\left(SR_{max,1} + SR_{max,2}\right)$, respectively.

The BESS rated active power sizing adopted in the simulated cases is reported in Table 3-2. It has been chosen starting from the Italian TSO Grid Code rules for conventional units (Annex 15 of [5]):

- the maximum primary reserve corresponds to the minimum primary reserve which can be required to each eligible conventional generation unit; this amounts to 1.5% of the rated active power output, 10% in case of the Sardinian power system and of islanded operation of Sicily;
- the maximum secondary reserve corresponds to the minimum secondary reserve which can be required to each eligible conventional generation unit; this amounts to 6% of the maximum available active power output for thermal power plants and 15% for hydro power plants.

In terms of absolute values, in case of a stand-alone BESS configuration the reserves are referred to a 10 MW reference generation unit (namely with rated power $P_{n,REF}$ = 10 MW), whereas in case of a BESS coupled with an NP-RES unit we consider a 10 MW wind generation unit or a 10 MW PV unit. Besides, for simplicity, for all the configurations the rated power has been adopted as the reference power with respect to which to compute the per cent values yielding the reserves.

Table 3-2 – BESS sizing

Stand-Alone BESS			
Case Nr	***PFR HB: HB_{PR_BESS} in % of $P_{n,REF}$***	***SFR HB: HB_{SR_BESS} in % of $P_{n,REF}$***	***BESS rated active power: P_n [MW]***
1	1.5	6	0.75
2	1.5	15	1.65
3	10	6	1.6
4	10	15	2.5
BESS Supporting an NP-RES Plant			
Case Nr	***PFR HB: $HB_{1\_PR\_BESS}$ + $HB_{2\_PR\_BESS}$***	***SFR HB: $HB_{1\_SR\_BESS}$ + $HB_{2\_SR\_BESS}$***	***BESS rated active power: P_n [MW]***
5	1.5% P_n +1.5% $P_{n,RES}$	6% P_n +6% $P_{n,RES}$	0.82
6	1.5% P_n +1.5% $P_{n,RES}$	15% P_n +15% $P_{n,RES}$	1.98
7	10% P_n +10% $P_{n,RES}$	6% P_n +6% $P_{n,RES}$	1.91
8	10% P_n +10% $P_{n,RES}$	15% P_n +15% $P_{n,RES}$	3.34

3.1.1.7. Economic evaluation criteria

The combination of the primary and secondary frequency response has been evaluated economically according to the current Italian market rules for conventional power plants as to PFR and SFR remuneration, plus imbalance rules for non-eligible generating units (i.e. the ones not enabled to provide ASs, namely the ones with nominal power lower than 10 MW and the non-programmable ones) as to SoC restoration, as described in Section 2.1.8.3. Economic evaluations have been carried out for the current Italian electricity market zones in the mainland (see Figure 3-3 for a scheme with all the zones): Northern Italy, Central Northern Italy, Central Southern Italy, Southern Italy (in this last case, also the limited production poles, i.e. the virtual market zones, of Foggia, Rossano and Brindisi have been included). Labels also adopted in the following for the zones are NORD, CNOR, CSUD and SUD, respectively.

Here, the year 2015 is considered, so the adopted parameters for PFR remuneration are p_1 = 119.82 €/MWh, p_2 = 51.83 €/MWh, p_3 = 54.99 €/MWh and p_4 = 13.58 €/MWh. As for the order of magnitude of the DAM price level, in 2015 the average in the four considered zones was 53, 51, 51 and 49 €/MWh, respectively.

As for SFR, the historical upward/downward accepted zonal prices in the BM (which has a 15 minute granularity) have been considered. In particular, as for the order of magnitude of the price level, in 2015 in the four considered market zones, NORD, CNOR, CSUD and SUD, the average accepted energy prices for upward SFR were 133, 146, 115 and 120 €/MWh, respectively, and the ones for downward SFR were 10, 14, 6 and 5 €/MWh, respectively.

Finally, as to BESS investment costs, the values adopted in the simulations are reported in Table 3-3 [31].

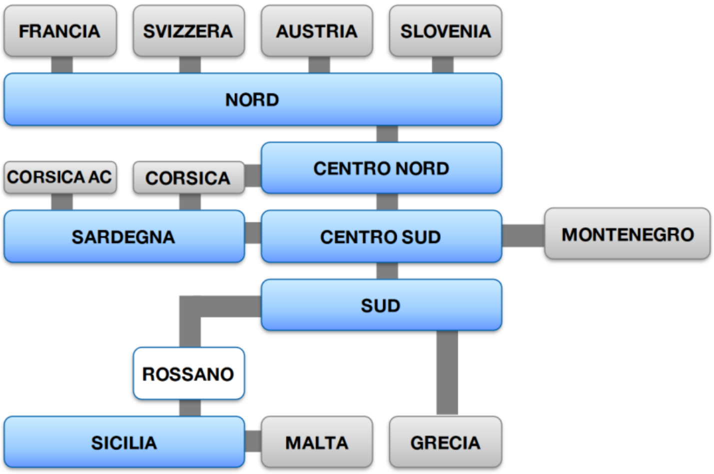


Figure 3-3 The Italian market zones with their connections (source: Terna)

Table 3-3 – BESS investment costs based on battery technology

	Li	NaS	$NaNiCl_2$
Battery [€/kWh]	600	400	583
Power conversion system [€/kW]	300	300	300

3.1.2. Simulation results: technical and economic evaluations

Simulations are carried out with reference to the 29-week time interval 1st June 2015-20th December 2015.

The three BESS technologies chosen (i.e. "NaS", "Li", "$NaNiCl_2$") have been simulated in each of the three following "configurations", both with and without the described SoC restoration mechanism:

- stand-alone BESS;
- BESS coupled with an NP-RES plant:
  - BESS coupled with a PV plant;
  - BESS coupled with a wind power plant.

Thus, in total 72 simulations of the BESS response to the requests of the two frequency response services along the reference time interval have been carried out.

For each simulation with a stand-alone BESS, absorption and injection energy exchanges with the grid have been computed, related to

- "ideal" and "actual" regulation requests by the PF and SF controllers;
- regulation requests accomplished by the BESS;
- regulation requests which cannot be accomplished, due to SoC saturation to 1 or 0, and so which are completely or partially "lost" for regulation purposes;
- SoC restoration.

Similarly, for each simulation with a BESS coupled to an NP-RES (wind or PV) plant, the same energy exchanges have been computed, together with the energy exchanges requested to the plant in case the BESS cannot accomplish the regulation requests completely.

We recall that the original requests coming from the PF and SF controllers, based on frequency and on the level signal, respectively, are called "ideal" requests. These are sent directly to the BESS in case of a stand-alone configuration, thus becoming "actual" requests for the BESS. In case of a coupled configuration, instead, when the power generated by the plant is below the threshold, the controllers' (ideal) requests are ignored by the BESS, i.e. the requests actually sent to the BESS are equal to zero.

Results about the considered energy exchanges are reported in the bar plots of Figure 3-4, in absolute value for simplicity.

In particular, the energy exchanges actually carried out for PFR are in the 7-56 P_n h range for a stand-alone BESS and 2-22 P_n h for a BESS coupled with an NP-RES plant, whereas the energy exchanges actually carried out for SFR are in the 425-1400 P_n h range for a stand-alone BESS and 166-665 P_n h for a BESS coupled with an NP-RES plant. As to energy exchanged for PFR, the maximum absolute value (around 55 P_n h both in absorption and in injection) is obtained with the 1.6 MW stand-alone BESS, which is characterized by SFR to PFR HB ratio equal to 6/10; the minimum absolute value (around 2 P_n h both in absorption and in injection) is obtained with a 1.98 MW BESS+PV plant (this BESS has SFR to PFR HB ratio equal to 15/1.5). As to energy exchanged for SFR, the maximum absolute value (around 1400 P_n h and 1000 P_n h in absorption and in injection respectively) is obtained with the 1.65 MW stand-alone BESS, which is characterized by SFR to PFR HB ratio equal to 15/1.5; the minimum absolute value (around 300 P_n h and 200 P_n h in absorption and in injection respectively) is obtained with a 1.91 MW BESS + PV plant (the BESS has SFR to PFR HB ratio equal to 6/10). The differences between the stand-alone configuration and the coupling with an NP-RES plant are not significantly affected by the BESS technology.

On the whole, with the BESS stand-alone configuration the total energy exchanged is about 4-5 and 2-3 times, for PFR and SFR respectively, the total energy exchanges with the BESS coupled to an NP-RES plant. The presence of the minimal threshold on the plant power production, in fact, implies that the requests for regulation actually sent to the BESS (and eventually to the NP-RES plant) are less, in absolute value, than the original ("ideal") requests coming from the PF and SF controllers.

NP-RES power fluctuations impact on BESS operation in particular in case of the BESS+PV configuration, since the time intervals in which NP-RES production is zero include the night hours as well; however, energy values for the BESS+wind configuration are not so different from the ones for the BESS+PV configuration, since the considered wind production profile is not so wide.

As to the comparison between the response to PFR and to SFR, instead, in general in absolute value of the energy exchanged for SFR is much higher than the energy exchanged for PFR, and this aspect is particularly emphasized for the stand-alone configuration. In more detail, the total energy exchanged by the BESS for SFR is on average about 50 times the total energy exchanged for PFR, and in particular, with a BESS in the stand-alone configuration this ratio is about 25-60 times (considering the different technologies and sizes), whereas about 30-80 times (again considering the different technologies and sizes) with a BESS coupled to an NP-RES plant. The presence of an NP-RES plant reduces the BESS contributions to regulation, but the reduction of the energy for PFR makes the ratio between the energy for SFR and for PFR increase. As already remarked, technology here does not seem to have a big impact: e.g. although the NaS BESS energy capacity is much larger than the Li one, the ratio between the NaS BESS actual energy exchanges and the Li BESS actual energy exchanges for PFR is around 1-1.2, for SFR it is around 1.1-1.3.

As to SoC restoration, one can observe that the related energy exchanges are rather small (some P_n h) for the stand-alone configuration cases, while they are not negligible for the BESS+NP-RES plant configuration (20-105 P_n h for the NaS case, 15-50 P_n h for the Li case, 15-75 P_n h for the $NaNiCl_2$ case). Such energy exchanges represent about 5%, as to charging energy, and 11%, as to discharging energy, of the total energy request for frequency regulation (PFR+SFR). On the whole, anyway, the chosen restoration strategy does not turn out to be very effective in improving the response performance (which is globally about 96% and 92% of PFR and SFR energy requests, respectively, independently of the presence or not of the SoC management), since the SoC restoration process is activated for a very short time. More precisely, the fraction of time in which the SoC restoration is carried out (light green bars in the plots) is very small in stand-alone cases, since the BESS is almost always requested to do SFR, to which PFR is also superposed; this fraction of time can reach a few percentage points in cases with an NP-RES plant, due to the presence of the NP-RES plant power threshold.

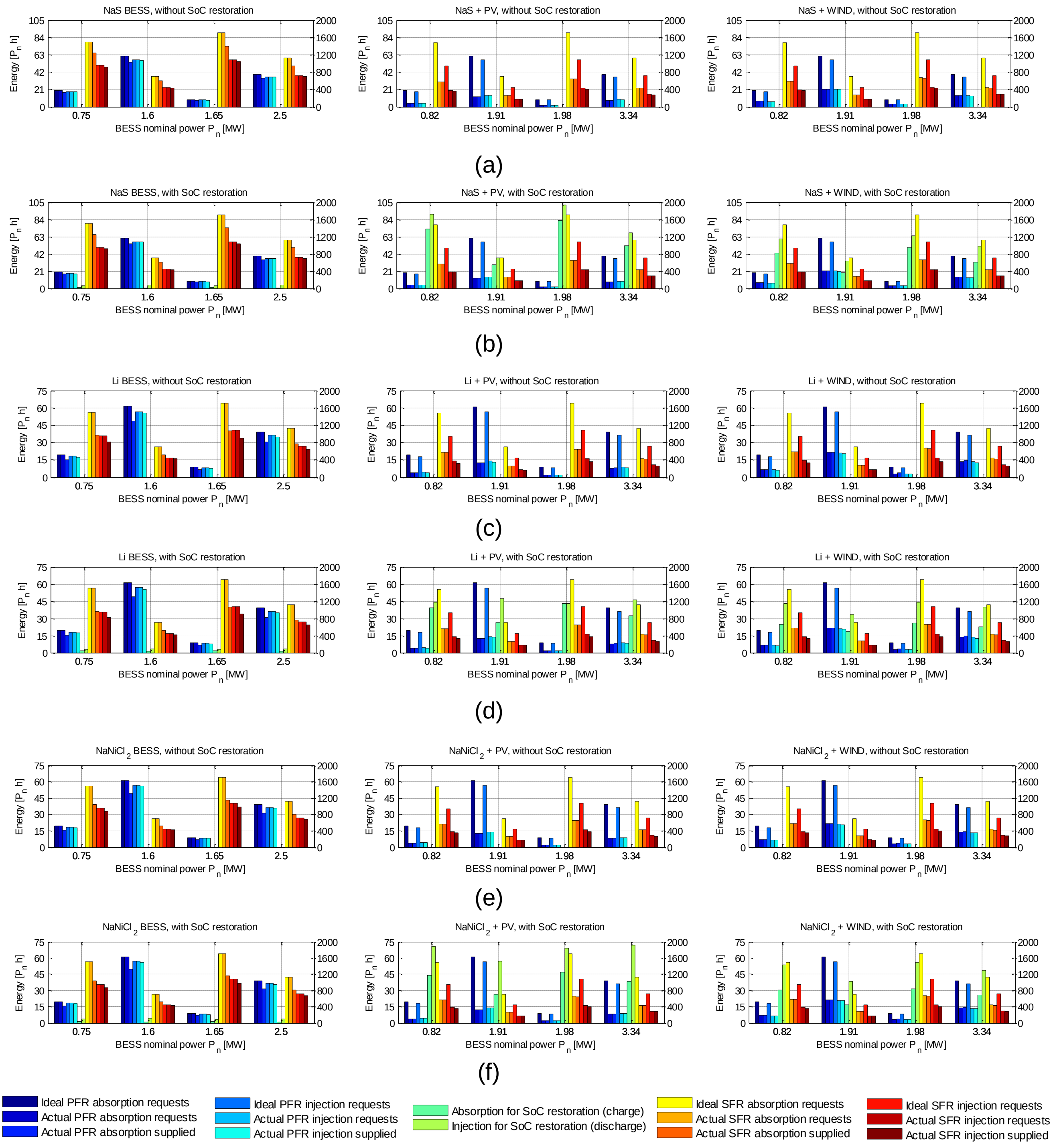


Figure 3-4 Energy exchanges in the different configurations considered, with partitioning of the exchanges for PFR and SFR proportional to the two related HBs; the left y axis in each plot is adopted for PFR and SoC restoration, the right y axis for SFR

From the economic point of view, Figure 3-5 shows the remuneration associated to the energy exchanges reported in Figure 3-4, for market zone NORD; for SFR, in particular, the average prices of the accepted UPs and DWs in each quarter of an hour have been adopted.

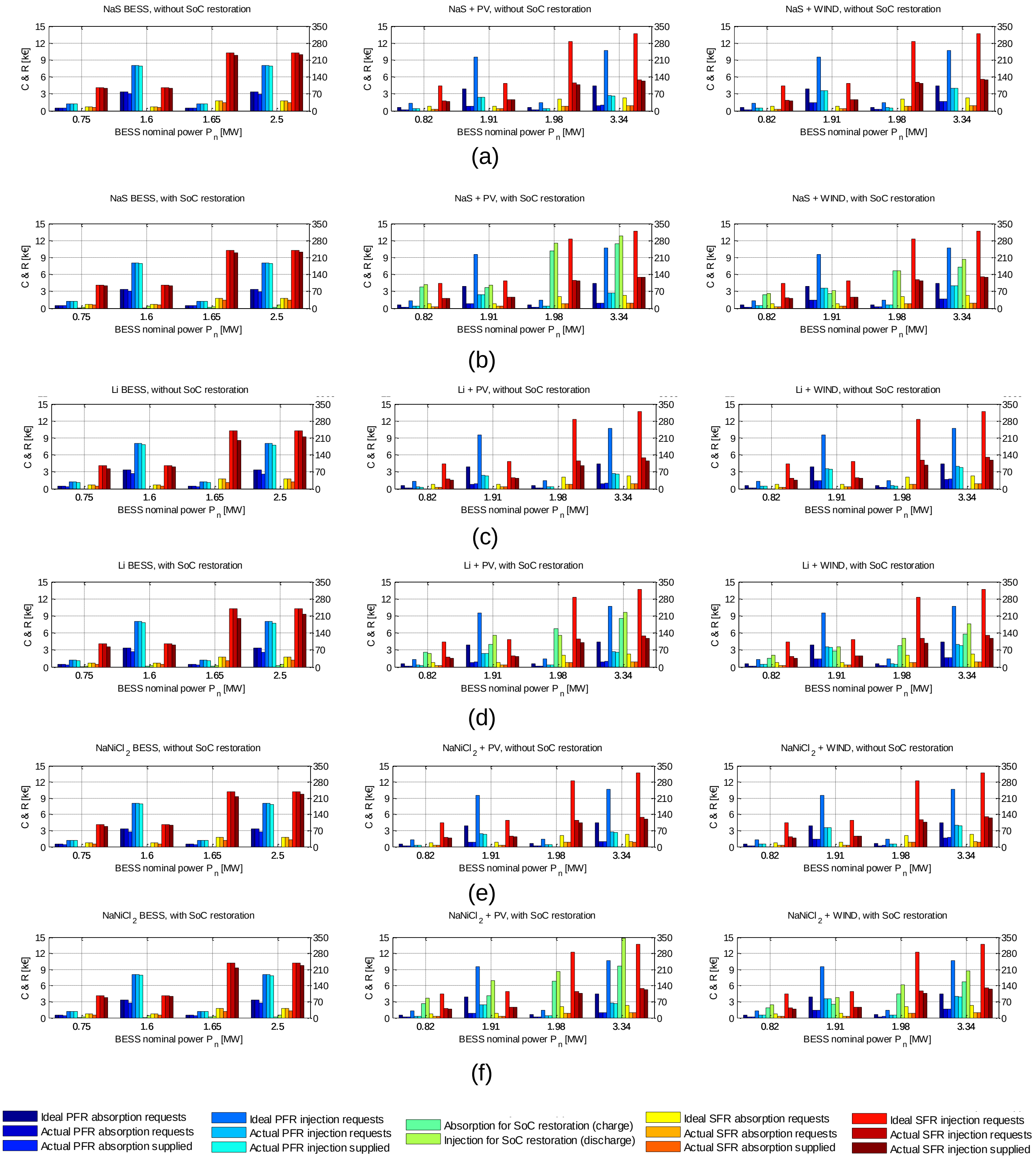


Figure 3-5 Costs and revenues associated to the energy exchanges in the different configurations considered, for the NORD market zone; the left y axis in each plot is adopted for PFR and SoC restoration, the right y axis for SFR

The PFR service generates a cash flow, in case of the stand-alone configuration, equal to approximately 2.5-3 times the one obtainable with a BESS coupled with a renewable plant: in particular, for the 1.6 MW and the 2.5 MW BESS, a maximum value for injection around 8 k€ is obtained and a maximum value for absorption around 3 k€ are obtained, against maximum values amounting to 3 k€ and 1 k€ respectively in the presence of a renewable plant coupled with a 1.91 MW and a 3.34 MW BESS. Again with the stand-alone configuration, the SFR service generates almost 240 k€ maximum revenue (against 35 k€ maximum cost) for a 1.65 MW and a 2.5 MW BESS, almost twice the revenue obtainable with a BESS coupled with a renewable plant. As to SoC restoration, the related cash flows, in terms of both costs and revenues, are much greater in the case of a BESS coupled with a renewable plant: in particular, the BESS+PV coupling shows a maximum revenue of almost 350 k€ with a $NaNiCl_2$ BESS and a maximum cost of about 280 k€ with a NaS BESS for a 3.34 MW BESS, while the BESS+wind coupling shows, for the same 3.34 MW BESS size, a maximum revenue of approximately 210 k€ and a maximum cost of approximately 175 k€ with the NaS technology.

In short, SFR, in particular for stand-alone configurations, is much more profitable than PFR (due to larger energy exchanges and more profitable prices). Besides, net revenues related to SFR are much higher than the net revenues associated to SoC restoration. More precisely, in the absence of SoC restoration, the maximum revenue obtainable with the secondary regulation is about 30 and 80 times that obtainable from the primary regulation, for a stand-alone and coupled BESS, respectively, against a cost about 11 and 35 times that obtainable from the primary regulation. An additional contribution to the revenue can be obtained with the restoration phase, but then a non-negligible cost component must also be considered.

As to the other three market zones considered here (CNOR, CSUD, SUD), the cash flow trend for the PFR service is very similar to that in the NORD zone, while the contribution from the maximum revenue from SFR decreases significantly. In the CSUD zone, in particular, for both the stand-alone and the coupled BESS configuration, the maximum revenue obtained is about half that in the NORD zone. In the CNOR and SUD zones, however, this reduction is less pronounced for the stand-alone configuration. It should also be noted that the reduction of the revenue is also accompanied by a reduction of the costs, sometimes more accentuated than that of the revenue; therefore, the contribution of revenues prevails in the net profit. Summing up, the most profitable zones are NORD and CNOR.

The economic sustainability of the considered services is estimated by assuming for the three BESS technologies the costs reported in Table 3-3 and by computing the PBP for all the simulation cases. Results are reported in Figure 3-6 for the NORD zone, which is not only the most profitable zone for PFR+SFR according to this analysis, but also the zone where most energy exchanges for SFR were actually carried out in the Italian ASM in 2015 (around 53% of the overall SFR downward exchanges and around 57% of the overall SFR upward exchanges). In the figure, different prices are adopted for SFR: the already mentioned average accepted prices in each quarter of an hour (“avg” label), plus the maximum accepted prices (“max” label), the minimum accepted prices (“min” label), the maximum upward accepted prices and the minimum downward accepted prices (“max-max” label), and the minimum upward accepted prices and the maximum downward accepted prices (“min-min” label); these last can be considered as the most and least profitable instance, respectively, which might have occurred.

On the whole, Figure 3-6 shows that investment costs could be recovered after a number of years which, for average SFR prices e.g., is in the range 7.9-15.8 years for a stand-alone Li BESS, 20.6-43.8 years for a Li BESS+NP-RES plant, 15.4-34.6 years for a stand-alone NaS BESS, 38.0-90.4 years for a NaS BESS+NP-RES plant, 10.0-21.2 years for a stand-alone $NaNiCl_2$ BESS, 25.5-58.2 years for a $NaNiCl_2$ BESS+NP-RES plant. The very high PBP values (tens of years) obtained in case a BESS is supporting an NP-RES plant are related, again, to the limited use of the BESS due to the minimum renewable power threshold for activating the provision of the services. For a BESS in the stand-alone configuration, in fact, the PBP is considerably reduced, more than a half.

The minimal values of the PBP and values relatively close to them are obtained for the cases where the ratio SFR HB/PFR HB is high, i.e. cases 2 (15/1.5) and 1 (6/1.5) and cases 6 (15/1.5) and 5 (6/1.5) of Table 3-3 above. This way, in fact, the profitability of SFR is exploited, and at the same time the investment for the BESS is not too high because of the relatively small BESS size. These values should anyway be compared with the batteries life, as discussed below.

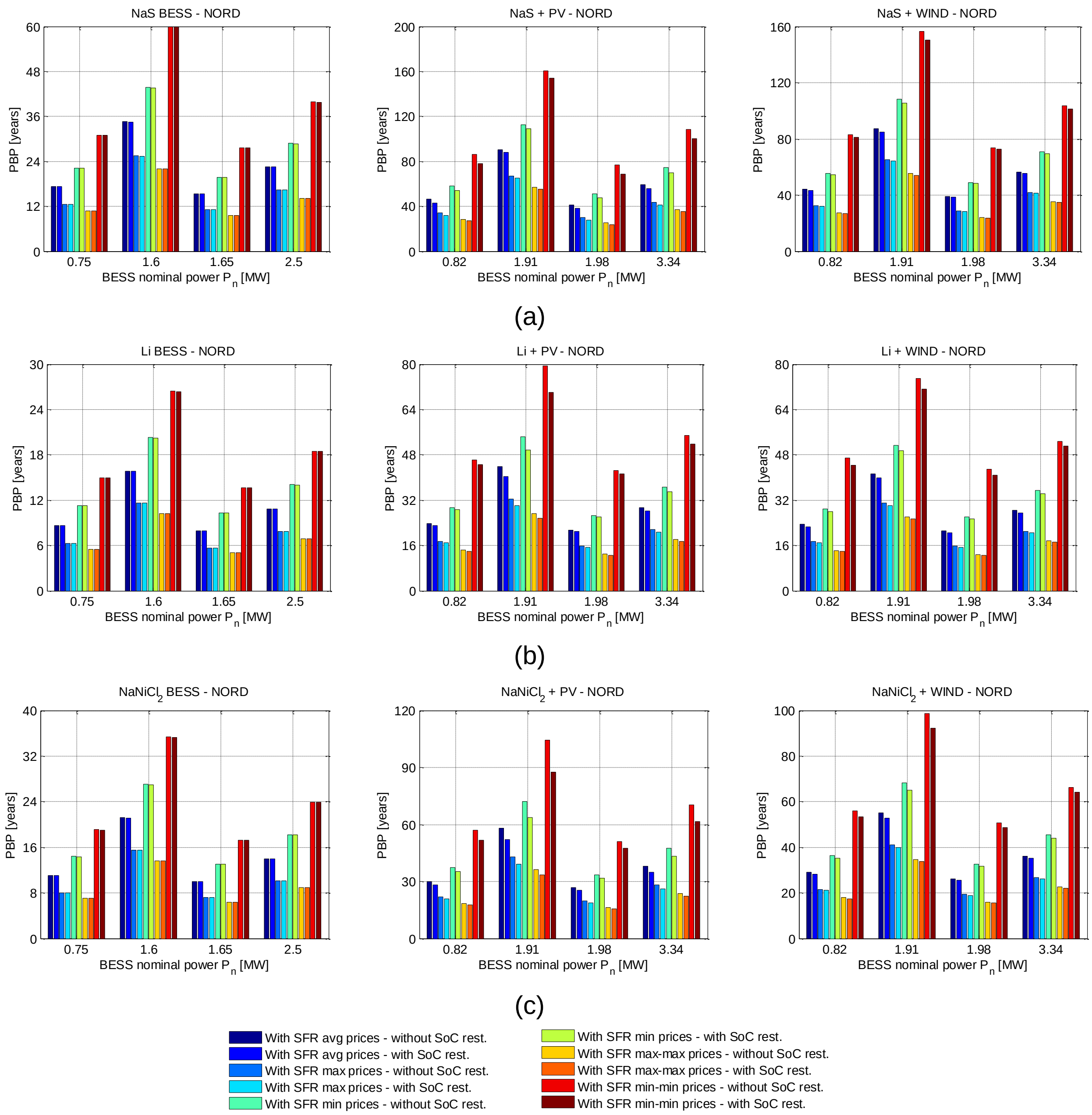


Figure 3-6 - PBP years, computed for the different BESS configurations considered and for a partition of the energy exchanges proportional to the two regulation HBs, for the NORD market zone only and with different assumptions on prices for SFR: (a) NaS BESS, (b) Li BESS, (c) NaNiCl$_2$ BESS

3.1.3. BESS aging estimation

The BESS cycling aging estimation with the standard method based on full equivalent cycles and with the refined method taking into account partial cycles and $n_{max}(DoD)$ characteristic curves is carried out for all the simulations. Results about the estimated BESS useful life are reported in Figure 3-7 (of course, they are independent of the partition of the energy exchanges between PFR and SFR, since the variations of the SoC depend on the overall exchanges, due to regulations and, if present, SoC restoration).

As to DoD_{avg} (not reported, for brevity) in particular, one can observe that, since smaller power variations due to PFR are superposed to larger ones due to SFR, the main effects on the DoD and aging are related to SFR. In fact, the power exchanges related to PFR are, on average, some per cent of the maximum power output, i.e. of the rated power P_n, while the ones related to SFR are on average on the order of 20-30% P_n; besides, with the assumptions made, the former are delivered on a 100 ms basis, while the latter are kept constant over 1 minute intervals; therefore, the DoD values related to SFR are larger and smoother than the ones related to PFR.

Furthermore, DoD_{avg} is significantly smaller than 100% or 80%: more precisely, in all the configurations, for NaS BESS it is between 2.3% and 4.2%, for Li it is between 6% and 17% and for $NaNiCl_2$ it is between 11% and 22% (and in each simulated case the it is essentially the same with or without the SoC restoration mechanism, because, as already mentioned, this mechanism activates for a short time, especially for the stand-alone BESS, e.g. since the level signal for SFR is rarely different from 50%). However, while for NaS and Li BESS battery life, in years, obtained with the average DoD approach is much longer (about 3-4 times) than the life values obtained with the standard approach, for $NaNiCl_2$ BESS it is comparable with them: this occurs since for small DoD values $n_{max}(DoD)$ is very large for NaS and Li BESS, but relatively small for $NaNiCl_2$ ones. Besides, coupling each BESS with an NP-RES plant yields much longer life than for the stand-alone BESS, again due to the minimum NP-RES generation threshold; however, this is not evident for the $NaNiCl_2$ BESS with the average DoD approach, again because for small DoD values $n_{max}(DoD)$ is relatively small for such BESS.

Finally, the computed battery life values are compared with the PBP values already determined. Battery life estimated at 100% DoD or 80% DoD is higher than the PBP for NaS BESS only (more precisely, in general the PBP is comparable to life, apart in case SFR HB/PFR HB = 6/10), while life estimated at the average DoD is higher than the PBP both for the NaS and for the Li BESS: for the $NaNiCl_2$ technology, in fact, the number of cycles performed is higher, as compared in particular to the NaS BESS, due to the smaller energy capacity, combined with a fairly similar maximum number of cycles curve as a function of the DoD.

One also has to remark that BESS cycling life, therefore the PBP too, must always be compared with the BESS duration linked to the decay of the batteries even in the absence of cycling, i.e. with their calendar life (typically 10-20 years, but variable depending on the specific technology).

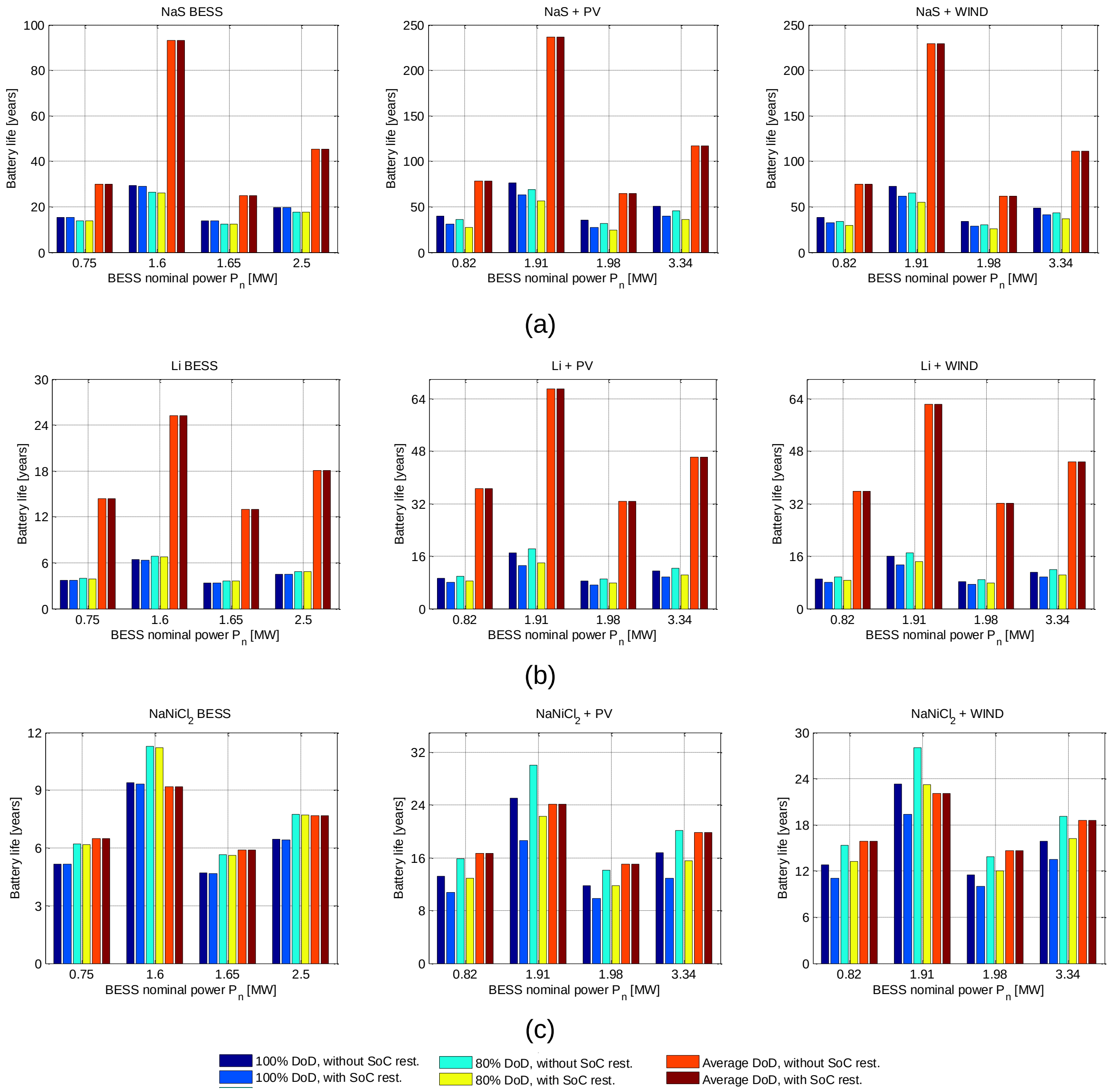


Figure 3-7 - Battery cycling life estimate, computed for the different BESS configurations considered: (a) NaS BESS, (b) Li BESS, (c) $NaNiCl_2$ BESS

3.2. BESS providing a Fast Frequency Response service

The possible performance of a stand-alone BESS in providing the EFR service is assessed here, with reference to the GB system and by considering the service technical requirements issued by the GB TSO. Some considerations will also be drawn in the assumption that such requirements were adapted to a very different synchronous system, namely the CE system: this latter is much larger than the GB one, it is a robustly interconnected system including several control areas, where TSOs can rely not only on local resources for AS supply, but also on shared resources, and where technical requirements for frequency regulation are different. The adaptation will be carried out based on the CE grid frequency statistical features.

3.2.1. Main assumptions

3.2.1.1. Input signals

The EFR is simulated by using historical frequency data:

- a system frequency series for the GB area spanning 2014 and 2015, with sampling rate 1 s (downloaded from the GB TSO's website [32]);
- a system frequency series for the CE area with the same sampling rate, obtained from LV measurements carried out at RSE from 4th April 2014 to 20th December 2015.

The GB frequency distribution (Figure 3-8, green curve) has two peaks, at around 49.981 Hz and 50.019 Hz (as highlighted in [33], these could be related to the fact that most regulating plants in GB are characterized by the same value for the primary frequency regulation deadband), the former being higher than the latter; the valley between the two peaks is at about 50.004 Hz. The CE frequency distribution (Figure 3-8, blue curve), instead, looks much like a Gaussian one.

The former has mean about 49.9997 Hz, standard deviation about 0.0544 Hz and almost no samples with distance from 50 Hz larger than 200 mHz (in both directions); the latter has mean about 50.007 Hz, standard deviation about 0.0207 Hz and almost no samples with distance from 50 Hz larger than 100 mHz (in both directions). The computed frequency distribution curves confirm the standard frequency deviation range of ±200 mHz and ±50 mHz for GB and CE respectively [23].

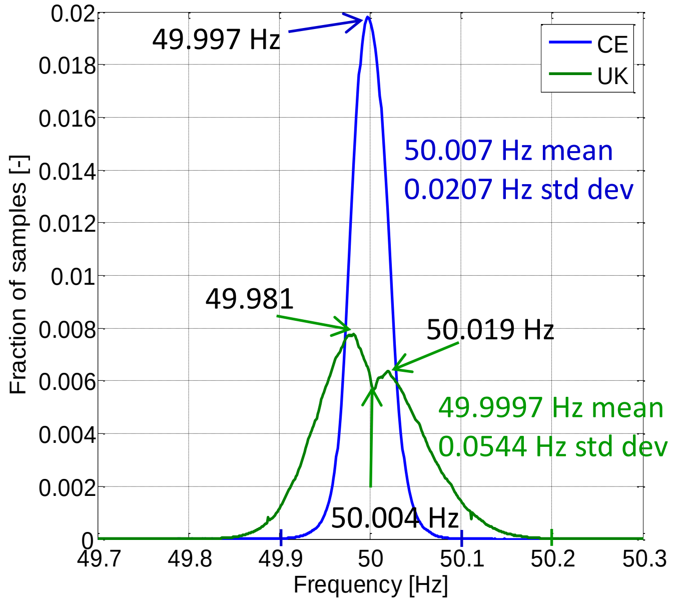


Figure 3-8 Comparison between the GB and CE system frequency distributions obtained from the available data

3.2.1.2. Technical requirements and performance indicators

As far as technical requirements for service supply are concerned, according to the rules defined by the British TSO, the power output of a device providing the EFR service in GB [18] has to be within the so-called "envelope" region, reported in **Figure 2-2**, at all times. Table 3-4 reports the values of the coordinates of the main points defining the envelope region. Two sets of coordinate values are foreseen, referred to as "Service 1" (with milder EFR requests) and "Service 2" (with stronger EFR requests). The same kinds of requirements are here assumed also for the CE system, so two sets of coordinates are devised for the CE system too, based on its measured frequency.

As to measuring performance in service supply, as described in Section 2.2.2, from the half-hourly SPM index one can compute the AF index, according to Table 3-5. We assume the same performance computation mechanisms and the same values of the parameters relating the SPM and the AF for both the GB and the CE system.

Table 3-4 – Parameters of the envelope region for the EFR service (load convention for the sign of power), for the GB and CE systems

	Service 1	**Service 2**
	GB (CE) [mHz]	***GB (CE) [mHz]***
$\Delta f_{A,F}$	500 (200)	500 (200)
$\Delta f_{B,E}$	250 (100)	250 (100)
$\Delta f_{C,D}$	50 (20)	15 (5)
	GB and CE [%Capacity]	***GB and CE [%Capacity]***
$P_{t,z}$	100	100
$P_{u,y}$	44.44444	48.45361
$P_{v,x}$	9	9

Table 3-5 – SPM and AF, for both the considered power systems

SPM	**AF**
SPM < 50%	0%
50% ≤ SPM < 75%	50%
75% ≤ SPM < 95%	75%
SPM ≥ 95%	100%

3.2.1.3. BESS model, study cases and SoC management

A BESS is assumed here to be completely devoted to the EFR service, so the tendered maximum capacity is assumed to always be equal to its nominal power P_n. At each sampling instant (every 1 s), a setpoint P_{req} for the BESS power generation or consumption for the service is issued, depending on the current value of the frequency and chosen inside the envelope region.

The BESS response to the setpoint request, namely the power it absorbs from or injects into the grid, i.e. $P_{abs} \geq 0$ or $P_{inj} \leq 0$ according to the load sign convention, does not depend only on P_{req} itself, but also on the dynamic behaviour of the battery SoC. Such behaviour is described by the same model adopted for PFR and SFR supply. For simplicity, the BESS power availability is assumed to be equal to $\pm P_n$ for the whole SoC range between 0 and 1.

In order to analyse EFR supply by a BESS, both for the GB and for the CE system, the BESS is assumed to receive requests to track a reference curve in the envelope region:

- the centre curve (Case 1);
- the bottom curve (Case 2);
- the top curve (Case 3);

In combination with the centre curve tracking, a SoC management strategy similar to the one adopted for PFR and SFR simulation is also considered (Case 4); the related parameters are $P_{restor,ch}$ = $P_{restor,disch}$ = $P_{v,x}$ = 9%P_n, to comply with the envelope, while $SoC_{tgt,min}$ = 0.4 and $SoC_{tgt,max}$ = 0.6.

3.2.1.4. BESS technological parameters, sizing and aging estimation

Three BESS technologies are considered: the NaS, the Li and the $NaNiCl_2$ one. For each of them, the assumption $\eta_{charge} = \eta_{discharge}$ is made; therefore, both the efficiency coefficients are now labelled η. For the NaS BESS, η = 0.866, for the Li and the $NaNiCl_2$ BESS, η = 0.922. The ideal value η = 1 is also considered, for comparison.

For each BESS with nominal power P_n, different E_n/P_n values are considered, ranging from 0.25 h to 10 h: 0.25 h, 0.5 h, 1 h, 1.5 h, 2 h, 2.5 h, 3 h, 4 h, 5 h, 6 h, 7 h, 8 h, 10 h. The initial value of the SoC is assumed as 0.5 in all the simulations.

Battery aging due to charge-discharge cycles related to EFR supply, and to SoC restoration if present, is here evaluated via the same two approaches followed for PFR and SFR supply: the standard method referring to 100%-DoD equivalent cycles and the empirical method based on life-cycle curves $n_{max}(DoD)$ and on the partial cycles carried out during the simulated operation. The same $n_{max}(DoD)$ curves already adopted in the simulations of PFR and SFR supply are employed (see **Figure 2-1**). For cycling life estimation in the 100% DoD assumption, the maximum number of cycles is taken here again as 4000 for NaS BESS, 3000 for Li BESS and 3000 for $NaNiCl_2$ BESS.

3.2.2. Simulation results: technical evaluations for the GB system

For each of the four considered cases (Case 1 to 4), Service 1 (“S1” later on) and Service 2 (“S2”) are simulated, for the three considered BESS technologies and the different energy to power ratio values. Some overall results are now reported for a BESS assumed to be connected to the GB system, with reference to the two-year long time interval T (T = 2 y) for which grid frequency data are available.

3.2.2.1. Energy exchange requests in each EFR Service

The energy exchanges requested by the EFR service over T, in absorption and in injection separately, are reported in Table 3-6.

Table 3-6 Energy requests for EFR over two years: GB system

Case	Service 1 (S1)		Service 2 (S2)	
	$E_{abs\ req}$ $[P_n\ h]$	$E_{inj\ req}$ $[P_n\ h]$	$E_{abs\ req}$ $[P_n\ h]$	$E_{inj\ req}$ $[P_n\ h]$
1 and 4 (centre curve)	226.61	-177.01	559.34	-539.67
2 (bottom curve)	84.00	-1529.48	235.43	-1588.43
3 (top curve)	1591.18	-46.51	1573.50	-181.16

In case of centre power-frequency characteristic curve (Case 1 and 4), for each Service (S1 and S2), the energy exchange requests are almost the same in absorption and in injection, because the power-frequency characteristic curve is symmetrical with respect to 50 Hz. In Case 2 (Case 3, respectively), instead, for each Service, the energy exchange requests in injection (in absorption) are much larger than the ones in absorption (in injection); this result is due to the power-frequency characteristic curve, which is the one at the bottom (at the top), so it requires energy injection (absorption) when frequency is in the deadband.

As to comparison between the requests of the two Services, in both Cases 1 and 4, S2, with its smaller frequency deadband and its larger power request (see point $P_{u,y}$), requires larger energy exchanges (around 3 times in injection, around 2.5 times in absorption) than S1 does. As for Cases 2 and 3, instead, the behaviour of the requests from the two Services is somewhat different from what expected, since the frequency distribution is not symmetrical: in Case 3, S2 requests to absorb slightly less energy than S1 does.

3.2.2.2. Energy exchanged by the BESS

Figure 3-10 (whose legend is reported preliminarily in Figure 3-9) describes the actual ability of the BESS to exchange energy in response to the EFR requests, in each Case. More precisely, again with reference to *T*, it reports

- the values, normalized with respect to the requests, of the energy not absorbed from the grid due to SoC saturation to 1, i.e. to the "full" value, and of the energy not injected into the grid due to SoC saturation to 0, i.e. to the "empty" value;
- in case of presence of the SoC restoration strategy (Case 4), also the values, again normalized with respect to the requests, of the energy absorbed and injected for SoC restoration.

Let us consider Case 1, first of all, and focus on the ideal efficiency value η = 1 for both Services (magenta curve for S1 and orange curve for S2). BESS with increasing energy capacity, i.e. with increasing nominal energy/nominal power ratio, are more and more able to satisfy the energy exchange requests. More precisely,

- as to injection requests, only BESS with $E_n/P_n \leq 1$ h are not able to fulfil them, both in case of S1 and in case of S2;
- as to absorption requests, instead, the BESS cannot fulfil them completely, even for large E_n/P_n ratios, because the SoC is limited and the absorption requests are larger than the injection ones;

in short,

- for S2, the energy not absorbed amounts to 2-3% of the requested amount for E_n/P_n at least 2 h, but it can reach more than 16% for smaller E_n/P_n;
- in case of S1, the energy not absorbed amounts to 20% at least of the requested amount, for all the considered E_n/P_n values; this although power absorption requests are lower than the ones for S2, because the SoC tends to keep higher and the BESS struggles to absorb further energy.

The main factor impacting the difference in BESS performance between S1 and S2 seems to be the difference in the deadband.

Focusing again on Case 1, but on the actual efficiency values associated to the different battery technologies considered, one can notice that, in general,

- again, BESS with increasing E_n/P_n values are more and more able to satisfy the energy exchange requests;
- the BESS ability to absorb/inject energy improves if efficiency decreases/increases.

For instance, the BESS with the lowest efficiency value considered (η = 0.866) are able to fulfil energy absorption requests already for E_n/P_n = 1.5 h (blue curve for S1 and light green curve for S2), but their injection performance is rather poor: the energy not injected amounts to 2% at least for S1 for all E_n/P_n, to 22% at least for S2 for all E_n/P_n.

As for Case 4, it has the same energy exchange requests with respect to Case 1, since the power-frequency characteristic is the same as in Case 1; however, the presence of SoC restoration increases the service fulfilment capability with respect to Case 1, thanks to non-negligible exchanges aimed at restoring the SoC.

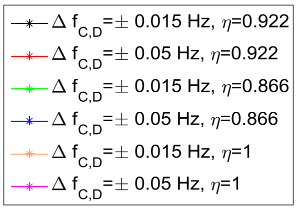


Figure 3-9 Legend for figures about energy exchanges, time fractions, average power values, SPM and AF

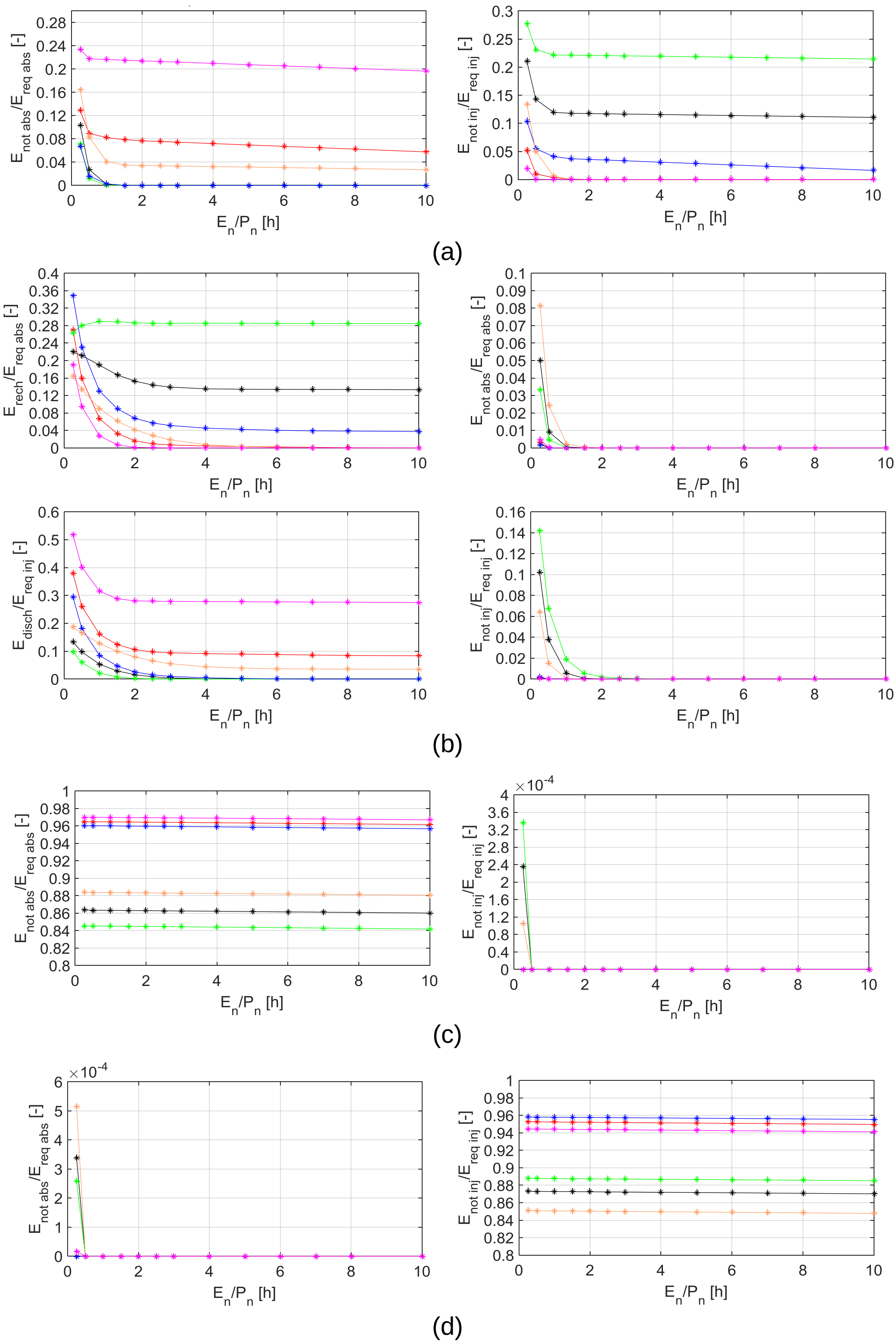


Figure 3-10 – Results for the GB system: normalized energy exchanges with respect to EFR requests: (a) Case 1, (b) Case 4, (c) Case 3, (d) Case 2

In particular, the energy exchanges not fulfilled are zero already for E_n/P_n = 1 h in case of absorption requests, already for E_n/P_n = 2 h in case of injection requests. The energy exchange requests not fulfilled increase, anyway, as the energy capacity becomes very small, and this effect is more evident for S2. As to energy exchanges for SoC restoration, they

- decrease considerably as E_n/P_n increases up to 2 h,
- then they decrease more slowly, up to E_n/P_n = 4 h,
- finally they are constant, for E_n/P_n > 4 h;

this behaviour exhibits an exception in the absorption direction for S2 with η = 0.866, for which there is an almost constant trend with a slight increase for very small E_n/P_n values, up to 1 h, probably because the charging losses are significant also in the restoration process for such a small efficiency value.

In Cases 2 and 3, finally, the fact that their power-frequency characteristic requires to inject or to absorb, respectively, a lot of energy implies that the exchange requests not fulfilled increase significantly with respect to Case 1, and for all the BESS energy sizes considered:

- in Case 2, the fraction of energy not injected with respect to the injection request is almost uniform and amounting to 85%-96%;
- in Case 3, the fraction of energy not absorbed with respect to the absorption request is almost uniform and amounting to 84%-97%.

Therefore, if one limits to the point of view of energy exchange capability, these extreme Cases, which correspond to the boundary characteristics of the envelope region, would not be suitable operating strategies themselves, but they would need to be accompanied by adequate SoC management strategies.

3.2.2.3. Service performance estimation (SPM and AF)

As to power performance in delivering the EFR service, the minimum, the mean and the standard deviation of the SPM and of the related AF along the whole simulated 2-year-long time interval have been computed, in all the considered Cases (1-4), for all the considered E_n/P_n values, the two Services (S1 and S2) and the three considered efficiency values. Results are reported in Figure 3-11 and Figure 3-12, respectively, for Case 1 and Case 4. The legend for the figures is again the one reported in Figure 3-9. Results for Case 2 and Case 3 are instead reported in Table 3-7 and Table 3-8, since the obtained values are constant or almost constant for each Service and each efficiency value (therefore, constant values or a mean of them for each Service and efficiency value are reported).

The mean value of the SPM is always higher than 98.6%; besides, its standard deviation is always less than 2%, which means that the SPM is in general rather close to the mean SPM. In all the four Cases, the mean SPM for S1 is higher than the mean SPM for S2.

Dependency of the mean SPM on E_n/P_n is remarkable only in Case 1 and in Case 4: it increases up to E_n/P_n = 1.5 h or 2 h, then it keeps constant. In Case 4, in particular, the mean SPM reaches 100% for E_n/P_n = 2 h. In Case 2 and in Case 3, instead, it keeps constant for all E_n/P_n values (and almost constant for different efficiency values), although it is different for the two Services: in Case 3, for S1 it is 99.52%, for S2 72.37%; in Case 2, for S1 around 99.98% and for S2 around 99.35%.

As expected, the SoC restoration mechanism in Case 4 improves the SPM with respect to Case 1, in terms of all the three considered variables, i.e. the minimum value, the mean value and the standard deviation. As for the minimum values, the worst performance, around 72% (recall that this means AF = 50 %, so half the remuneration for service supply), is exhibited by the BESS with the smallest E_n/P_n value (0.25 h) and efficiency 1, in Cases 1 and Case 4 for S2, and also in Case 3 for all the considered E_n/P_n values for S2.

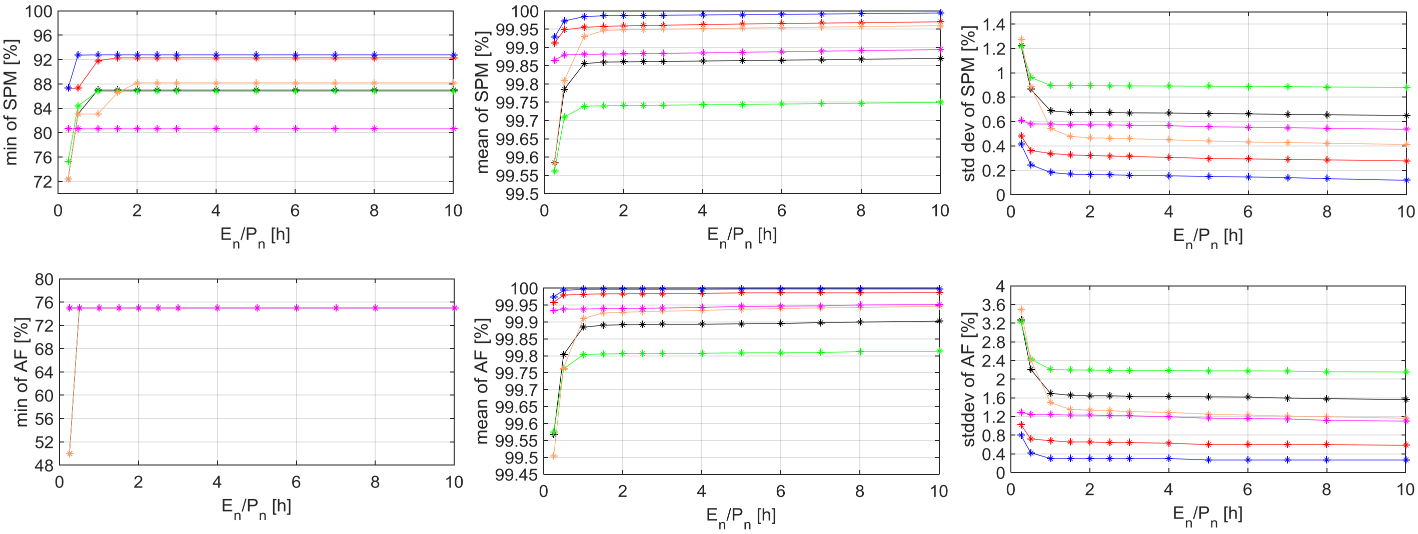


Figure 3-11 - Case 1: SPM and AF results.

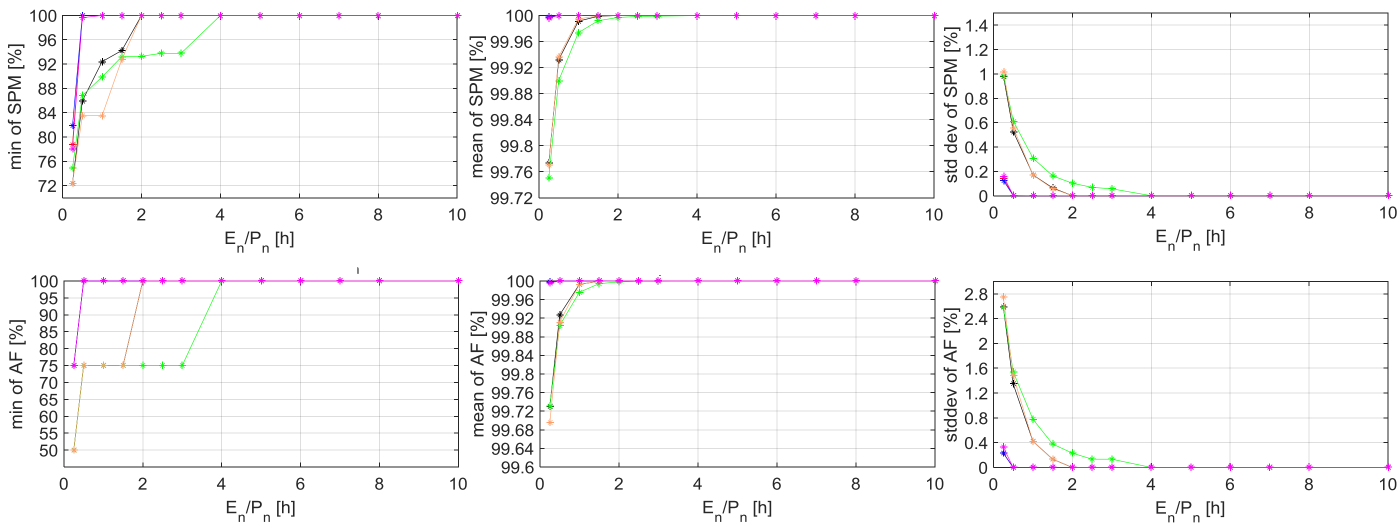


Figure 3-12 - Case 4: SPM and AF results.

Table 3-7 Performance for EFR over two years for the GB system, Case 2 and Case 3: SPM

Case	Efficiency	Service 1: SPM			Service 2: SPM		
	η [-]	*Min [%]*	*Mean [%]*	*Std dev [%]*	*Min [%]*	*Mean [%]*	*Std dev [%]*
2	0.866	91.41	99.74	0.59	85.91	99.04	1.45
	0.922	91.41	99.74	0.59	85.91 (84.08 for E_n/P_n = 0.25 h)	99.04	1.45
	1	91.41	99.74	0.59	85.91 (79.52 for E_n/P_n = 0.25 h)	99.04	1.45
3	0.866	78.04	99.52	1.02	72.37	98.73	1.95
	0.922	78.04	99.52	1.02	72.37	98.73	1.95
	1	78.04	99.52	1.02	72.37	98.73	1.95

Table 3-8 Performance for EFR over two years for the GB system, Case 2 and Case 3: AF

Case	Efficiency	Service 1: AF			Service 2: AF		
	η [-]	*Min [%]*	*Mean [%]*	*Std dev [%]*	*Min [%]*	*Mean [%]*	*Std dev [%]*
2	0.866	75	99.97	0.812	75	99.345	3.994
	0.922	75	99.97	0.812	75	99.355	3.966
	1	75	99.97	0.812	75	99.365	3.934
3	0.866	75	99.78	2.324	50	98.575	5.808
	0.922	75	99.78	2.324	50	98.545	5.847
	1	75	99.78	2.324	50	98.535	5.876

Again, results in Case 2 and Case 3 are not exactly symmetric with respect to each other; in Case 3, the mean and standard deviation values are slightly worse than the ones in Case 1, and on the whole the minimum values are worse; in Case 2, the mean values are worse than the ones in Case 1, but the minimum and the standard deviation values are better.

As to the AF itself, its mean value is always higher than 98.5%, so it can be considered to be rather satisfactory: we recall, in fact, that the AF is the factor weighting the contracted remuneration in each half an hour. The AF standard deviation is always less than 3.6% and 2.8% in Case 1 and Case 4 respectively, but it reaches 6% and 4% in Case 3 and Case 2 respectively. The minimal AF values reached are 50% in Cases 1, 4 and 3, 75% in Case 2.

On the whole, the standard deviation values obtained for the SPM and for the AF could have a negative impact on the BESS remuneration for the service. Therefore, a closer look has to be taken to the SPM and AF statistical distributions. Globally, the SPM distribution is concentrated above the 85-90% level in the four Cases, and the AF distribution is significantly concentrated on 100%, with values equal to 75% which can reach, for instance, up to 3% of the samples in Case 1, up to 2% of the samples in Case 4; very few 50% AF values are also present.

For more clarity, one can analyse the SPM and the AF (empirical) Cumulative Distribution Function (CDF). In Case 1 and Case 4 respectively, one can notice that the CDF of the SPM for SPM = 95% is, for all the considered E_n/P_n values, for all the three considered efficiency values and for S2, less than 2.5% of the samples and always less than 1.5% of the samples (Case 4 shows better performance than Case 1, thanks to SoC restoration): correspondingly, the probability that the AF is less than 100%, so 75% or less, is less than 2.5% and 1.5% respectively. In Case 1 and Case 4 respectively, the CDF of the SPM for SPM = 95% for S1 is always less than 1% of the samples and always less than 0.5% of the samples (Case 4 shows better performance than Case 1, thanks to SoC restoration): correspondingly, the probability that the AF is less than 100%, so 75% or less, is less than 1% and 0.5% respectively.

In Case 3 and Case 2 respectively, one can notice that the CDF of the SPM for SPM = 95% is, for all the considered E_n/P_n values, for all the three considered efficiency values and for S2, less than 6% of the samples and always less than 3.5% of the samples: correspondingly, the probability that the AF is less than 100%, so 75% or less, is less than 6% and 3.5% respectively. In Case 2 and Case 3 respectively, the CDF of the SPM for SPM = 95% for S1 is always less than 1.5% of the samples and always less than 0.5% of the samples: correspondingly, the probability that the AF is less than 100%, so 75% or less, is less than 1.5% and 0.5% respectively.

3.2.2.4. BESS cycling aging estimation

Results about battery cycling aging are documented in Figure 3-14: for Case 1 and for each simulation,

- the maximum number of cycles $n_{max,avg}$ computed with the "average DoD" approach;
- the number of equivalent cycles done at DoD_{avg} per year;
- the number of equivalent cycles done at 100% DoD per year;
- the computed DoD_{avg} value;
- the useful life estimated from DoD_{avg};
- the useful life estimated at 100% DoD.

A common legend is shown preliminarily in Figure 3-13.

With the standard, 100% DoD approach, the number of cycles done per year appears to be similar for all the BESS technologies and efficiency values; simply, S1 and S2 are associated to less or more cycles done, while the number of cycles done decreases for increasing E_n/P_n, as expected. Correspondingly, the estimated life increases for increasing E_n/P_n, as expected (the minimal values, attained for E_n/P_n = 0.25 h, are in a range from 3 to 11 y); this increase appears to be linear; besides, as expected again, the estimated life is longer for S1 than for S2. Very long life values are obtained not only for the largest E_n/P_n value, but also already for smaller E_n/P_n values, as also remarked later on.

According to the estimates obtained with the average DoD approach, again life for S1 is in general longer than for S2. However, while the considered NaS and Li BESS can live 10 y or much longer if they are employed for S2, and 30 y or much longer if they are employed for S1, the $NaNiCl_2$ BESS can live 3-4 y if they are employed for S2 and 6-7 y if they are employed for S1. Such results, of course, depend on

- the computed DoD_{avg}: this latter turns out to be very small. DoD_{avg} is globally lower than 13%, and even lower than 0.5%: in more detail, it is between 2.7% and 12.6% for the smallest E_n/P_n (0.25 h), between 1.1% and 1.7% for E_n/P_n = 2 h, between 0.2% and 1.1% for the largest E_n/P_n considered, i.e. 10 h;
- the number of cycles carried out, per year, at DoD_{avg}: this number is decreasing for increasing E_n/P_n values in case of Li and NaS BESS, first increasing and then decreasing for increasing E_n/P_n in case of $NaNiCl_2$ BESS; however, it is always higher, and often much higher, than the number of equivalent cycles carried out at 100% DoD;
- the maximum number of cycles allowable at DoD_{avg}: recall that this is not so large for small DoD_{avg} for $NaNiCl_2$ BESS, especially as compared to the other two BESS technologies.

One can remark that, with both approaches, the *computed* BESS life can in many cases (more precisely, in all cases except for $NaNiCl_2$ BESS with the "average DoD" approach) reach hundreds of years. Obviously, hundreds of years are not realistic numbers: they mean that the energy exchanges for service supply are so small that BESS, even with a rather small energy to power ratio like $E_n/P_n \leq 2$ h, work very little. Of course, aging results due to cycling must be compared to the battery *calendar* life, which although technology dependent, is usually in the 10-20 y range.

Such comparison yields, e.g., that service S1 (the milder one) is not critical for BESS life, for $E_n/P_n \geq 1$ h and all considered BESS if DoD = 100% is assumed, for $E_n/P_n \geq 0.5$ h and the Li and NaS BESS if the average DoD is considered, because the computed cycling life is then longer than calendar life; it can be critical, instead, for $NaNiCl_2$ BESS if the average DoD is considered, because then life is around 7 y only. As to S2 (the more requiring one), it is not critical for BESS life, for $E_n/P_n \geq 2$ h and all considered BESS, if DoD = 100% is assumed, but it also behaves differently if the average DoD is considered: for $E_n/P_n \geq 0.5$ h and the Li and NaS BESS it is not critical, while for all the considered E_n/P_n values for the $NaNiCl_2$

BESS it yields a short BESS life, around 3 y, which is also constant for $E_n/P_n \geq 0.5$ h. This result is significantly different from the one obtained with the 100% DoD computation, which yields a linear increase of the BESS life with respect to E_n/P_n. Therefore, the $n_{max}(DoD)$ characteristic assumed for $NaNiCl_2$ BESS, which is much lower than for the other two technologies for small DoDs, implies that working at small DoDs may be critical, so that this technology may not be suitable for the specified EFR requirements.

The aging results for the other Cases are rather similar to the ones for Case 1, therefore they are not reported in detail. In short, in Case 4 e.g., DoD_{avg} is almost the same as in Case 1, the number of cycles done per year at DoD_{avg} is similar and the related life estimate is similar; on the whole, shorter life values, as compared to Case 1, are found with both the considered approaches, because the BESS work more due to the SoC restoration mechanism, but the previous considerations about $NaNiCl_2$ BESS and about the comparison with calendar life still hold. In Cases 2 and 3, DoD_{avg} is on the whole smaller than in Case 1, so the related life estimates are longer; the number of cycles done per year in the 100% DoD assumption is smaller, instead, because the BESS work less in such Cases, so the related life estimate is much longer; again, the previous considerations about $NaNiCl_2$ BESS and about the comparison with calendar life hold.

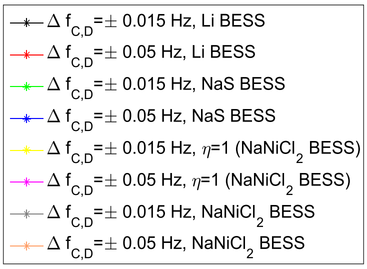


Figure 3-13 – Legend for figures about aging results

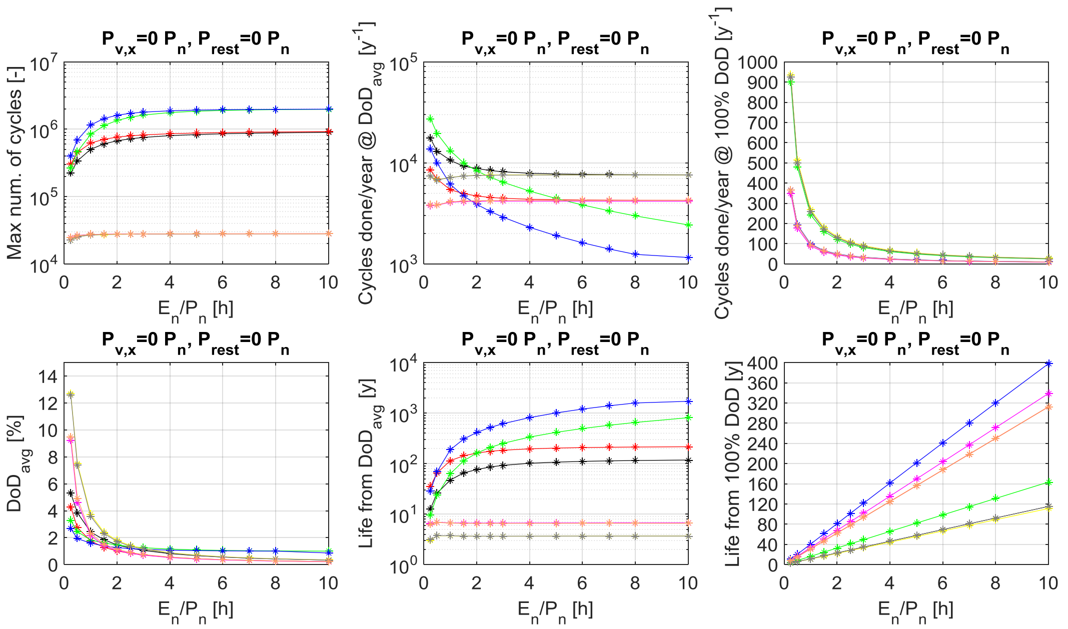


Figure 3-14 - Case 1: cycling aging results

3.2.3. Simulation results: technical evaluations for the CE system (hints)

As already remarked, for the CE synchronous system, a service with features similar to the GB EFR has been simulated, based on adapting the envelope parameters to the CE grid frequency statistical distribution. The analysis has been carried out with reference to the same battery technologies and sizes already considered for the GB system. The overall simulated time interval *T* is 1.7y long, but results have been extrapolated to 2 years to ease comparison with the GB cases.

As to energy exchanges requested for the service, they are collected in Table 3-9; in Table 3-10, their ratio with respect to the ones for the GB system is shown: except for the injection requests in Cases 2 and 3, the requests for the CE system are smaller than the ones for the GB system. One can also notice that the energy exchanges and actually carried out for the service (not reported, for brevity) often turn out to be smaller for the CE system than for the GB one. These results can be related to the specific values chosen for the frequency bandwidth values in the envelope. Therefore, the proposed design yields a service which is often milder than the one for GB (therefore, it may be less critical for $NaNiCl_2$ BESS).

Table 3-9 Energy exchange requests for EFR for the CE system

Case	Service 1				Service 2			
	$E_{abs\ req}$ $[P_n\ h]$	$E_{inj\ req}$ $[P_n\ h]$	Estim. $E_{abs\ req}$ in 2 years $[P_n\ h]$	Estim. $E_{inj\ req}$ in 2 years $[P_n\ h]$	$E_{abs\ req}$ $[P_n\ h]$	$E_{inj\ req}$ $[P_n\ h]$	Estim. $E_{abs\ req}$ in 2 years $[P_n\ h]$	Estim. $E_{inj\ req}$ in 2 years $[P_n\ h]$
1 and 4	144.67	-134.57	168.77	-156.99	435.26	-429.21	507.77	-500.71
2	51.65	-1336.65	60.25	-1559.33	159.12	-1344.15	185.63	-1568.08
3	1352.63	-47.44	1577.98	-55.34	1345.20	-148.08	1569.31	-172.75

Table 3-10 Energy exchange requests for EFR: comparison between CE and GB over 2 years

Case	Service 1		Service 2	
	$E_{req\ abs\ CE}/E_{req\ abs\ GB}$	$E_{req\ inj\ CE}/E_{req\ inj\ GB}$	$E_{req\ abs\ CE}/E_{req\ abs\ GB}$	$E_{req\ inj\ CE}/E_{req\ inj\ GB}$
1 and 4	0.745	0.887	0.908	0.928
2	0.717	1.020	0.788	0.987
3	0.992	1.190	0.997	0.954

As to SPM and AF, results for the CE system are structurally similar to those for the GB system (e.g., SPM minimum, mean and standard deviation values in Cases 2 and 3 are constant or almost constant as E_n/P_n varies). Besides, in all the Cases, the SPM mean and standard deviation values are comparable to the ones obtained for GB (specific differences can be related to the different distribution of the energy exchange requests, i.e. to the different distribution of the frequency and to the slightly different proportion in the adopted EFR service parameters). The performance results, therefore, can be considered to be satisfactory, as already remarked for the GB ones.

As far as cycling aging is concerned, results for BESS assumed to be connected to the CE system exhibit trends similar to the GB ones, due to the frequency bandwidths scaling adopted. In more detail, a Case-by-Case comparison shows, apart from some exceptions in Case 3 for Service 1, less cycles done, so longer life, computed at 100% DoD, since the EFR conceived here for CE is often slightly less demanding than the one devised in the GB; values for DoD_{avg} and life estimated from it may be larger or smaller, depending on the Service and on the BESS technology, i.e. $n_{max}(DoD)$ curve. The same comments drawn for the GB service about the comparison between cycling aging and calendar aging hold, although some specific differences arise in the results due, again, to the fact that the EFR conceived for CE is often slightly less demanding, so life estimate from DoD_{avg} can increase remarkably. For example, as a difference with respect to the results obtained for GB system, one can highlight a significant improvement, with respect to Case 1, in $NaNiCl_2$ BESS life estimate from DoD_{avg} in Case 2 for Service 1: it is around 20 years, so comparable to or even longer than calendar life.

3.2.4. Preliminary economic evaluations for EFR in the GB system

Some preliminary economic remarks can be carried out in order to understand how E_n/P_n could be chosen properly for a BESS devoted to the EFR service in GB. The starting point can be the obtained technical results and, e.g., the results of the first tender round issued in 2016 by National Grid ESO for EFR capacity procurement. All successful tenders (eight bids, see Table 3-11) were from BESS, for a total of 201 MW of EFR and at a total cost, for the TSO, of 65.95 M£, i.e. by assuming 1.0 £ = 1.194 €, 78.7 M€.

Table 3-11 – Successful tenders for the EFR service (source: National Grid ESO [34])

Provider Name	Site Location/Name	Type of service	Provider Type	Enhanced Response (MW)	Estimated Start Date	Total Cost of tender £m	GWh of EFR holding	Service Hours	Average price of tender £/MW of EFR/ h	Does this tender exclude typical TRIAD hours
EDF Energy Renewables	T_WBURB-4	Service 2	Storage	49	Dec-17	£ 12.035	1719.312	35088	£ 7.00	FALSE
Vattenfall	Pen Y Cymoedd	Service 2	Storage	22	Apr-17	£ 5.749	771.936	35088	£ 7.45	FALSE
Low Carbon	Cleator	Service 2	Storage	10	Dec-17	£ 2.681	337.6	33760	£ 7.94	TRUE
Low Carbon	Glassenbury	Service 2	Storage	40	Mar-18	£ 12.668	1350.56	33764	£ 9.38	TRUE
E.ON UK	Sheffield	Service 2	Storage	10	Nov-17	£ 3.891	350.88	35088	£ 11.09	FALSE
Element Power	TESS	Service 2	Storage	25	Feb-18	£ 10.079	877.2	35088	£ 11.49	FALSE
RES	RESEFR7-PT	Service 2	Storage	35	Feb-18	£ 14.651	1228.08	35088	£ 11.93	FALSE
Belectric	Nevendon	Service 2	Storage	10	Oct-17	£ 4.200	350.88	35088	£ 11.97	FALSE
Total				**201**		**£ 65.954**			**£ 9.44**	

Let us now consider the obtained simulation results.

First of all, one can notice that battery life values computed with the DoD_{avg} approach are rather small for E_n/P_n = 0.25 h; however, this E_n/P_n value should not be chosen, since in practice the TSO requires E_n/P_n = 0.5 h at least; this, in turn, implies that cycling life will not be a critical issue, except for $NaNiCl_2$ BESS. As already remarked, increasing E_n/P_n means increasing technical performance in service supply, e.g. in terms of energy exchanges, but such an improvement can be moderate from the DoD_{avg} point of view and also from the AF point of view: for instance, DoD_{avg} becomes rather small for E_n/P_n = 4 h and even smaller for E_n/P_n > 4 h, and part of the available energy would not actually be employed. Therefore, one had better not to increase E_n/P_n too much, since the technical improvement would not be significant and since the higher E_n/P_n the higher the BESS investment cost. Best-suited E_n/P_n values could be 1 h or 2 h.

Now, the average awarded price in the considered tender was 9.44 £/MW/h = 11.27 €/MW/h. Besides, we recall that, according to the obtained results, the probability that the AF is less than 100% ranges between 0.5% and 1.5% for S1 and between 2.5% and 6% for S2 in the different Cases and for the different E_n/P_n values and for the different battery technologies. Therefore one could take as a favourable example, for a preliminary economic evaluation, a situation with the supply of S1 and 1% as the probability that the AF is less than 100%. So, by assuming AF = 100% for 99% of the hours in a year, and, for simplicity, AF = 0% in the rest of the hours of the year, the net annual revenue would be 97.74 k€/MW/y. If the BESS investment costs were those already considered for the supply of PFR and SFR (Table 3-3), then, in order to ensure a PBP lower than or equal to 10 y with the average awarded price, as shown in Figure 3-15,

- a Li or $NaNiCl_2$ BESS should have E_n/P_n around 1 h at most; this means that particular attention should be paid for the $NaNiCl_2$ case, since the estimated cycling life is shorter than 10 y and the current technology is characterized by E_n/P_n = 2-4 h [35] (no problems Are envisaged for the Li BESS, since the current technology is characterized by E_n/P_n up to 6 h and even up to 8 h [36]);
- a NaS BESS should have E_n/P_n around 1.5 h at most; again, this may be an issue, since such values cannot be obtained with the current NaS technology, which is characterized by E_n/P_n = 6-8 h [35].

Similar considerations can be drawn from Figure 3-15 by considering the minimal and the maximal prices awarded in the tender. For these last, e.g., economically suitable E_n/P_n values would not be higher than 2.5 h: notice that such values cannot be obtained with the current NaS technology, but are suitable for the Li and the $NaNiCl_2$ ones.

One can also notice that the PBP would decrease significantly if the BESS investment cost decreased: e.g., for 300 k€/MWh, a 1 MW/1 MWh BESS would have PBP = 3.07 y with the considered average price.

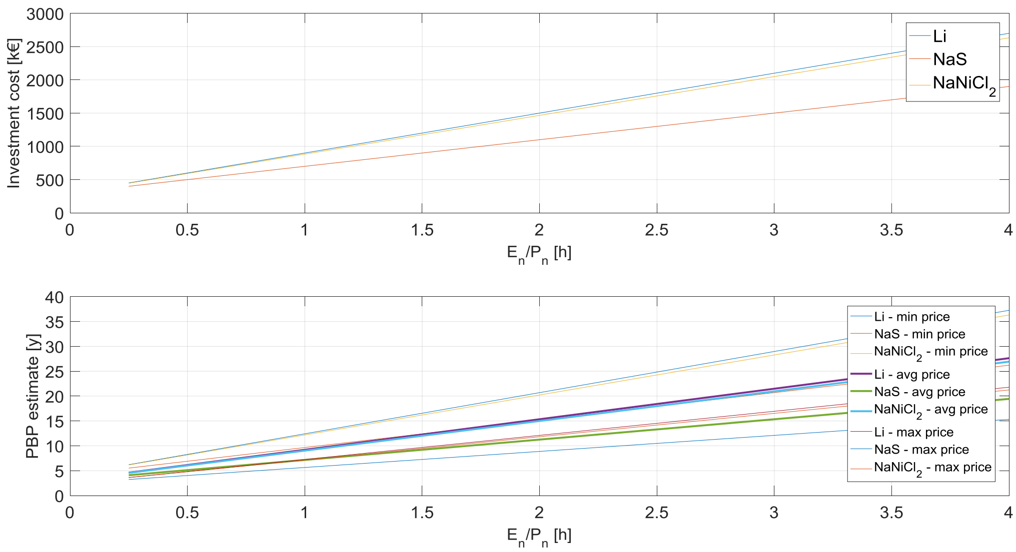


Figure 3-15 – BESS investment cost for different E_n/P_n values and related PBP associated with the minimum, average o maximum price awarded in the first EFR tender

3.3. BESS providing Balancing Services

The profits achievable by a stand-alone BESS from balancing service supply on the Italian BM are inquired by means of a deterministic “ex-post” optimization approach, by assuming bid prices and acceptance/rejection status values as known inputs derived from BM historical results [24]. After computing the optimal annual energy bid profile by solving a MILP optimization problem, the BESS PBP and battery useful life are derived, from the maximal profit and the SoC time profile respectively. A sensitivity analysis of the PBP and of battery life is carried out with respect to the bidding prices and to the BESS nominal energy to nominal power ratio. Among the results, the profitable ones are selected, as those for which the PBP is small enough and smaller than the estimated battery life.

Simulations refer to the one-year time interval from 1st August 2016 to 31st July 2017. For this interval, here called *T*, the prices of the accepted bids for the BSs in the Italian Northern market zone are employed both to derive (average or probable) prices to adopt in bids and as a comparison term to simulate bid acceptance/rejection on the market (the market itself is not simulated). The chosen values for the BESS efficiency coefficients and cycling aging features are compatible with the lithium-ion technology.

3.3.1. Main assumptions

3.3.1.1. Input signals

The bid prices adopted in the simulations have been derived, separately for UPs and DWs, from the mentioned historical data (i.e. along *T*), by means of simple averaging or statistical elaborations: thus, the following “price schemes” [24] have been obtained:

S1: day-of-the-week (from Monday to Sunday) hourly average prices, namely the average prices in each of the 24 hours of Mondays, the average prices in each of the 24 hours of Tuesdays, etc.;

S2: day-of-the-month hourly average prices: an average month composed of 31 days (each of which composed of 24 hours) is considered;

S3: day-of-the-week-of-the-month hourly average prices, i.e. an average week (from Monday to Sunday, with 24 hours for each day) is considered for each month [37];

S4: monthly hourly average prices, i.e. an average day (with 24 hours) for each month is considered;

S5: calendar season day-of-the-week hourly average prices, i.e. an average week (from Monday to Sunday) is considered for each season, assuming that winter is composed of January, February and March, spring of April, May and June, etc.;

S6: seasonal day-of-the-week hourly average prices, i.e. an average week (from Monday to Sunday) is considered for each season, with seasons defined as groups of three months with similar weather conditions: December, January and February for winter, March, April and May for spring, etc.;

S7: hourly average prices, i.e. in the 8760 hours of the year;

S8: seasonal hourly average prices, with a distinction between working and non-working days (the former are the days from Monday to Friday in each week, except for festivities occurring during the week; the latter, of course, are Saturdays, Sundays and all festivities); seasons, as just mentioned, refer to three-month periods with similar weather conditions;

S9: daily hourly average prices with a distinction between working and non-working days;

S10: quarter-of-an-hour average prices, i.e. in the 35040 quarters of an hour of the year; this price scheme can be considered as an ideal one, because ¼ h prices cannot be used actually, because bids have to be made on an hourly basis; however, ¼ h prices from this scheme are adopted here in both formulations of the cost optimization procedure;

S11: hourly most probable price: in each hour of the year, the historical price most accepted in that hour;

S12: hourly prices from the distribution of the accepted prices: the statistical distribution of all the accepted prices throughout the year are estimated via triangular kernel density functions, and 8760 samples from it are taken;

S13: hourly average prices from the distribution of the accepted prices: from the statistical distribution of all the accepted prices already estimated in S12, 35040 samples are taken, then the mean of the four samples related to each hour is taken.

One can also remark that price schemes S7 and S10 can be considered to be "ideal" ones because they mean assuming to know in advance the average upward and downward accepted prices, which, in turn, are always lower than the upward accepted prices and higher than the downward accepted prices; with the considered acceptance criterion, therefore, such prices are always accepted (except for hours or quarters of an hour in which there are no accepted UPs or DWs); for this reason, the optimization algorithm can choose the energy to bid so as to reach the maximum profit ever, or a profit close to it.

One can observe, e.g., that in S7 and S10 most UP prices are in the 40-600 €/MWh range and most DW prices in the 0-80 €/MWh range; this also holds for the adopted realizations of S11 to S13, with the exception that no 0 €/MWh values are present in the S13 DW prices. In the other schemes (S1 to S6, S8, S9) UP prices are mainly in the 65-350 €/MWh range and DW prices in the 10-60 €/MWh range.

3.3.1.2. BESS sizing and economic evaluation criteria

The techno-economic parameters of the considered BESS are collected in Table 3-12. They are compatible with a lithium-ion BESS; also a characteristic curve "maximum number of cycles versus DoD" compatible with the lithium-ion technology is adopted for battery cycling life estimation (see **Figure 2-1**). The BESS total investment cost is $IC = UIC_E \cdot E_n$, where UIC_E is the overall unit cost of the equipment (for simplicity, here costs are not split explicitly into an "energy part" and a "power part"). The unit price for cycling aging is obtained, to a first approximation, as $p_{cycl} = (UIC_E \cdot E_n)/(N_{max,100} \cdot E_n)$ = 77.78 €/MWh. This means that IC is spread over the whole energy that the BESS can exchange throughout its life, namely $N_{max,100} \cdot E_n$ (efficiency is neglected, for simplicity).

Table 3-12 – Battery technological and economic parameters

Parameter	Value
P_n [MW]	5
$P_{max,abso}$ [MW]	P_n
$P_{max,erog}$ [MW]	P_n
Discharge efficiency $\eta_{discharge}$ [-]	0.933
Charge efficiency η_{charge} [-]	0.933
Initial and final SoC	0.5
Battery and power conversion system unit investment cost: UIC_E [k€/MWh]	350
Maximum number of cycles to end of life, at 100% DoD: $N_{max,100}$ [-]	4500

3.3.1.3. Sensitivity analysis

A sensitivity analysis is carried out with respect to

- the BESS nominal energy to nominal power ratio: the values E_n/P_n = 3 h, 4 h, 6 h, 8 h, 10 h are considered[5];

[5] For on-the-shelf lithium-ion BESS, typical E_n/P_n values range from 0.5 h to 6 h, while values higher than 8 h have not been reached yet. In the present analysis, anyway, values from 3 h to 10 h have been chosen for similarity with the current Italian regulatory framework for Mixed Virtual Eligible Units ("Unità Virtuali Abilitate Miste" in Italian [68]), which requires to be able to carry out spinning or replacement reserve services for a time window ranging from 180 minutes to 540 minutes (plus 15 minutes for response activation).

- the bid price levels: for each price scheme assumed and for each hour or ¼ h, the UP/DW price of the scheme is varied by a fixed fraction Δ ($-1 \leq \Delta \leq 1$), which can be called an uplift factor:
  - $\Delta = 0$ (reference case) means using the UP and DW prices from the chosen scheme (S1 to S13);
  - $\Delta \neq 0$ means using the scheme UP price · $(1 + \Delta)$ and the scheme DW price · $(1 - \Delta)$; this roughly means that, if $\Delta > 0$ ($\Delta < 0$, respectively), prices become more (less) favourable for the BESS, so a decrease (an increase) of the probability of their acceptance on the market is expected;
- taking or not into account cycling aging in the cost function, namely considering weighting factor p_{cycl} = 77.78 €/MWh or 0 €/MWh;
- the time slot in which bids are formulated, which is directly associated to problem Formulation, namely 1 or 2: we recall that Formulation 1 is the cost optimization with bids made on an hourly basis, Formulation 2 is the cost optimization with bids made on a quarter-of-an hourly basis.

Therefore, optimization simulations are carried out for all the combinations of these parameters. Among the variables of interest computed in each simulation (see Section 2.3.4), attention can be drawn on the PBP and on the useful life, in order to evaluate the service profitability. In particular, from all the mentioned simulations one can select the "best simulated cases" as the values of E_n/P_n and of Δ, for the various price schemes and for each Formulation, for which the PBP is lower than or equal to the estimated life and small enough, i.e. lower than or equal to a threshold. As to useful life, the estimate obtained via the "average" DoD approach can be assumed to be more accurate than the one obtained via the 100% DoD approach, so it is the one adopted in the comparison with the PBP value.

The selected best simulated cases are now discussed.

3.3.2. Selected cases

In the following, the obtained PBP and cycling life values are discussed for the selected Δ values, for each considered E_n/P_n value and for each Formulation of the optimization problem, with and without cycling aging penalization. The legend for all the reported graphs is shown separately and preliminarily in Figure 3-16. The threshold for the PBP and battery life in the graphs is set equal to 20 y, to appreciate results variability. However, since the condition that PBP to be lower than or equal to the estimated life always holds for the selected results, i.e. independently of the threshold value, the selected results corresponding to lower thresholds, which are more consistent with actual battery life values and with PBP values acceptable for stakeholders, can also be found in the graphs, as a subset of the results selected for the 20 y threshold itself. In particular, 10 y can be considered as a fair PBP for an investment on a BESS. The selected results are therefore discussed by considering a 10 y threshold value.

As to this value and to battery life assessment, a further remark is needed. Battery life assessment should include a comparison between cycling life and calendar life. This latter is neglected here, but it is currently around 10 y for lithium-ion technologies and it can be expected to reach around 15 y or more in the future [38] [39] [40]. Therefore, if the computed cycling life is longer than 10-15 y, one can assume that cycling is not a critical issue for the considered BESS. If it is shorter, it may be a critical issue; however, in the cases selected here to define investment attractiveness, the fact that cycling life is shorter than calendar life is not an issue, because these cases are selected so that the PBP is also smaller than (or, at most, equal to) the computed cycling life itself.

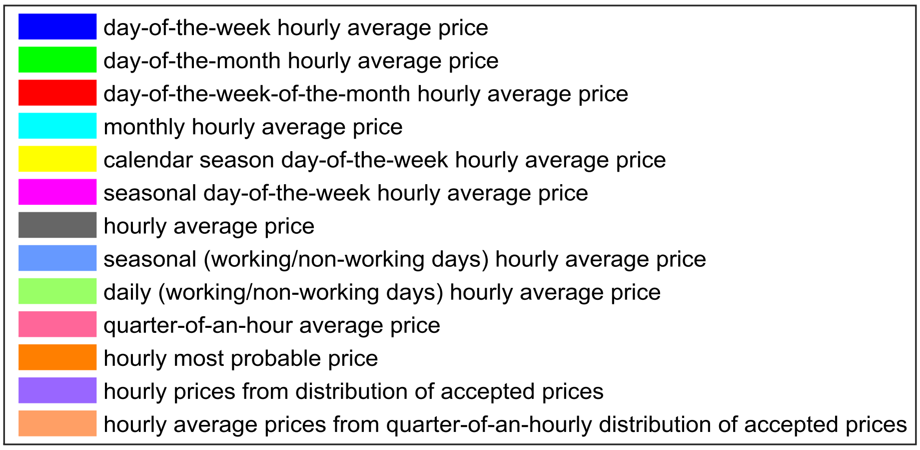


Figure 3-16 – Legend for the graphs in Section 3.3.2

3.3.2.1. Results without cycling aging in the cost function

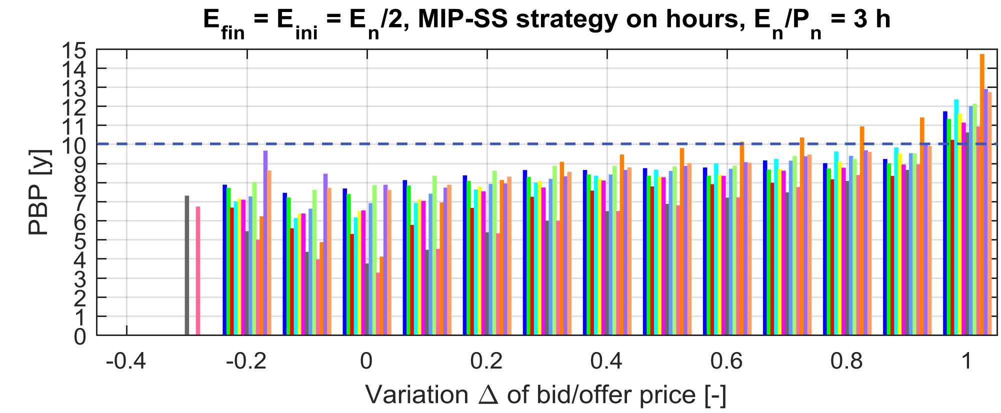
The selected results are now reported for the mentioned BESS without considering cycling aging in the cost function, so that the net profit from the BS only is optimised.

3.3.2.1.1. Formulation 1 (bids made on an hourly basis)

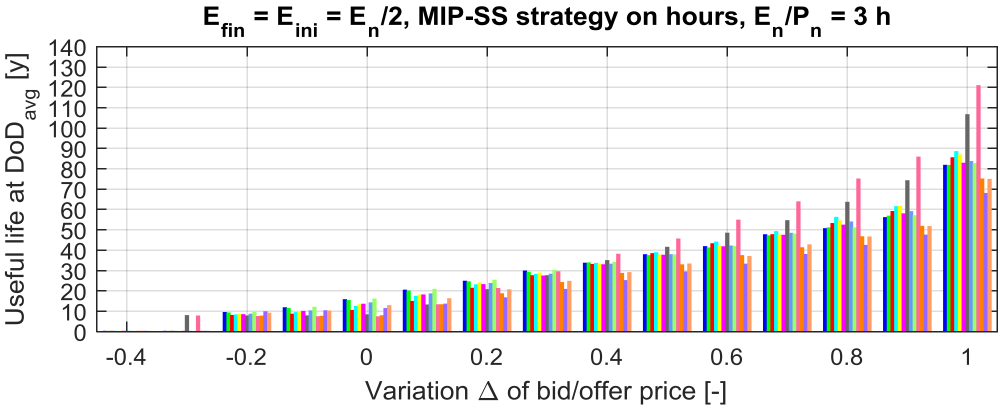
The simulation cases for which the PBP is lower than or equal to the estimated life at the "average" DoD and lower than or equal to 20 y are depicted in Figure 3-17, just in terms of the PBP and the estimated battery life. A dashed line is added to highlight the 10-y threshold actually considered.

Setting the threshold equal to 10 y and focusing on E_n/P_n = 3 h first of all, one can notice, e.g., that, for $-0.2 \leq \Delta \leq 0.5$, all the considered price schemes allow a PBP of less than 10 y to be obtained, and so do almost all of the price schemes for $-0.2 \leq \Delta \leq 0.9$: for $0.6 \leq \Delta \leq 0.9$, in particular, scheme S11 yields PBP > 10 y: S11, in fact, has DW prices very similar to S7 and UP prices rather similar to S7, but these UP prices are sometimes much higher, so they are unlikely to be accepted, especially for increasing Δ values, and sometimes lower so that, although they are accepted they are not so profitable for the BESS. Besides, as expected, the S7 and S10 schemes are, for each Δ such that $-0.2 \leq \Delta \leq 0.9$, the most profitable ones; as Δ increases, the useful life globally tends to increase for each price scheme: in fact, as Δ increases bid prices are more favourable to the BESS, so they are less likely to be accepted, so the BESS exchanges less energy thus carrying out less charge or discharge cycles.

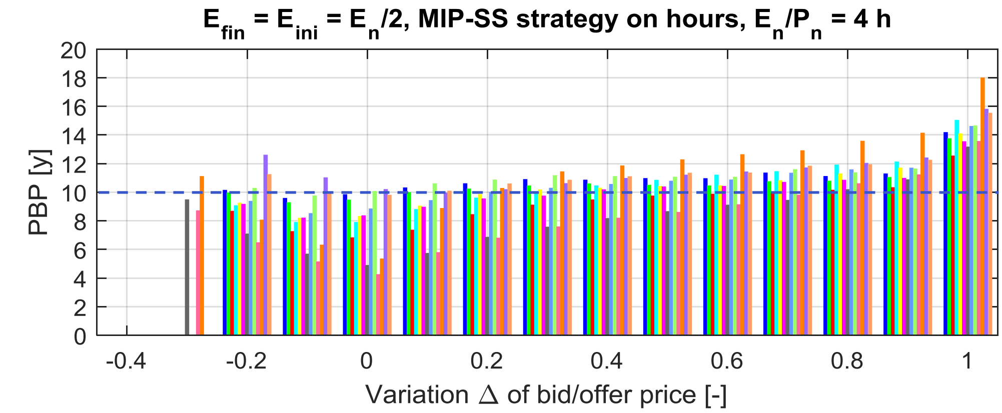
As to E_n/P_n = 4 h, the PBP and the useful life tend to increase; more precisely, although the PBP increases in a limited way or moderately, there are less selected results than for E_n/P_n = 3 h. Similarly, the PBP and the useful life tend to increase as E_n/P_n increases from 4 h to 6 h; besides, for E_n/P_n = 6 h the number of selected cases decreases significantly, and such cases are obtained mainly with S7 and S10 price schemes and $-0.2 \leq \Delta \leq 0.2$. For E_n/P_n = 8 h, there are three selected cases only (for S7 and S10 with Δ = 0 and for S10 with Δ = -0.1), and there are none for E_n/P_n = 10 h (S10 with Δ = 0 yields a PBP slightly longer than 10 y).



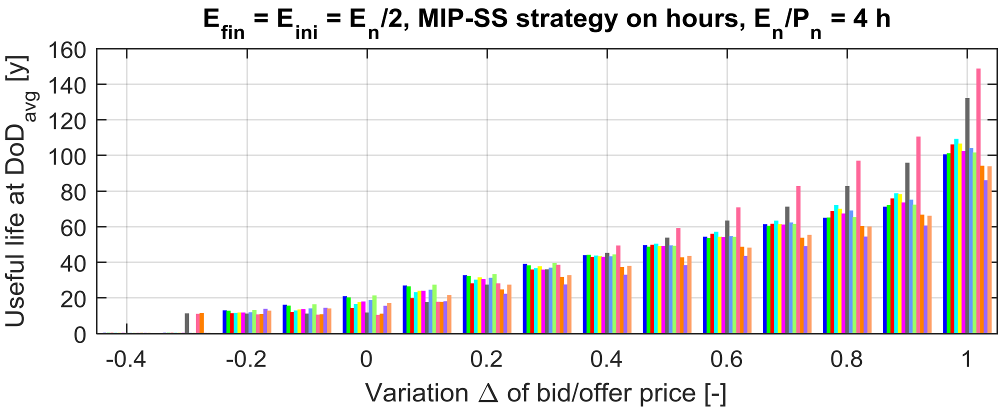
E_fin = E_ini = E_n/2, MIP-SS strategy on hours, E_n/P_n = 3 h
PBP [y]
Variation Δ of bid/offer price [-]



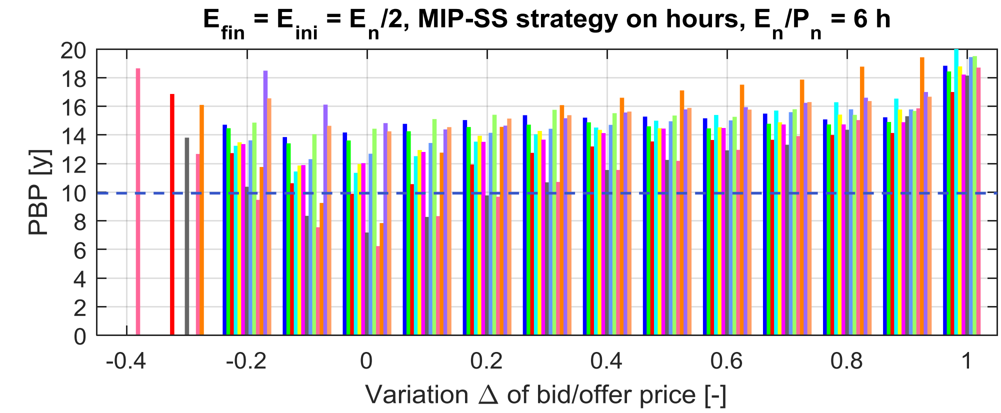
E_fin = E_ini = E_n/2, MIP-SS strategy on hours, E_n/P_n = 3 h
Useful life at DoD_avg [y]
Variation Δ of bid/offer price [-]

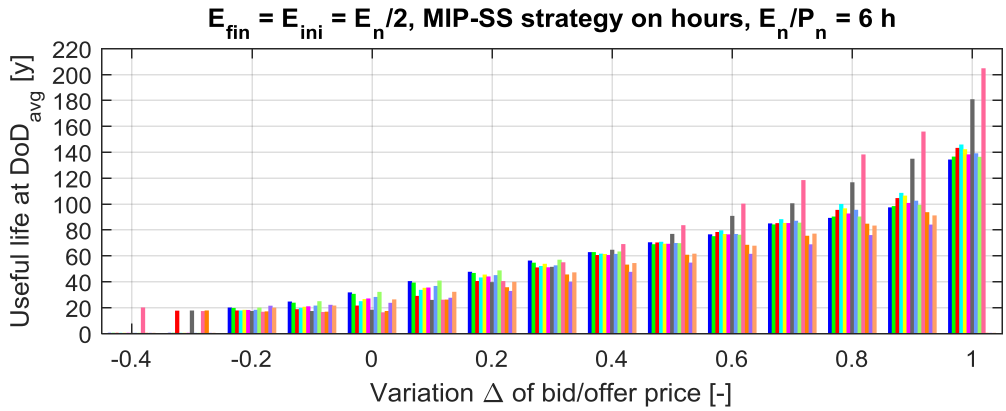


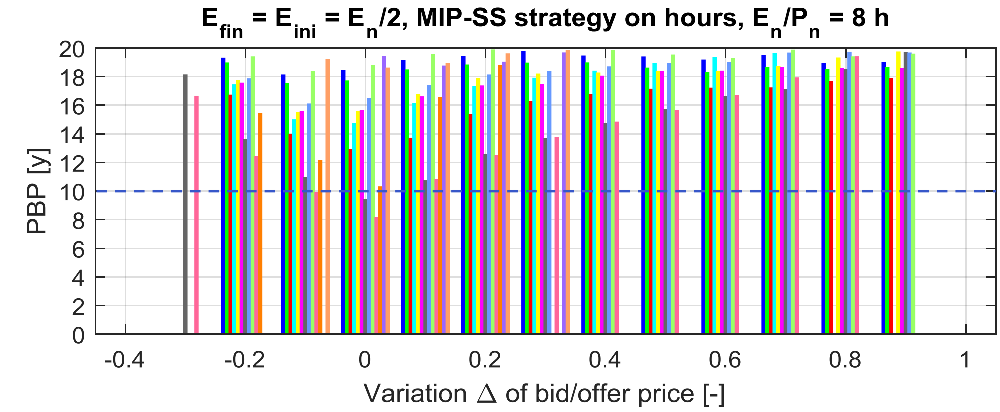
E_fin = E_ini = E_n/2, MIP-SS strategy on hours, E_n/P_n = 4 h
PBP [y]
Variation Δ of bid/offer price [-]

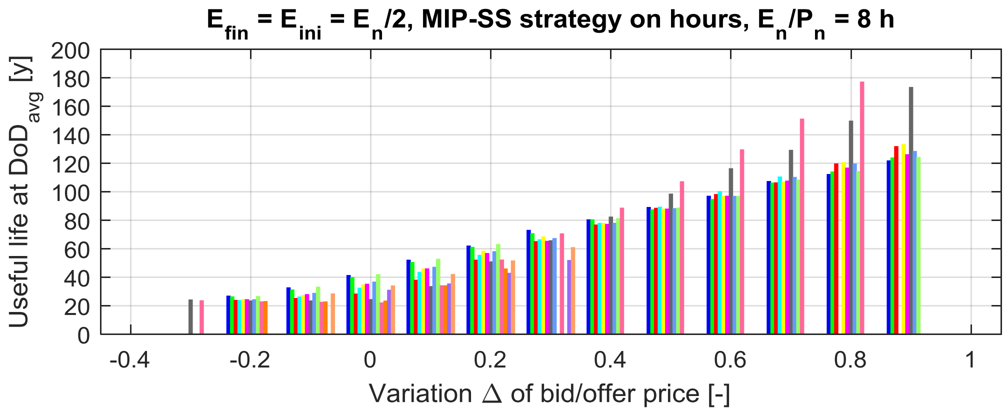


E_fin = E_ini = E_n/2, MIP-SS strategy on hours, E_n/P_n = 4 h
Useful life at DoD_avg [y]
Variation Δ of bid/offer price [-]


$E_{fin} = E_{ini} = E_n/2$, MIP-SS strategy on hours, E_n/P_n = 6 h
PBP [y]
0 2 4 6 8 10 12 14 16 18 20
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1
Variation Δ of bid/offer price [-]


$E_{fin} = E_{ini} = E_n/2$, MIP-SS strategy on hours, E_n/P_n = 6 h
Useful life at DoD_{avg} [y]
0 20 40 60 80 100 120 140 160 180 200 220
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1
Variation Δ of bid/offer price [-]


$E_{fin} = E_{ini} = E_n/2$, MIP-SS strategy on hours, E_n/P_n = 8 h
PBP [y]
0 2 4 6 8 10 12 14 16 18 20
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1
Variation Δ of bid/offer price [-]


$E_{fin} = E_{ini} = E_n/2$, MIP-SS strategy on hours, E_n/P_n = 8 h
Useful life at DoD_{avg} [y]
0 20 40 60 80 100 120 140 160 180 200
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1
Variation Δ of bid/offer price [-]

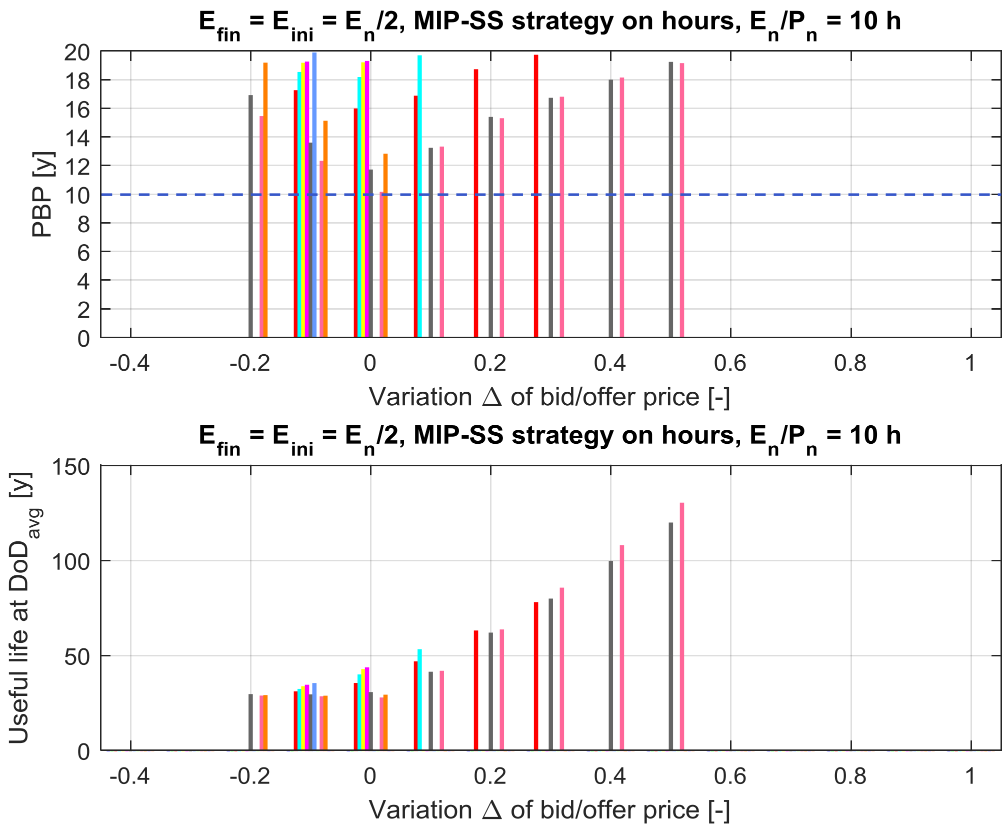


Figure 3-17 – PBP lower than or equal to 20 y and to life estimated with the "average DoD approach", in case bids are made on an hourly basis and cycling aging is not considered in profit optimization; a dashed line marks the considered 10-y threshold for the PBP

3.3.2.1.2. Formulation 2 (bids made on a quarter-of-an hourly basis)

Setting, again, the threshold equal to 10 y, similar considerations as the ones for Formulation 1 can be drawn.

More precisely, for E_n/P_n = 3 h, first of all, one has that, for -0.2 ≤ Δ ≤ 0.7, all the considered price schemes allow a PBP of less than 10 y to be obtained (so do almost all of the price schemes for -0.2 ≤ Δ ≤ 0.9) and, as expected, the S7 and S10 schemes are, for each of these values of Δ, the most profitable ones or among the most profitable ones; as Δ increases, the useful life globally tends to increase for each price scheme. Four selected results are also present for Δ = -0.4 and Δ = -0.3. As to E_n/P_n = 4 h, there are less selected results than for E_n/P_n = 3 h; for the selected results common to the two E_n/P_n values, the PBP and the useful life tend to increase in a limited way when considering E_n/P_n = 4 h. Similarly, the PBP and the useful life tend to increase as E_n/P_n increases from 4 h to 6 h; besides, for E_n/P_n = 6 h the number of selected cases decreases significantly, and such cases are obtained mainly with S7 and S10 price schemes and -0.2 ≤ Δ ≤ 0.2. For E_n/P_n = 8 h, there are four selected cases only (S10 for Δ = -0.1 and Δ = 0, S7 and S11 for Δ = 0). For E_n/P_n = 10 h, there is one selected case only (S10 with Δ = 0).

On the whole, with respect to Formulation 1, there are some more selected results, but the improvement in the PBP is of the order of some months, so it is not very large.

3.3.2.2. Results with cycling aging in the cost function

Let us consider the mentioned BESS again and include an estimation of cycling aging in the optimization problem via the p_{cycl} weighting factor; here p_{cycl} = 77.78 €/MWh. Let us also set the PBP threshold equal to 10 y. With Formulation 1 (i.e. with bids made on an hourly basis) one obtains no selected results for the considered E_n/P_n values; with Formulation 2 (i.e. with bids made on a quarter-of-an hourly basis) there are only four selected cases, all for E_n/P_n = 3 h and corresponding to price scheme S10 (for Δ = 0 or 0.4 to 0.6). This strong difference with respect to taking p_{cycl} = 0 can be explained by recalling that the majority of DW prices is below 50 €/MWh, so by adding almost 78 €/MWh one obtains DW prices rather similar to UP prices, therefore the incomes from accepted UPs are much reduced or even almost cancelled out by costs from accepted DWs, so the PBP can increase significantly (anyway, if one considers 20 y, or also 15 y, as a threshold for the PBP, there are still selected results, for E_n/P_n = 3 h, 4 h and 6 h, or for E_n/P_n = 3 h and 4 h respectively, both with Formulation 1 and with Formulation 2).

3.3.3. Concluding remarks

Service profitability can be deemed to be acceptable if the BESS investment PBP is lower than or equal to 10 y and, at the same time, to the battery useful life.

Without considering cycling aging in the cost function, and by formulating bids hourly, such two conditions can be met rather easily, i.e. in many cases, for E_n/P_n = 3 h or 4 h, while in few cases for E_n/P_n = 6 h or 8 h and in no cases for E_n/P_n = 10 h, where a case is associated to a price scheme and to the variation (uplift) Δ of prices from the schemes; more precisely, for E_n/P_n = 3 h the two conditions can be met for almost all the considered price schemes for $-0.2 \leq \Delta \leq 0.9$, and for E_n/P_n = 4 h for almost all the considered price schemes for $-0.2 \leq \Delta \leq 0.1$; the reduction of the number of cases meeting the two conditions for increasing E_n/P_n values can be related to the increase of BESS investment cost, against the fact that service accomplishment cannot increase so much (because it depends on the acceptance or not of the presented bids, which in turn depends on the adopted bid prices and, by assumption, cannot be higher than the estimated historical acceptance rate); one can also notice, in particular, that schemes S7 and S10, i.e. the ones here which are the closest to “ideal” *a priori* price knowledge, allow to reach, for $-0.1 \leq \Delta \leq 0.1$ on the whole, PBP values down to 3-4 y for E_n/P_n = 3 h, 4-5 y for E_n/P_n = 4 h, 6-7 y for E_n/P_n = 6 h, 8-10 y for E_n/P_n = 8 h.

Without considering, again, cycling aging in the cost function, but formulating bids on a quarter-of-an-hourly basis, profitability results similar to the ones just mentioned can be obtained; more precisely, PBP values are slightly improved with respect to the ones obtained by formulating hourly bids, i.e. reduced by some months roughly, and there are few more cases in which the two conditions are met (even one case for E_n/P_n = 10 h, for S10 and Δ = 0).

Considering cycling aging in the cost function via a weighting factor, instead, allows to meet the two conditions in very few cases, and provided that bids are made on a quarter-of-an-hourly basis. Anyway, the thus selected results do not exhibit improved values of the PBP and of battery life, as compared to the previous results obtained by neglecting cycling aging. This could suggest that, at least when looking for the *a-priori* optimal profit from the service, the effort, in terms of irregular charge-discharge cycles, related to service accomplishment is not too heavy for the battery, so that the related stress for the battery can be neglected.

One could therefore conclude that, with the price schemes and life estimation procedure adopted, the maximal profits achievable from the balancing service can yield satisfactory PBP values, without wearing the battery out, even neglecting cycling aging in the formulation of bids; this occurs for BESS nominal energy to nominal power ratio around 3-4 h, so when this ratio is not very high.

3.4. BESS optimization for the supply of multiple services

In this section, the tool called MUSST, whose formulation has been presented in Section 2.4, is applied to the test case of the sizing of a BESS to be installed in the NORD market zone of the Italian power system, in particular to be connected to a specific access point of the transmission network; here an access point is indicated as a Grid Supply Point (GSP), according to the nomenclature available on the website of the Italian Nominated Electricity Market Operator (NEMO), called Gestore dei Mercati Energetici (GME) [41]. In the following subsections, first the hypotheses of this test case will be discussed along with the characteristics of the scenarios for the stochastic optimization; then the results of the optimal sizing will be presented and discussed.

3.4.1. Main assumptions

The test case here considered refers to the sizing of a BESS to be installed in the NORD market zone of the Italian power system, in particular to be connected to a GSP of the Italian transmission network which we label as “GSP 22”. This GSP has been chosen since it can be considered to be representative of a multiplicity of plants, in terms both of their number and of their technology. Besides, in the NORD zone, a large amount of energy is traded on the markets, and by a large number of plants and operators, so one can expect that a new player connected there - especially if its size in terms of power is not large as compared to the other connected plants - could easily enter the market without impacting too much the market results themselves. This last consideration allows to assume the new BESS as a price taker for what concerns its participation in the energy markets (day-ahead market in particular), and also to consider market historical results as inputs for the optimization. This test case is in particular based on the results of the Italian energy markets for the year 2019, which are publicly available on the GME website [41].

3.4.1.1. Services

The considered BESS has to be sized in order to provide the following services:

- PFR;
- SFR, by participating in the real-time stage of the Italian ASM, namely in the already mentioned Balancing Market (BM);
- tertiary frequency regulation, by participating, for simplicity, only in the ex-ante stage of the Italian ASM, here labelled as “MSD”.

The BESS is expected to participate in the Day-Ahead Market (DAM) too. Furthermore, it is adopted to reduce the imbalances of a 30 MW PV plant.

3.4.1.2. PV imbalances

An equivalent 30 MW PV plant coupled to the BESS has been obtained as an aggregation of a set of small PV plants monitored by RSE. The imbalances of the aggregated plant have been defined by rescaling actual imbalances deriving from forecasting errors on the monitored PV plants.

3.4.1.3. Frequency deviations

Frequency deviation data come from actual measurements performed by RSE.

3.4.1.4. Secondary regulation signal ϕ_2

Data related to the signal sent by the Italian TSO to the units providing secondary regulation come from Terna's website.

3.4.1.5. Modules characteristics

As said in section 2.4.1.4, the mathematical model behind MUSST is based on the strong hypothesis that the BESS is made up of modules of given energy capacity C_m and nominal power $\overline{p}_m$. For the BESS considered in this test case, the characteristics of the modules are gathered in Table 3-13.

In order to be able to consider the BESS as a price taker in the DAM, the maximum possible size in terms of power is set to 20 MW.

Table 3-13 – BESS module characteristics

Energy capacity C_m	500 kWh
Nominal power $\overline{p}_m$	250 kW

3.4.1.6. Investment costs

Investment costs per unit of installed capacity and nominal power and as a function of the size of the BESS have been chosen considering an average of the actual market costs in year 2019 and are gathered in Table 3-14.

Table 3-14 – BESS investment costs depending of the size

Installed capacity	Investment costs per unit of installed capacity
< 2 MWh	550 €/kWh
2-10 MWh	450 €/kWh
> 10 MWh	300 €/kWh
Nominal power	**Investment costs per unit of nominal power**
< 1 MW	400 €/kW
1-5 MW	350 €/kW
> 5 MW	300 €/kW

3.4.1.7. Remuneration mechanisms and bidding strategies

Having imposed a maximum size of 20 MW, it is possible to consider the BESS as a price taker on the DAM, thus the hypothesis made is that all bids (to sell or purchase) are presented with a price that is always accepted. Being the DAM a system marginal price market, the remuneration for each accepted bid is at the resulting price for market zone NORD, where the BESS is assumed to be installed.

For what concerns MSD and the BM, in which the pricing scheme is pay-as-bid, a very simple bidding strategy has been chosen: selling (purchase, respectively) bids are always presented at the historical average accepted price and they are considered as accepted if this bid price is lower (higher) than the maximum (minimum) historical accepted price in each reference time interval: in this case bids are called "on-price" bids.

The constant bidding prices considered, both upward and downward and for both MSD and the BM, are indicated in Table 3-15 (for the MSD prices, the average has been taken of historical prices associated to the "step 1" service only).

Table 3-15 - Bidding prices on MSD and BM

	Upward bidding price [€/MWh]	Downward bidding price [€/MWh]
MSD	91.53	29.67
BM	109	26

As to PFR supply, we have assumed, as already done for the simple simulation of PFR+SFR supply, the current regulated price scheme holding for dispatchable power plants and described in Subsection 2.1.8.3.

Finally, as to the NP-RES imbalance reduction functionality, we have adopted the rules to compute imbalance penalties defined by the Italian energy authority (ARERA) [42] [43]; in such computations, the value and sign of the macro-zone imbalances, which are published by Terna [44], are used.

3.4.2. Scenarios definition

In Subsection 3.4.1.7 it has been said that the selling (purchase, respectively) bids presented on the BM and MSD are considered as accepted if the bidding price is lower (higher) than the maximum (minimum) historical accepted price in each reference time interval.

If on the BM for secondary regulation this can be fairly considered as true, since the energy exchange is used mainly for balancing purposes, on MSD for tertiary regulation the energy is procured by the TSO in order to be able to solve many different possible network problems. The scope behind the acceptance of each bid is not specified in the published market results and it remains known to the TSO only. As a consequence, the economical merit order is, in general, not sufficient to indicate whether a bid can be considered as accepted or not in simulations.

To cope with this lack of information, for this test case four different scenarios of acceptance have been defined, each with a given chance to occur:

- Scenario 1 refers to the situation in which all the on-price bids are accepted; since this is a very unlike scenario, it has been given a chance of 10% to occur.
- Scenario 2 refers to the situation in which 70% of the on-price bids are accepted; it has been given a chance of 20% to occur.
- Scenario 3 refers to the situation in which only 50% of the on-price bids are accepted; it is a likely scenario, so it has been given a chance of 40% to occur.
- Finally, scenario 4 refers to the situation in which only 30% of the on-price bids are accepted; it has been given a chance of 30% to occur.

These scenarios are resumed in Table 3-16.

Since the minimal market time resolution is here 15 minutes (the resolution of the BM), the reference timeframe chosen for the simulation is 15 minutes (which is one order of magnitude larger than 1 minute and therefore allows to reduce the computational burden in the presence of a set of scenarios; see Subsection 2.4.1.2 for further clarifications).

Table 3-16 - Scenarios characteristics

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
$\boldsymbol{\theta_s^{acc}}$	100%	70%	50%	30%
$\boldsymbol{\psi_s}$	10%	20%	40%	30%

3.4.3. Results

In Figure 3-18 the trend of the ratio between (annual) incomes and (investment) costs as a function of the energy size of the BESS is shown.

The particular shape of this trend is a consequence of the discrete definition of the investment costs depending on the BESS size (see Table 3-15). By plotting the trend of specific incomes as a function of the size of the BESS in terms of number of modules (Figure 3-19), it is possible to see that, in general, the smaller the size, the higher the specific incomes. So, if the specific investment costs were independent of the size, then the best investment would be on the smallest possible BESS. Economy of scale, then, has a major impact on the investment decision, making the optimal size to be 5.25 MW in terms of nominal power and 10.5 MWh in terms of installed capacity.

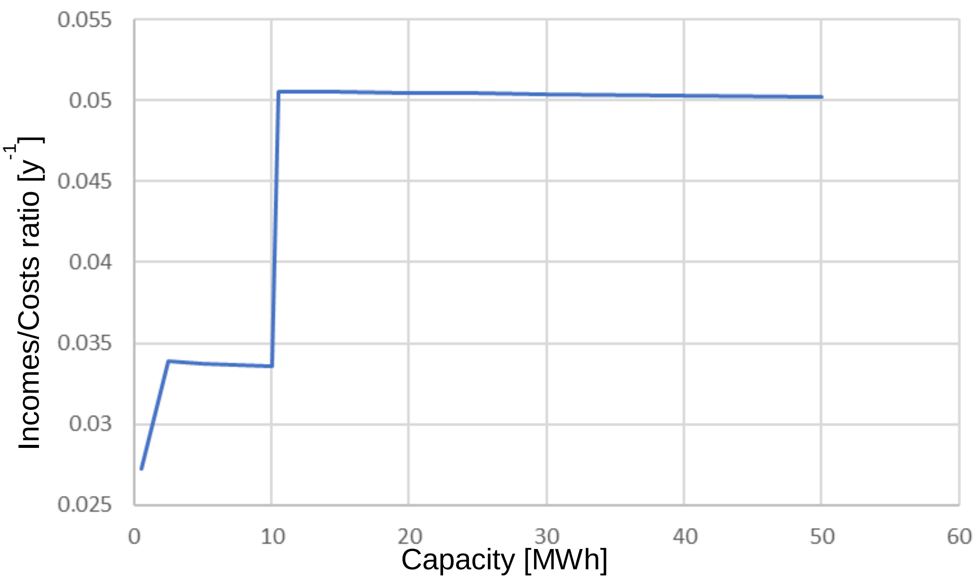


Figure 3-18 – Incomes over costs ratio as a function of the energy size of the BESS

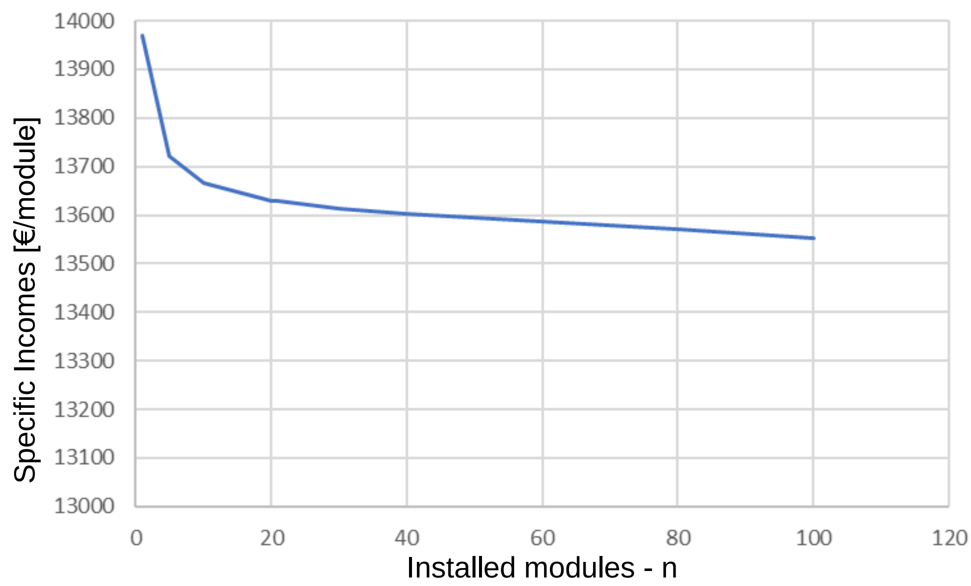


Figure 3-19 - Specific incomes per module

The resulting expected PBP of the investment for the optimal size is a little shorter than 20 years, too long if compared to the expected lifetime of a BESS (around 15 years): this investment is not profitable.

It is however worth taking a look at the optimal power share among the considered services, shown in Figure 3-20.

First, the share of power dedicated to primary regulation, β_1, is always equal to 1.5%, which is the minimum requirement from the Italian network code (see Subsection 2.4.1.5), thus the provision of this service is not profitable with the present remuneration mechanism.

Second, the share of power dedicated to the reduction of the PV plant imbalances, β_{sb}, decreases as the size of the BESS increases, which makes sense considering that the imbalances are a function of the size of the PV which does not change with the BESS size. However, from Figure 3-19 it is possible to see that specific incomes are higher exactly when the power dedicated to the imbalances reduction is higher: this means that this is the most profitable “service” for the BESS; the small value of β_{sb} is a consequence of the low level of imbalances associated to PV generation (both because forecast is accurate and because PV plants produce energy only in half the hours of a year).

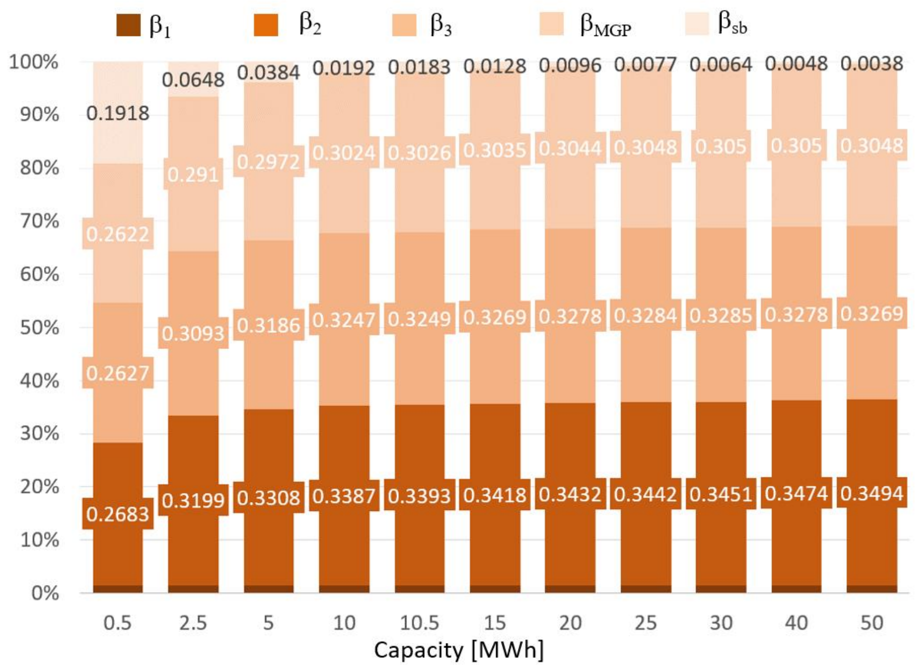


Figure 3-20 - Power shares among the considered services as a function of the BESS size; β_1 is always equal to 1.5%

As a last remark, the share of power dedicated to secondary regulation (β_2), to tertiary regulation (β_3) and to the participation to the DAM (β_{MGP}) is almost equally subdivided among them. If it is reasonable that the profitability of the provision of secondary and tertiary regulation is comparable, since MSD and BM prices are usually similar, it is unexpected that participation in the DAM, where prices are usually less competitive than in MSD and BM, has a similar share of power. The only explanation is that it is important for the BESS to participate in the DAM for technical reasons, in particular linked to the bounds on the state of charge.

In the end, it is worth investigating the impact of the uncertainty of the bids’ acceptance in MSD on the economic performance of the BESS. To do so, we ran the sizing tool for the unlikely situation in which scenario 1 has a 100% chance to occur.

The result is that for the optimal size (that is still 5.25 MW in terms of nominal power and 10.5 MWh in terms of installed energy capacity, due to the influence of the economy of scale, as discussed above) the expected PBP lowers to 14 years, which is now compatible with the 15 years of the expected lifetime of a BESS.

But what is really interesting is how the partition of the nominal power among the services changes, as shown in Figure 3-21. First of all, no power is dedicated to the reduction of imbalances from the PV plant, and this is unexpected since this was the most profitable service in specific terms when uncertainty was considered.

Then, the share of power β_2 dedicated to the provision of the secondary regulation lowers to the bound imposed by the network code (15%), indicating that also this service loses its profitability.

The share of power β_3 dedicated to the provision of tertiary reserve increases up to about 42%, indicating that this is the most profitable of the considered services. However, again surprisingly, participation in the DAM does not lose its appeal, confirming that it is necessary for technical reasons.

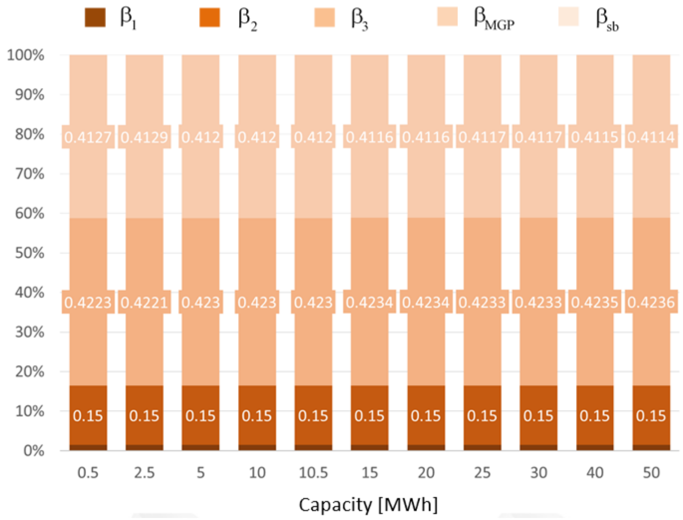


Figure 3-21 - Power shares among the considered services as a function of the BESS size, in Scenario 1 only; again, β_1 is always equal to 1.5%

3.4.4. Final wrap-up

The proposed sizing tool MUSST has been applied to the case of a BESS to be installed in the NORD market zone of the Italian power system, and associated to a chosen GSP, and to be designed to provide primary regulation, secondary regulation and tertiary regulation and to reduce the imbalances of a PV plant, beside exchanging energy on the DAM. To get a remuneration for the provision of the considered services/functionalities, the BESS is assumed to be participating in the energy market and in the ASM: this, in turn, implies, on the one hand, that the BESS can try to benefit economically from the stacking of revenues from multiple streams and, on the other hand, that it is thus "subject" to the same market mechanisms and price levels as the other participating units are (especially if its size is small with respect to the other participants' size), in other words that its revenues can be deeply affected by the competitiveness of its bids, in this case on the ASM, since the DAM is a marginal price market but a BESS can still be considered as a price taker.

The results obtained for the simulated case show that secondary and tertiary regulation may be attractive from an economic point of view, and so may NP-RES imbalance reduction.

However, the high BESS investment costs and, mainly, the uncertainty of bid acceptance in the ASM, especially for tertiary regulation, turn out to have a negative impact on the economic performance of the BESS investment by a new potential BSP.

4. Results of an international survey about BESS use for ancillary service supply

An international survey has been carried out among the ISGAN partners in the form of a questionnaire, to inquire if and how BESS can participate in ancillary service supply in different European countries.

Answers for four countries, namely Austria, Germany, Sweden and the United Kingdom, have been obtained and are now summarised. Some information is also included about Italy. The concerned countries belong to three main synchronous systems in Europe: Austria, Germany and Italy to the CE system (the former UCTE system), Sweden to the Nordic system (the former NORDEL system), the UK to the Great Britain system of course. These three systems are or will soon be interconnected to each other via HVDC links (the connection between the NORDEL and the GB system, namely the North Sea Link, is foreseen to become operational in 2021 [45]; it is a 1400 MW, ±515 kV-DC, more than 700 km-long submarine cable).

The questions proposed in the survey are the following ones:

Question 1. *Is there a regulatory framework already established for BESS participation in ancillary service supply? E.g. grid code requirements, grid connection rules, market rules…*

Question 2. *Can BESS participate in the energy (day-ahead, intraday) market as well?*

Question 3. *To which ancillary services are BESS eligible?*

Question 4. *Are rules for BESS participation in ancillary service supply the same as for conventional generators or are there specific rules for BESS? E.g., is there a minimal size to pre-qualify for a service? Is there a minimal size of bids for a service?*

Question 5. *Are there pilot projects about such a participation? If so, for which services?*

Question 6. *What are the remuneration schemes for ancillary services supply by BESS?*

Question 7. *Who can own and operate BESS for ancillary service supply?*

Question 8. *Can ancillary services be supplied together and/or together with other functionalities (which functionalities?)? Are there specific constraints/rules to be met when more than one service/functionality is supplied? E.g., are there separate power bands to be devoted to each service/functionality?*

Question 9. *How many MW installed of BESS for ancillary service supply are already present?*

Question 10. *Are such BESS stand-alone or coupled with other plants (PV, wind, conventional plants…?)?*

Question 11. *At what voltage level are such BESS installed?*

Question 12. *How many market operators are already present who include, in their portfolios, BESS for ancillary service supply? How many MW of BESS do they handle?*

Question 13. *How many MW of BESS for ancillary service supply are foreseen to be installed in the future?*

Question 14. *Does the Transmission System Operator (TSO) specify a need for a minimal amount of storage systems and in particular of BESS?*

Question 15. *In your opinion, which are, if any, the main barriers to BESS participation in ancillary service supply in your country? E.g., technological ones (too strict requirements for connection, too long time availability for service supply…), economic ones (high investment costs, lack of incentive mechanisms, poor remuneration…), other barriers?*

In the following, the answers for each country are summarised and, if necessary, commented on; in the text, questions are recalled in square brackets as [Qi], i = 1, 2, …, 15. The answers themselves are reported, for the sake of completeness, in the appendix (Chapter 6).

4.1. Austria

As far as the regulatory framework is concerned, one can recall [46] that in Austria storage facilities (including BESS) can participate in the electricity markets, including intraday and balancing [Q1, Q2]. In 2018 the NEMO called European Power Exchange SPOT SE (EPEX) [47] introduced loop block orders, where two block orders (one for "charge" and one for "discharge", to represent for example the storage cycle) are accepted or rejected together [Q2]. The loop block orders in the EPEX platform regard only six (NL, FR, BE, DE, GB, AT) of the EPEX member States.

Besides, in particular, batteries undergo the same requirements (such as prequalification) as other units eligible to provide services, since the rules have been conceived to be technologically neutral [Q4]. There is a minimal size to prequalify for a service (1 MW), however pooling is allowed.

In Austria BESS are eligible for FCR and FRR supply [Q3]. In distribution networks, they are expected to provide additional services in terms of voltage control. Participation in black start is not foreseen.

The minimal bid size to participate in AS supply is lower than or equal to 1 MW for FCR, while 1 MW < aFRR ≤ 5 MW, mFRR ≤ 1 MW.

There are pilot projects for new ancillary services, similar to fast frequency response that aim at new, faster technologies (including BESS) [Q5].

For the FCR and FRR services there is a market platform organized by the TSO/TSOs, where the former is remunerated via marginal pricing auctioning schemes, the latter via a pay-as-bid mechanism; as already hinted at, BESS participate with the same rules as for the other plants [Q6] [48]. There are no products where the payment depends on how fast the response of the power plant is.

Plant operators and BSPs can own and operate BESS for AS supply, while system operators cannot [Q7].

Multimodal operation is in theory allowed. However, pre-qualification might be an issue, since a guarantee needs to be provided that the service can be supplied no matter what [Q8].

BESS currently cover 14.04% of the FCR market, i.e., considering around ±71 MW on the whole, around ±10 MW. As to aFRR, BESS cover 11.24% of the market, whose size is ±200 MW [Q9]. The considered BESS include both stand-alone ones and BESS working in combination with hydro power plants [Q10] (other types of hybrid power plants are envisioned [Q10]). The point of common coupling (PCC) of such BESS is usually at medium voltage (10 or 30 kV), depending on the size [Q11].

In terms of market operators already present who include, in their portfolios, BESS for ancillary service supply, there are currently few of them, handling some MW each [Q12].

Among the barriers to BESS participation in ancillary service supply [Q15] there is the fact that requirements lack flexibility to account for the particularities of BESS.

4.2. Germany

In short, in Germany DERs can participate in AS supply, in an aggregated form if they are of small size; BESS can also participate, on their own or in an aggregated form [Q1].

[46] recalls that the general legal framework consists of three legislative pieces:

- the Energy Act (Energiewirtschaftsgesetz - EnWG);
- the Renewable Energy Act (Erneuerbare Energien Gesetz - EEG);
- the Framework of the prequalification and the provision of the FCR (Eckpunkte Freiheitsgrade bei der Erbringung von Primärregelleistung).

There is globally non-discriminatory market access (EPEX). In 2018 the EPEX energy exchange introduced loop block orders.

Batteries can individually or via aggregation participate in the electricity markets (the threshold for direct participation is 1 MW), so in the energy market as well [Q2], as long as storage is part of a nomination for which a balancing responsible party exists. According to [46], batteries are eligible to provide FCR services [Q3].

With respect to other technologies (conventional or DERs), there are no special rules for BESS to participate in AS supply [Q4]. We recall that the minimal bid size to participate in AS supply is lower than or equal to 1 MW for FCR, while 1 MW < aFRR ≤ 5 MW, 1 MW < mFRR ≤ 5 MW.

As to pilot projects about BESS participation in AS supply [Q5], one can recall

- the pilot about FCR by Sonnen and NextKraftwerke (**https://www.next-kraftwerke.com/news/sonnen-next-kraftwerke-co-operate-fcr-home-batteries**);
- the large-scale hybrid BESS used by Be.storaged for FCR again (**https://be-storaged.de/referenzen/referenzprojekt-hybridgrossspeicher-varel/**);
- the FRESH project, which analyses the possibility to integrate BESS from mobile transportation vehicles into the Virtual Power Plant (VPP) of NextKraftwerke for FCR again (**https://en-ergyinformatics.springeropen.com/track/pdf/10.1186/s42162-020-00129-1.pdf**);
- STEAG's 90 MW/120 MWh battery storage project for frequency regulation (**https://www.steag-energyservices.com/uploads/pics/Electrify_Europe_Optimized_operation_of_large_scale_battery_systems_-_experiences__new_opportunities_and_big_data_eng_13.pdf**);
- Bordesholm 10 MW/15 MWh Energy storage for FCR provision, black start capability, islanding capability (**https://www.res-group.com/media/342363/bordesholmcase-study_280819.pdf**);
- WEMAG (Schwerin) 10 MW/14.5 MWh battery for frequency regulation and balancing services for renewable energy generation (**https://www.aggreko.com/en/news/2017/global-news/july/expanded-wemag-battery-park-goes-online**).

In Germany, BESS participate in the "standard" market for FCR, i.e. in the related daily/weekly auctions [Q6]; the remuneration was formerly pay as bid, now with marginal pricing [49] [48].

BESS are operated by BSPs/aggregators, who can also coincide with owners [Q7]. Ownership ranges from private households (e.g. with Sonnen) to companies (Be.storaged, FRESH) and typically it is not a limiting factor for ancillary service supply [Q7].

Using BESS for multiple purposes is currently subject to research in Germany as well [Q8]. Ideas for this are for example providing peak-shaving for industrial consumers, while participating in intraday trading at the same time. However, in practice BESS typically address only one service/functionality at the moment.

In 2017 in Germany the FCR market was 600 MW, to which BESS contributed with 200 MW.

In 2019 in Germany more than 380 MW BESS were made available for FCR [Q9]. In 2020, 415 MW BESS supplied FCR [50], to be compared with 573 MW market size (the FCR market size in 2021 is 562 MW). Large-scale storage is normally employed for FCR. Anyway, one can recall that, at the end of 2018, there were also 415 MW BESS installed at homes.

BESS participate both stand-alone as well as coupled/aggregated with other plants in ancillary services/FCR [Q10]. An example of how BESS can support the volatility of the variable renewable energy generation can be found in the ALT-DABER 2 MW/2 MWh BESS project integrated in the 67.8 MWp PV farm (https://belectric.com/archive/pdf/_press_reviews/PV-Tech_power_article_BELECTRIC-EBU_460480-Volume.pdf). Aggregation is especially used for small BESS (< 1 MW).

BESS are installed both at low and at medium and at high voltage levels [Q11].

There are currently around 30 market participants that have been prequalified for FCR; however, the number of market operators/aggregators including BESS in their portfolio for FCR is unknown; besides, the number of market operators/aggregators including BESS in their portfolio and supplying services different from FCR could be higher [Q12].

TransnetBW has a plan for a “grid booster” to be provided by a 500 MW BESS at Kupferzell by 2025, to allow the load demand to go beyond the existing technical capability (https://www.tscnet.eu/transnetbws-grid-booster-confirmed/) [Q12] [Q13]. This project is included in the National Grid Development Plan 2030 by the German TSOs (see, e.g., https://www.spglobal.com/marketintelligence/en/news-insights/trending/_GQgJi6WJjXBMhUzHN3VRw2 and https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2020/02/Meldung/direkt-account.html), which aims in particular to increase the utilization of the existing network by using controllable generation and large-scale battery energy storage. Indeed, German TSOs plan to trial massive batteries (just acting as grid boosters), 1300 MW in total, to be installed at vulnerable locations so as to reduce redispatch costs and defer investments for grid expansions (https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/NEP_2030_V2019_2_Entwurf_Teil1_0.pdf).

Another project, by REDT Energy and WWF Solar, regards two 40 MWh Vanadium Redox Flow units to be adopted for secondary frequency control supply, with construction to be started in 2019 and release foreseen for 2020 (https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/2018_Innovation_report_ancillary_services.pdf; https://renews.biz/media/20444/renews_energystorage2019.pdf). This project is part of a wider project where 700 MWh at least are foreseen to be built (https://www.investegate.co.uk/redt-energy-plc/rns/redt-sign-deal-for-700mwh-of-german-grid-projects/201807260700107972V/).

The future evolution of AS supply by BESS in Germany is currently hard to predict [Q13]. As BESS already have a high share in the frequency containment market, the attractiveness of this market is likely to decline; in addition, flexibility in general is only slowly beginning to become valuable, making new business models for BESS feasible in the future.

As to possible barriers for BESS participation in AS supply [Q15], at present no critical barriers seem to be present for FCR. However, on the whole, two main challenges are the regulatory framework and economical investment [Q2]. For instance, there is no remuneration for fast response ASs in Germany (unlike what occurs in the USA), therefore the BESS cannot compete yet with the conventional options in the market. The BESS is at the early stage of the market adoption, which requires technical requirements and a suitable regulatory framework to enhance BESS competitiveness in the market.

Battery solution providers in Germany are increasingly setting their sights on the secondary reserve market (https://www2.deloitte.com/content/dam/Deloitte/bg/Documents/energy-resources/gx-er-challenges-opportunities-global-battery-storage-markets.pdf). Finally, regarding ASs in distribution grids, there is currently a lack of regulation/incentives for DSOs to make use of the BESS’ flexibility.

4.3. Sweden

As to the regulatory framework [Q1], [46] recalls that in Sweden owners of energy storage facilities are allowed to offer flexibility both in energy [Q2] and in balancing markets. BSPs can operate BESS for AS supply, while DSOs (and the TSO) are restricted to use storage only for grid operational purposes and not commercial trading [Q1] [Q7]. The TSO, Svenska Kraftnät, is currently developing the market for flexibility services such as Frequency Restoration Reserves (FRR) and Replacement Reserves (RR).

BESS are eligible to all frequency regulation markets given that they fulfil technical requirements, bid sizes, and data collection ([Q3], see also [46]).

Rules for BESS participation in AS supply [Q4] are the same as for conventional generators. The minimal bid size to participate in AS supply is 0.1 MW for FCR-N and FCR-D, 5 MW for aFRR, 1-10 MW for mFRR (depending on price area and type of activation). Remuneration schemes are pay as bid for FCR-N/D and aFRR, marginal pricing for mFRR [Q6]; for FCR-N, aFRR and mFRR there are both a capacity payment, i.e. a payment for power availability, and an energy compensation; for FCR-D there is only a capacity payment [51].

As to pilot projects about BESS participation in AS supply, one can recall the FCR-D supply project from Vattenfall by a 5 MW/20 MWh BESS in Uppsala [Q5].

Barriers for BESS participation in AS supply include prequalification schemes, lack of support for aggregators, uncertainty about bid profitability because the main frequency regulation is conducted by cheaper hydro units [Q15].

4.4. UK

As to the regulatory framework for AS supply [Q1], in the UK BESS can participate in all ancillary services; however, the minimum size, in terms of energy and power, and service duration are decisive factors. The Grid Code and Distribution Code specify the technical requirements for connecting to the system. In the UK BESS can also participate in the energy market [Q2]. BESS are eligible to all ASs if they meet the technical requirements, about minimum capacity, response time, service duration, etc. ([Q3], see also [46]).

The technical requirements for providing ASs are applicable to all providers (BESS and conventional generators). There are minimum sizes for the different services. From April 2021 BESS are exempt from paying Balancing Services Use of System charges for energy taken off the grid [Q4]. We also recall that the minimal bid size to participate in AS supply is the same for FCR, mFRR and RR: 1 MW < FCR ≤ 5 MW, 1 MW < mFRR ≤ 5 MW, 1 MW < RR ≤ 5 MW.

There are pilot projects (Power Potential) about BESS participation in AS supply, in particular for frequency regulation, voltage support, transmission congestion management [Q5]. E.g., there are projects handled by the TSO itself, like the Pathfinder projects (**https://www.nationalgrideso.com/future-energy/projects/pathfinders**) and the Power Potential project (**https://www.nationalgrideso.com/future-energy/projects/power-potential**): the former, where assets of different technologies, including BESS, and also connected to the distribution grid can participate, feature interventions on the transmission system, requested by the TSO by means of tenders, to solve voltage problems, stability problems and constraint management; in the latter, again assets of different technologies, including BESS, and also connected to the distribution grid are involved, but this time the aim is to expand the number of technologies involved, to engage the DSO more and more (also to increase coordination between the TSO and the DSO) and to test new ways to exchange ASs (frequency regulation, voltage regulation, black start, etc.) on the market.

As to the remuneration schemes for AS supply by BESS, they depend on the service and they include availability payments, energy payments, window initiation payments, etc. [Q6].

Registered and non-registered (to National Grid ESO) balancing mechanism providers can own and operate BESS for AS supply. Electricity network companies are currently prevented from owning storage [Q7].

As long as service provision targets are met for each AS, providers can participate in multiple service provisions [Q8].

There are 0.9 GW of BESS installed as of 2019. However, it is not known what share of this is providing ancillary support [Q9]. The 0.9 GW figure referring to 2019 has become 1.3 GW for 2021 (4.5 GW are foreseen by the end of 2022) [52]. Such BESS include both stand-alone ones and BESS coupled to other plants [Q10], and they are installed both at transmission and at distribution level [Q11].

National Grid Future Energy Scenarios 2020 includes 3.6-9.1 GW by 2030 and 12.5-25.3 GW of battery storage installation by 2050. However, the share of these which will be providing ancillary services is not known [Q13], and a need for a minimal amount of BESS has not been specified by the TSO [Q14].

As to barriers to BESS participation in AS supply, they are mainly economic. There is a lack of incentives and little remuneration, which makes the economic case difficult [Q15].

4.5. Italy

In Italy a regulatory framework has not been established yet for BESS participation in ancillary service supply [Q1] [Q3] [Q4]. However, pilot projects have been started, by the national energy Authority (ARERA), allowing such participation, as explained shortly below [Q5]. However, BESS cannot participate in the energy (day-ahead, intraday) market yet [Q2].

Only dispatchable generation units defined as relevant, i.e. with size 10 MVA at least, have always been eligible for participation in the Italian ASM, while small generation units, NP-RES plants, loads (except for some large loads supplying the interruptible service as an emergency DSR) and BESS were not eligible. On the basis of the European guideline on Capacity Allocation and Congestion Management [53] and of the 2012/27/EU directive on energy efficiency [54], ARERA has recently started an evolution process for the regulatory framework, and a first step in this process [55] consists of opening the ASM to new participants and making new dispatching resources available (indeed in the form of additional assets to supply ASs or of new, more stringent requirements for already existing ASs or of newly defined ASs). This first step has been taken via the institution, promoted and organised by the TSO (Terna) and approved by ARERA, of pilot projects, each devoted to the supply of one or more ASs. BESS, in particular, are or were allowed to participate in almost all such projects [Q5] [Q10]. This means that, if the transient rules enforced in the pilot projects become permanent, many barriers to BESS participation in AS supply in Italy will be overcome [Q15]: e.g., technological barriers like long time availability for tertiary regulation supply or the minimal size to be eligible for ASM participation; other barriers could instead be more difficult to remove, e.g. economic ones like the BESS high investment costs, the lack of incentive mechanisms, the possible poor remuneration coming from the remuneration of energy exchanges only (as remarked below, in some pilot projects there is an additional remuneration for the available power, but it is uncertain whether it will be confirmed or not after the end of the pilots).

Here is a list of the pilot projects currently going on and to which BESS can take part:

- Mixed Virtual Elibigle Unit (in Italian “Unità Virtuale Abilitata Mista” – UVAM [56] [57]):
    - an UVAM is an aggregation of assets allowing the presence both of non-relevant – programmable and/or non-programmable – Production Units (PUs), including stationary and mobile (electric vehicles [58]) storage systems, and/or relevant PUs not subject to mandatory ASM participation which share their

connection point with consumption units, and of consumption units; the aggregation has to be within a geographical perimeter identified by the TSO and not exceeding the boundaries of a market zone;
    - the project is for the supply of programmed congestion management, spinning and replacement tertiary reserve, balancing;
    - the supply of upward and/or downward flexibility has to be for 1 MW at least;
- Relevant Production Unit (in Italian “Unità di Produzione Rilevante” – UPR [59]):
    - a UPR is composed of relevant PUs currently non-eligible, which can include or not storage systems;
    - the project is for the supply of spinning and/or replacement tertiary reserve and of balancing;
- Integrated Relevant Production Unit (in Italian “Unità di Produzione rilevante Integrata” - UPI [60]):
    - an UPI is composed of a PU integrated with a BESS;
    - the project is for the supply of PFR, which should be taken care of mainly by the BESS, so as to “relieve” the PU itself;
- Fast Reserve or “UVA by a Storage system” (UVAS) [61], to test a new service for a fast frequency regulation, called Fast Reserve Service (FaReS), as described in more detail in Subsection 4.5.1;
- SFR supply by relevant plants not yet eligible and by plants already included in UVAM pilot projects [26]:
    - the supplying assets can be relevant PUs (fed with P-RES or NP-RES and/or composed of storage systems) or UVAM with the requested technical features and with at least quarter-of-an-hourly validated measured data;
    - the supply can also be asymmetric, namely in one direction only or with different half-bands in the two directions, although the *total* (i.e. at the national level) procured half-bands will be symmetric;
    - the supply of upward and/or downward flexibility has to be for 1 MW at least;
- pilot projects for the supply of voltage regulation.

The minimal size to participate in the services on the ASM is now

- 1 MW for the UVAM, UPI and SFR projects,
- 2 MW for the UPR one in case of balancing,
- 5 MW for the UPR one in case of spinning and replacement reserve.

The maximum response time for service supply is

- 15 minutes for the UVAM and UPR projects,
- 120 minutes for the UVAM one in case of replacement reserve,
- 30 s for the UPI one (recall that this time is the time required to PFR to reach a new regime after a perturbation).

The supplier of a service has to be able to keep service supply for at least

- 2 h, in case of a UPR and of an UVAM;
- 8 h, in case of an UVAM, for the replacement reserve service;
- 15 minutes for an UPI;
- 1 h for the SFR project.

As to remuneration schemes [Q5] [Q6], while some pilot projects adopt the same rules as the ones already enforced for traditional suppliers of traditional ASs (e.g., in the SFR project there are the pay-as-bid remuneration of the energy exchanged according to the level signal sent by the TSO and penalties for the energy not exchanged/imbalances; for the UPI project, the same rule as for standard PFR is applied (see Paragraph 2.1.8.3), some others adopt partially different rules: in the UVAM project, e.g., there is not only the pay-as-bid remuneration of the energy exchanged after bid acceptance (and penalties for the energy not exchanged/imbalances), but also a payment for power availability (capacity payment). As to this latter, there are tenders to bid for availability in specific hour ranges (in the afternoon or in the evening, Monday to Friday); in the presence of such additional payment, anyway, a strike price is imposed on the price of energy bids.

The TSO has not specified yet a need for a minimal amount of storage systems and in particular of BESS [Q14] [Q9]. However, for the UVAM project, e.g., the TSO has limited to 1000 MW the procurement of available power, from all technologies (and there are two procurement areas: North and Centre-North versus Centre-South, South, Sicily, Sardinia and Calabria); similarly, the TSO has limited to 230 MW the procurement of available power for the FaReS and to 500 Mvar the procurement of reactive power for the voltage regulation project.

Some figures about the UVAM project results [Q12], with reference to the situation on 31st December 2019: there are 231 qualified UVAM units, and almost all of them have been awarded long-term contracts for power availability (around 1350 MW for the upward service and around 207 MW for the downward [62]); such plants are handled by 34 BSPs and are located mainly in the NORD zone (171 UVAM), the others are in CNOR (22 UVAM), CSUD (24 UVAM), SUD (10 UVAM), Sardinia (1 UVAM) and Sicily (3 UVAM). All these UVAM have qualified for the upward service (with power from 1 MW to 62 MW); 28 UVAM only have also qualified for the downward service (with power from 1.5 MW to 28 MW).

In pilot projects, ASs can be supplied together and also together with other functionalities (e.g. self-consumption, which is typical for household BESS coupled with PV panels) [Q8]. Of course, availability of the contracted power has to be ensured in order to avoid penalties; this holds in particular for the FaReS, which has specific constraints/rules to be met when other services are supplied.

BESS belonging to UVAM or to units qualified for the FaReS can be connected to any voltage level [Q11].

We also recall that, in Italy, BESS for AS supply can be owned and operated [Q7] by end users and BSPs only, but not by the TSO or DSOs.

4.5.1. Focus: the Fast Reserve service

In the Italian power system, fossil-fuel generators are being gradually replaced by inverter-based generators fed with NP-RES (wind energy, solar energy). This generation-side evolution contributes to decreasing the provision of ASs by traditional providers (large synchronous generators). Therefore, the “lost” resources for AS supply need to be replaced by new resources, e.g. by new assets and/or by new ASs.

From the system balancing point of view, a critical aspect is the frequency deviation containment after a significant instantaneous imbalance (e.g. a generator tripping event); in fact, without the natural mechanical inertial support by synchronous machines and the very fast transient power output response by the gas units and by the coal-fired power plants, the frequency deviation in the very first seconds after the imbalance can be very large in amplitude, which also means that the associated ROCOF can be very large.

In order to contain such high ROCOF values, a FaReS has been introduced by TSO Terna as a pilot project [54].

4.5.1.1. Service specifications (technical requirements, remuneration mechanisms)

The FaReS must be activated within 300 ms from an initiating event in terms of frequency deviation, with full activation time of 1 s and with maximum duration time of 30 s (see Figure 4-1 and Figure 4-2). After such 30 s and if the frequency does not exceed a suitably large threshold, the FaReS can be stopped with a linear de-ramping regulating power exchange (lasting e.g. 300 s; see Figure 4-2 again); if the frequency exceeds the mentioned threshold, instead, the regulation must be kept, up to 15 minutes. The FaReS requires a symmetrical active power exchange capability, and the ability to carry out an automatic power-frequency response (via a droop controller) and to track a power output set-point signal sent directly by the TSO (in this latter case, the initial activation time is 1.3 s and the full activation time is 2 s); the two responses can also be superposed to each other.

The FaReS is supplied by Fast Reserve Units (FRUs), which can include stand-alone assets like production units, consumption units, BESS units, or aggregated assets of the just mentioned technologies; such assets can also be DERs.

The FaReS procurement is based on an annual tender with pay-as-bid settlement rules. The tender is open to FRUs whose minimum and maximum qualified power is 5 MW and 25 MW respectively. The tender run takes place through multiple sessions (up to five) with a reverse auction scheme with a price cap (called reserve price). The FaReS is remunerated based on the capacity, i.e. the power, made available (availability price) and on the energy actually exchanged for the service (activation price). The availability price refers to the tender results (expressed in €/MW/year) according to the pay-as-bid mechanism; for each hour when the FaReS is requested, the activation price is the (hourly) DAM zonal energy price of the area where the FRU is located. Furthermore, in case of total/partial failure in delivering the FaReS or in availability, the FRU owner (or BSP) must pay a penalty.

The TSO (Terna) initially identified an annual reserve requirement amounting to 230 MW, divided into 200 MW in the Peninsula synchronous area + Sicily and 30 MW in Sardinia; the requirement for the continental area is divided into 100 MW in the Continental Centre-North area (composed of two market zones: Northern Italy and Central Northern Italy) and 100 MW in the Continental Centre-South area (composed of four market zones: Central Southern Italy, Southern Italy, Sicily and the most recently introduced zone called Calabria). This FaReS has been sized in order to ensure enough fast reserve capacity to handle critical time intervals identified by Terna, initially amounting to 1000 h/y for 2025-2030 (and such 1000 h are divided into blocks of consecutive hours; at the beginning of each block, the ability to keep regulating at the awarded power for 15 minutes upwards and 15 minutes downwards is required). Each FaReS provider can bid up to 40% of the total area requirement.

The price cap for FaReS is currently fixed at 80 k€/MW/y; this value is determined on the basis of the expected benefits from the FaReS according to 2025 and 2030 energy scenarios. In particular, the FaReS must ensure the secure operation of the Italian power system during critical time intervals with very high NP-RES generation output and minimum conventional generation output. In fact, in the absence of the FaReS, the activation of a minimum conventional capacity (mainly from open-cycle gas turbines and combined-cycle gas turbines) would be needed to keep the system secure, which would imply the curtailment of about 150-210 GWh generation by NP-RES and the procurement of additional ASs on the ASM, which in turn would cost 18-25 M€/y.

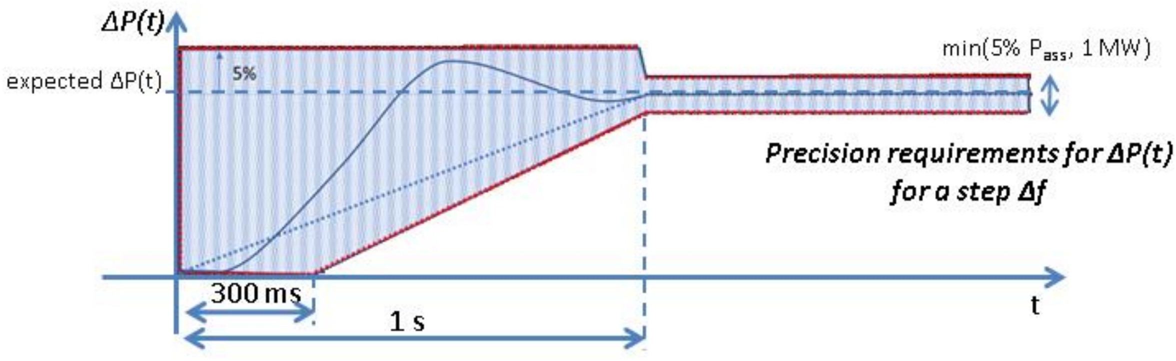


Figure 4-1 – Active power output, for the FaReS, in response to a measured network frequency error step: precision requirements

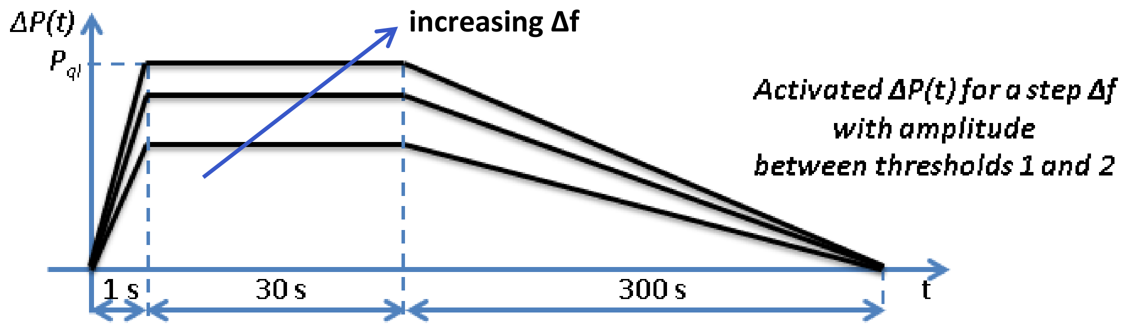


Figure 4-2 - Transient active power response, for the FaReS, to a measured network frequency error step, with the linear de-ramping period

4.5.1.2. Preliminary economic evaluation

Based on the characteristics of the new service called Fast Reserve, just introduced as a pilot project, some initial considerations can be drawn on BESS capability to do this service.

From a technical point of view, the results of the recent experimentation by Terna (https://www.terna.it/it/sistema-elettrico/innovazione-sistema/progetti-pilota-accumulo) about "Power Intensive" and "Energy Intensive" storage suggest that BESS are able to perform PFR with times to reach a new regime (1 s) and response duration values which are fully compatible with the requirements indicated in the FaReS pilot project rules: this both with technologies with small energy content (Li ones with nominal energy to nominal power ratio E_n/P_n between 0.5 and 1.2 hours, and $NaNiCl_2$ ones with E_n/P_n between 2 and 3.5 hours) and with technologies with large energy content such as NaS ones with E_n/P_n around 6.7 hours. As for performance in terms of the time to begin the response (300 ms), and as for the Li technology e.g., the field experiences reported in [63] for some applications, worldwide, of Fast Frequency Response show the ability to intervene within the time requested in the pilot project.

From an economic point of view, first of all one can observe that, if a BESS qualified all its nominal power P_n and won the auction for the FaReS with a remuneration equal to the price cap of the auction itself, its investment cost could be substantially covered by the service. For example, by assuming 300 k€/MWh plus 300 k€/MW cost (compatible with Li technologies with size of the order of few MW) and by neglecting the necessary expenses to recharge the battery, the investment could be covered in 5.6 y in case of E_n/P_n = 0.5 h, or in 11.3 y in case of E_n/P_n = 2 h. One can also remark that E_n/P_n = 2 h would allow to emphasize the possibility, for the BESS, to perform other services in addition to the FaReS, such as SFR according to the pilot project rules, which require to be able to keep supplying the service for 1 hour at least (the current rules for eligible plants for standard SFR, instead, require 2 hours at least). The expenses for recharging the battery can be neglected to a first approximation: in fact, by considering the obligation to guarantee the availability of P_n for the service in each direction for ¼ h every two consecutive hours, in the worst case the BESS would need to buy, every year, an amount of energy equal to (1,000 h/8)*P_n; by assuming to buy such energy at a DAM zonal price around 60 €/MWh (this was the average price in the NORD zone in 2018), the annual expenditure would be about 7,500 €/MW, i.e. approximately 9.4% of the capacity payment. On the other hand, the costs to maintain the SoC at values such as to guarantee the ability to perform the service could be covered by carrying out a set of other services/functionalities, in addition to participation in the DAM: in fact, since, at present, as already recalled, a limited number (1,000) of annual hours of availability is required for the FaReS, in the rest of the hours of the year the BESS could participate not only in the DAM, but also in the ASM (MSD/BM), in order to collect additional earnings, as illustrated, e.g., in

Section 3.4. Thanks to a stacking effect involving the various economic benefits, in fact, the return on investment might turn out to be favourable on the whole. By considering, e.g., a deterministic setting for the optimal sizing tool and by neglecting the supply of tertiary regulation, results for the NORD market zone again yield the following figures [64]:

- a 6 MW/6 MWh BESS (with 4.5 M€ investment cost) would earn annually about 245 k€ from PFR, SFR, participation in the DAM and reduction of PV imbalances; by assuming, for simplicity, that these functionalities are not performed in the 1,000 hours of availability for the FaReS, the BESS would get annual earnings of approximately 217 k€, to be added to the capacity payment for the FaReS (480 k€/y in this case): this way, the BESS investment PBP would be 6.5 y.
- Similar considerations can be made for a 2 h BESS and for a 0.5 h BESS, thus finding investment PBP values of the order 6 y and 5 y respectively (the profit estimate for the 0.5 h BESS has been obtained by extrapolating linearly the profit results, obtained from the combination of the different services considered, for the 2 h BESS and for the 1 h BESS).

These very first results can be deemed to be promising, but deeper analyses are of course needed to assess the profitability of the FaReS, also in combination with other services/functionalities, more accurately.

4.6. Overall remarks

As emerged from the survey on three countries in the European Union and on the UK, and also from the comprehensive analysis in [46], only few countries have already introduced mandatory standards for the installation and operation of battery storage according to their technology. However, this is not considered as a barrier to BESS deployment. Indeed, BESS are already present in many countries, both as large stationary devices and as small distributed ones (and also as small mobile ones like electric vehicles), and they are often allowed to participate in wholesale energy exchange (on the day-ahead and/or intraday market) and/or in ancillary service supply (by participating in the related market in particular). Where they supply ASs, they are usually involved in FCR and aFRR, sometimes in mFRR and in RR; at present, the BESS installed power devoted to ASs can range from few MW to some tens of MW to some hundreds of MW in the different countries; such BESS are managed by few operators, who are mainly BSPs.

In very few countries there are specific rules for BESS (i.e. rules tailored to their technology) for participation in electricity markets: participation rules are in fact often the same as the ones traditionally enforced for conventional power plants. This could be perceived by operators as a set of barriers, such as in terms of prequalification requirements (e.g. if a large minimum size is required to be eligible to AS supply), of service technical specifications and performance requirements (e.g. in case long or even unlimited duration is required in the supply of a service), of remuneration schemes. As to this last item, one can recall that the remuneration of standard ASs does not include a specific economic evaluation of the response speed in service provision: this lack may be a disadvantage for a BESS, whose high speed of response is a distinctive feature.

In order to overcome these barriers, in some countries pilot projects have been started, in order to explore how BESS, and more generally new technologies (including loads and distributed generators), could be involved in AS supply, both with reference to ASs traditionally supplied by large dispatchable generation units and with reference to new possible ASs. In particular, new ASs which are currently under test via pilot projects or in the early implementation stage by TSOs are, respectively, the so-called Fast Reserve and Enhanced Frequency Response services, which require a particularly prompt response; for this reason, such ASs, despite being defined, of course, in a technology-neutral way, turn out to be particular interesting for BESS.

One can remark, anyway, that BESS are undergoing a rapid development process, especially in Continental Europe and in the UK. This development can be motivated by noticing that Continental Europe is characterised by a high level of cooperation among countries as to balancing service procurement and by a high degree of integration of the platforms for energy exchange and balancing service exchange: this way, BESS could find opportunities like exchanging energy physically in one country and exchanging it economically in another country. As to the UK, it is characterised by a very high segmentation of its ASs: several different ASs are present, with different and detailed specifications, to better adapt to the possible different needs of the power system on the one hand, and to offer more business opportunities to market operators, including BESS operators, on the other hand.

5. Conclusion

Among the many applications in which BESS could support the transition to a decarbonised, but secure and resilient power system there is the supply of ancillary services, where BESS flexibility can be exploited, in particular in terms of high speed of response and of a decoupled variation of active and reactive power. The main drawbacks are the limited energy content and the degradation due to cycling aging; besides, investment costs are still rather high.

The supply of different ancillary services, also combined with participation in the day-ahead market or other functionalities, by a BESS, in a stand-alone configuration or coupled with an NP-RES plant, has been analysed, from a technical and an economic point of view, to inquire how able BESS could be to respond to service requests in terms of power/energy exchanges, how such exchanges could impact on the battery cycling life, how profitable such exchanges could be for the BESS owner/BSP. The main lessons learnt from the simulated applications shown in this report can be summarized as follows.

5.1.1. Primary and secondary frequency regulation

The provision of PFR and SFR together, with the same remuneration schemes adopted for the Italian conventional power plants participating in the ASM, can be profitable for a stand-alone BESS thanks to the contribution of SFR, which is characterized by upward prices significantly higher than the DAM prices and downward prices which can be significantly lower than the DAM prices and by much larger energy exchanges than those for PFR. The SoC management strategy chosen here does not change the results significantly, since it acts only when there are no requests from the two services, therefore it acts only for a very short time in this case. We remark, incidentally, that no penalties are here introduced for the energy not exchanged for the two services in case the SoC is too high or too low.

The obtained results also suggest that the main “items” impacting on the BESS investment profitability are the BESS investment costs themselves and the bid (and accepted) prices for SFR. Therefore, if a “strategy” were implemented to choose prices to bid for SFR on the ASM, the service profitability for the BESS could be improved. However, in this case the improvement may not be enough to reduce the PBP so as to make it shorter than BESS cycling life, e.g. for sodium-nickel chloride BESS, whose useful life can be deeply affected by the charge-discharge cycles carried out. Therefore, a “good” bidding strategy should also take into account how many and how deep the cycles related to service supply could be; a solution could be, e.g., to resort to supplying even more than two ASs together, by devoting different power bands to them, so as to exploit different revenue streams, as aimed at by the BESS size optimization tool presented in this report (see also Subsection 5.1.4).

Finally, one can remark that, if a BESS is coupled with a wind or a PV plant, to supply PFR and SFR on its behalf, the profitability of these two services may be impacted negatively. For instance, if a threshold is put on the power generated by the plant, so that the BESS regulation action is switched off when such power is below the threshold, then the time devoted to carrying out the services can become rather small if the plant does not produce so much, as in the case studies considered here: the considered wind plant and PV plant generate at least 10% of their nominal power for about 50% of the time only, and this causes the BESS PBP (and its cycling life) to roughly double as compared to the stand-alone BESS case studies already analysed; incidentally, we recall that here a partial support from the plant for downward regulations, in case the BESS cannot fulfill their requests, is included, but its effect (notwithstanding the fact that it implies additional costs, since more energy is bought/less energy is generated and sold) is not so relevant. If the mentioned threshold were removed, results similar to the ones obtained for stand-alone BESS could be recovered, but, since they are not so profitable, the same considerations already carried out about the need for suitable strategies to improve economic efficiency would hold; such strategies could anyway be more articulated because they could include a coordination between the BESS and the NP-RES plant.

5.1.2. Fast Frequency Response

As a fast frequency regulation service, the EFR devised by the British TSO is here taken as a reference, with its technical specifications and performance indicators (the SPM and the AF; notice that the AF also “weights” the contracted remuneration). Therefore, it is interesting to analyse the BESS ability to keep inside a pre-defined envelope region in the frequency-power plane while responding to frequency variations. Being outside the region and farther and farther from it implies lower and lower performance, so a lower and lower weight (the AF) for the remuneration.

The results obtained with the GB frequency show that a stand-alone BESS is not always able to exchange all the energy which would be requested to track the centre curve of the envelope, especially if its nominal energy to nominal power ratio (E_n/P_n) is smaller than 2 h. Of course, it is even less able to absorb or to inject the large amount of energy requested by either of the boundary curves of the envelope. However, the considered performance indexes measure the ability not to go outside the envelope in terms of power exchanges, so that, provided that the frequency deviation is not too large (frequency deviation is so large for a short time indeed), zero exchanged power means being inside the envelope. Therefore, such indexes assume on the whole very high, i.e. very good, values in all the simulated cases; e.g., the statistical distribution of the AF computed for each half an hour is significantly concentrated on the full-performance, 100% value (the SPM statistical distribution is concentrated above the 85-90% level), with very few 50% AF values present, and with values equal to 75% which can reach, for instance, up to 3% of the samples in case the central curve in the envelope is considered, up to 2% of the samples in the same case with the addition of a SoC management strategy similar to the one adopted in the PFR+SFR simulations. In case the top or the bottom curve of the envelope is considered (i.e. one of the boundary curves), so that large energy absorption or large energy injection is requested, respectively, one has that the probability that the AF is less than 100%, so 75% or less, is globally lower than 6% in all the simulated cases.

Of course this technical analysis is preliminary (e.g., a smart strategy to handle the SoC has to be developed), but such figures show that, if the contracted remuneration is high enough, technical performance does not seem to be an issue which could decrease the remuneration significantly. However, cycling aging could be critical, depending on the BESS technology: the life estimates obtained with the average DoD approach, in fact, show that $NaNiCl_2$ BESS can live 3-4 years and 6-7 years, respectively, if they are employed for the service with the more or less demanding parameters, while the considered NaS and Li BESS can live at least 10 years or 30 years, respectively. The aging topic, anyway, has to be inquired more deeply, since the cycles DoD is not the only operating feature affecting battery useful life. Also the impact of SoC management on battery cycling aging has to be further analysed.

5.1.3. Balancing services

As to the supply of balancing services on the real-time stage of the Italian ASM, deterministic *a-posteriori* optimization of energy exchanges, at known bidding prices and known acceptance times, turns out to be rather profitable for a BESS, since it allows to reach a

BESS investment PBP lower than or equal to 10 years and, at the same time, lower than or equal to the battery useful life. This “profitability condition” occurs, in the considered simulations, for bidding prices derived by averaging the historical accepted prices or derived from the statistical distribution of the historical accepted prices, and also in case the derived upward and downward bidding prices just mentioned are varied by a factor 1+Δ and 1-Δ respectively, with Δ between -1 and 1, so that the price variation can be rather large but it keeps limited. Among the examined E_n/P_n values, the ones for which the profitability condition is met for a lot of the mentioned bidding prices (including their variations by means of factors 1+Δ and 1-Δ) are 3 h and 4 h, which can in fact be considered as the most suitable to handle the time frame of the service (which can be related to the provision of tertiary frequency regulation, in particular of replacement reserve) while not being too expensive. One can also remark that these satisfactory economic results are achieved without wearing the battery out, and they are obtained by neglecting cycling aging in the formulation of bids. This could suggest that, at least when looking for the *a-posteriori* maximum profit from the service, the effort, in terms of irregular charge-discharge cycles, related to service accomplishment is not too heavy for the battery, so that the related stress for the battery can be neglected.

By keeping quarter-of-an-hourly bid acceptance, formulating energy bids on a quarter-of-an-hourly basis instead of on an hourly basis can decrease the PBP by some months, which is not a remarkable improvement on the whole. This, in turn, seems to suggest that actually improved economic results should be sought for by developing “true” bidding strategies, based on the choice of both energy bids and of bidding prices. On the other hand, some *caveats* remain: in particular, one should include in the optimization approach the uncertainty on bid acceptance, which could heavily impact on the economic performance; therefore, it could also be useful to try and supply more services together. Stacking more services would require more complex handling or optimization both of the BESS operational planning and of the BESS real-time technical management, but it would allow to benefit from multiple revenue streams. Some preliminary hints are given by the proposed optimization of BESS sizing.

5.1.4. BESS optimization for the supply of multiple services

A simulation tool has been developed to design a BESS to provide primary, secondary and tertiary frequency regulation, to reduce the imbalances of an NP-RES plant and to exchange energy on the DAM, currently with reference to the Italian regulatory framework. The design, including the BESS nominal power and energy and the partition of the nominal power into bands each of which devoted to each considered service/functionality, is obtained via a stochastic optimization approach, which maximises the ratio between the net annual revenues from all the considered services/functionalities and the BESS investment cost while taking into account uncertainties, e.g. those about acceptance/rejection, on the ASM, of bids for tertiary frequency regulation.

As partially expected from the results of the previous analyses, the outcomes of this optimization suggest that economic benefits can be obtained by a suitable choice of the BESS size (so as to keep the BESS investment cost under control) combined with a stacking of the revenues from different services, in particular those services which appear to be more attractive if considered separately, here secondary and tertiary frequency regulation (we also recall that a functionality which could be economically attractive is NP-RES imbalance reduction, although it is, of course, strictly related to the amount of imbalances to be counteracted, so to the NP-RES plant considered).

However, one has to remark that bid acceptance on the ASM does not depend on merit order only, thus it may be affected by a high degree of uncertainty, which can have a negative impact on the actual profitability of the supply of ASs like tertiary frequency regulation or even secondary frequency regulation. This holds especially for a new participant, like a BESS, entering the market and being comparatively small with respect to the market size and to the other participants. Therefore, again, being able to formulate an “appealing” (for the market) bidding strategy is crucial (for the BESS operator).

5.1.5. Overall remarks

Different kinds of services/functionalities have been analysed in this discussion paper. They can be roughly divided into two main classes:

- “power” services, where an immediate power response is requested, but where the energy exchanges in each direction may be moderate; among such services one can include fast frequency regulation and also standard primary frequency regulation;
- “energy” services, where the requested power response is slower but rather large energy exchanges in each direction are involved; such services include tertiary frequency regulation (so also balancing) and NP-RES imbalance reduction;

secondary frequency regulation could be considered as in-between the two classes, since the requested power response is on time scales slower than the ones for primary frequency regulation and faster than those for tertiary frequency regulation, and the energy exchanges carried out in each direction are much larger than the ones involved in primary frequency regulation.

As to remuneration schemes, some main items to take into account are

- payment for availability; this is usually related to the power made available for the service; examples are the capacity payment in the Italian pilot projects called Fast Reserve (for a fast frequency regulation service, we recall) and UVAM (for tertiary regulation, balancing and congestion management) and the one for the British Enhanced Frequency Response service;
- payment for activation; this is usually related to the energy actually exchanged to carry out the service; examples are the standard ASs in Italy and the pilot projects in Italy;

the two forms of payment can be present together, as in the Italian pilot projects called Fast Reserve and UVAM.

Of course, the profit from a service may be reduced due to penalties related to unavailability or nonconformity of service supply; however, here penalties have been disregarded to a first approximation; only the availability factor for the EFR service has been analysed in some detail.

According to the results obtained in the simulations, “power” services remunerated with a payment for activation may be not profitable enough for a BESS, since the involved energy exchanges are rather small (this happens, e.g., for the Italian standard primary frequency regulation). In that case, the presence of a remuneration for the power made available is fundamental to determine the economic attractiveness of such services. For “energy” services, instead, payment for activation can be profitable, since the energy exchanges involved are rather large; of course, the actual profitability is also determined by the energy prices: e.g., in the Italian ASM, upward/downward prices for secondary and for tertiary frequency regulation (and balancing) seem to be sufficiently high/low (although a more thorough analysis of historical market results would be needed, to understand how uncertainty on bid acceptance could affect the BESS economic results). Notice that, in other European countries, these services can benefit of a double remuneration, i.e. both for availability and for activation: for instance, in Germany and in Switzerland, all the services except FCR have this double remuneration, while FCR has only an availability payment; in Great Britain, the Short-Term Operating Reserve (STOR), which is similar to tertiary frequency regulation, has the double remuneration. In the presence of a double remuneration, higher revenues could of course be expected for a BESS, however the specific remuneration prices should be analysed in order to understand whether acceptable return on investment could be obtained.

Finally, as for the survey obtained from the answers to a ***Questionnaire***, shared among the ISGAN partners, on the current development of the BESS technology in power system applications, with focus on AS supply, in European countries, one can remark that BESS are undergoing a rapid development process, especially in Continental Europe and in the UK. This current status can be motivated by the penetration level of NP-RES generators that more and more replace the large dispatchable power generation units, thus decreasing the amount of ASs supplied by these units: in fact, the applications of BESS connected to the transmission system are mainly for the provision of ASs such as FCR (primary reserve) and automatic FRR (secondary reserve), by means of BSPs/aggregators. This development level can also be motivated by the maturity of electricity markets (e.g. in the Great Britain system) and by the level of interconnection and cooperation among countries (think, e.g., of the high degree of integration of the platforms for energy exchange and balancing service exchange across Continental Europe): these drivers, in fact, are leading to increasing business opportunities for market operators, including BESS operators.

6. Appendix: answers to the international survey

	Austria 1	Austria 2	Germany 1	Germany 2	Sweden	United Kingdom
Question 1. Is there a regulatory framework already established for BESS participation in ancillary service supply? E.g. grid code requirements, grid connection rules, market rules…	Yes, but the whole framework is technology agnostic	yes, for frequency control	There is no separate regulatory framework addressing BESS in particular. However, BESS are subject to the legal frameworks that apply to DER in general. Thus, BESS can both participate in ancillary services on their own (if they meet the requirements) and be part of an aggregation (e.g. virtual power plant) participating in ancillary services.	Standards for the grid connection in Germany are VDE-AR-N 4105 for the low-voltage grid, the VDEAR-N 4110 for the mid-voltage grid, and the VDE-AR-N 4120 for the high-voltage grid. Renewable Energy Source Act (Erneuerbare-Energien-Gesetz:EEG 2017) obligates grid operators to connect all renewable energy resources to the grid with a higher priority compared to conventional power plants. The BESS is also included in the legislation if the BESS stores electricity from renewable energy resources regarding the § 3 subsection (1) sentence 1 EEG 2017, stated that “which originates exclusively from renewable energy sources […] and convert it into electricity”.	Yes	BESS can participate in all ancillary services, however the minimum capacity (energy and power) and service duration are decisive factors. The Grid Code and Distribution Code specify the technical requirements for connecting to the system.
Question 2. Can BESS participate in the energy (day-ahead, intraday) market as	Yes. EPEX has in 2018 launched loop block orders covering its 6 Member States (NL, FR, BE, DE, UK, AT) which are suited for storage.	yes, why not	Yes, just like all other types of DER.	Practically and technically yes. The investment cost is still a challenge for the BESS in this regard.	Not sure	Yes

well?						
Question 3. To which ancillary services are BESS eligible?	Frequency Containment Reserves (FCRs)/Primary Frequency Control,Frequency Restoration Reserves (FRRs)/Secondary Frequency Control. In distribution networks, storage are expected to provide additional services such as voltage control, reactive power or used as a phase shifter. Black start is limited to hydropower plants	frequency control	There are already BESS participating in both primary and secondary frequency containment reserve. In addition, they may participate in / be activated for redispatch measures (depending on their installed capacity).	Frequency control, black start, flexible ramping support, voltage support	All frequency regulation markets given that they fulfill technical requirements, bid sizes, and data collection.	All ancillary services if they meet the technical requirements (minimum capacity, response time, service duration etc.)
Question 4. Are rules for BESS participation in ancillary service supply the same as for conventional generators or are there specific rules for BESS? E.g., is there a minimal size to pre-qualify for a service? Is there a minimal size of bids for a service?	Yes, the same. There is a minimal size to prequalify for a service (1MW), however pooling is allowed.	yes, as far as I know the rules have to be technological neutral	There are no special rules for BESS. Minimum capacity / bid size requirements are the same for BESS as for different types of DER, depending on the specific ancillary service.	There are no specific rules for the BESS compared to the conventional yet. Traditionally, the minimum size to provide frequency restoration reserve is between 1-5 MW Useful link https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Market%20Committee%20publications/ENTSO-E_AS_survey_2017.pdf	Yes for all services, FCR-N and FCR-D = 0.1 MW, aFRR = 5 MW, mFRR, 1-10 MW (depending on price area and type of activation)	The technical requirements for providing ancillary services are applicable to all providers (BESS and conventional generators). There are minimum sizes for the different services. From April 2021 BESS will be exempt from paying Balancing Services Use of System charges for energy taken off the grid.
Question 5. Are there pilot projects about such a	There are pilot projects for new ancillary services, similar to fast frequency response that	Yes	For primary frequency containment reserve, sonnen and NextKraftwerke run a pilot:	Yes. 1. STEAG's 90 MW / 120 MWh battery storage project for frequency regulation.	FCR-D from Vattenfall by a 5MW/20 MWh BESS in Uppsala, that I know of.	Yes. Frequency regulation, voltage support, transmission congestion management,

participation? If so, for which services?	aim at new, faster technologies (including BESS)		https://www.next-kraftwerke.com/news/sonnen-next-kraftwerke-co-operate-fcr-home-batteries Also, be.storaged uses a large-scale hybrid BESS for primary frequency containment reserve (source unfortunately only in German): https://be-storaged.de/referenzen/referenzprojekt-hybridgrossspeicher-varel/ Additionally, the FRESH project analyses the possibility to integrate BESS from mobile transportation vehicles into the VPP of NextKraftwerke for primary control reserve: https://energyinformatics.springeropen.com/track/pdf/10.1186/s42162-020-00129-1.pdf	https://www.steag-energyservices.com/uploads/pics/Electrify_Europe_Optimized_operation_of_large_scale_battery_systems_-_experiences__new_opportunities_and_big_data_eng_13.pdf 2. Bordesholm Energy storage 10 MW/15 MWh for primary control energy provision, black start capability, islanding capability https://www.res-group.com/media/342363/bordesholmcasestudy_280819.pdf 3.WEMAG (Schwerin) Battery 10MW/14.5MWh for frequency regulation and balancing services for renewable energy generation.		
Question 6. What are the remuneration schemes for ancillary services supply by BESS?	Same as for other power plants. Notice that in Austria there are no products where the payment depends on how fast the response of the power plant is.	Frequency control is organized in a market with auctioning schemes	BESS participate in the "standard" market schemes for frequency containment reserve. In Germany, this is done via participation in the daily / weekly auctions on the platform regelleistung.net.	There are different schemes from no remuneration to regulated prices, bilaterally negotiated prices, and bidding. Traditionally, mandatory service, tender, and bilateral agreements are common practices among European TSOs.	Pay as bid for FCR-N/D and aFRR, Marginal pricing for mFRR.	Depends on the service: availability payment, energy payment, window initiation payment etc.
Question 7. Who can own and operate BESS for	Unlike in other European countries, system operators cannot own and operate	energy suppliers, plant operators	Operation of BESS is usually done by an aggregator that has market access and is able	Independent power producer (IPP) where the TSO has the authority to operate the BESS when	Not the DSO or TSO. Soon BSP will be used, not sure if that is a current service.	Registered and non-registered (to National Grid ESO) balancing mechanism providers.

ancillary service supply?	BESS		to achieve pre-qualification. Ownership ranges from private households (e.g. with sonnen) to companies (be.storaged, FRESH) and is typically no limiting factor for ancillary service supply.	the ancillary services are required.		Electricity network companies are currently prevented from owning storage.
Question 8. Can ancillary services be supplied together and/or together with other functionalities (which functionalities ?)? Are there specific constraints/rules to be met when more than one service/functionality is supplied? E.g., are there separate power bands to be devoted to each service/functionality?	Multimodal operation is in theory allowed. However pre-qualification might be an issue, since a guarantee needs to be provided that the service can be provided no matter what.	no answer	Using BESS for multiple purposes is currently subject to research. Ideas for this are for example providing peak-shaving for industrial consumers, while participating in intraday trading at the same time. However, in practice BESS typically address only one service / functionality at the moment.	Not sure what it means here e.g. at the same time? Each ancillary service can be supplied and complemented to each other. The BESS can provide several ancillary services as long as it still has the capability. For the frequency control, the TSO must ensure the active power reserves (e.g. generator, storage, demand response) to provide the frequency restoration. In Germany, it defines the boundary of frequency restoration e.g. primary frequency control within 30 seconds, secondary frequency control between 30 seconds and 15 mins, tertiary frequency control from 15 mins.		As long as service provision targets are met for each ancillary service, providers can participate in multiple service provisions.
Question 9. How many MW installed of BESS for ancillary service supply are already	14.04% of the FCR market comes from storage, 11.24% for mFRR	somewhere arround 10MW	In Germany, 380 MW installed capacity of BESS had been prequalified for frequency containment reserve in Germany. That is about 50% of the German market for	From the pilot projects, it ranges between 10-90 MW. The accumulated number is required an intensive survey.		There are 0.9 GW of BESS installed as of 2019. However, it is not known what share of this is providing ancillary support.

present?			primary frequency containment reserve.			
Question 10. Are such BESS stand-alone or coupled with other plants (PV, wind, conventional plants…?)?	Stand-alone and in combination with hydro. Other type of hybrid power plants are envisioned	both	BESS participate both stand-alone as well as coupled / aggregated with other plants in ancillary services / frequency containment reserve. Aggregation is especially used for small BESS (< 1 MW).	Yes. The BESS can supply the volatile of the variable renewable energy generation for example ALT-DABER BESS 2 MW/2MWh project integrated in the 67.8 MWp PV farm https://belectric.com/archive/pdf/press_reviews/PV-Tech_power_article_BELECTRIC-EBU_460480-Volume.pdf		Both.
Question 11. At what voltage level are such BESS installed?	Some at 10kV, others at 30kV	medium voltage, depending on the size	low voltage (0.4 kV), medium voltage (20 kV), and high voltage (110 kV).	Medium voltage 6-60 kV and high voltage 60 – 220 kV		Transmission and Distribution level.
Question 12. How many market operators are already present who include, in their portfolios, BESS for ancillary service supply? How many MW of BESS do they handle?	To the best of my knowledge, less than 5, handling ~10MW	1-2	There are currently ~30 market participants that have been prequalified for frequency containment reserve; however, the number of market operators / aggregators including BESS in their portfolio is unknown. For frequency containment reserve, they handle about 400 MW of capacity (380 MW in 2019).	Regarding published data, TransmetBW has a plan for grid booster provided by the BESS. https://www.tscnet.eu/transnetbws-grid-booster-confirmed/ According to the National Grid Development Plant 2030, one of its goals to increase the utilization of existing network by using controllable generation and large scale battery energy storage. However, it is not explicit in the current plan but only considered implicitly. To reduce the future network expansion investment, the TSO, therefore, designed the pilot projects and		This information is not available.

				examined their benefits as part of redispatch calculations. https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/NEP_2030_V2019_2_Entwurf_Teil1_0.pdf		
Question 13. How many MW of BESS for ancillary service supply are foreseen to be installed in the future?	I cannot find public information on this.	unknown	That is currently hard to predict. As BESS already have a high share in the frequency containment market, the attractivity of this market is likely to decline; and flexibility in general is only slowly beginning to become valuable, making new business models for BESS feasible in the future.	TransnetBW GmbH is planning to integrate a battery of 500 MW at Kupferzell by 2025 as the grid booster to allow the load demand goes beyond existing technical capability. https://www.spglobal.com/marketintelligence/en/news-insights/trending/_GQgJi6WJjXBMhUzHN3VRw2 https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2020/02/Meldung/direkt-account.html 50 MWh Vanadium Redox Flow in Eberswalde, Germany connected to the 110-kV https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/2018_Innovation_report_ancillary_services.pdf		National Grid Future Energy Scenarios 2020 includes 3.6-9.1 GW by 2030 and 12.5-25.3 GW of battery storage installation by 2050. However, the share of these will be providing ancillary services is not known.
Question 14. Does the Transmission System Operator (TSO) specify	No to the best of my knowledge.	no, not so far	No, there are currently no specific requirements for BESS from the TSOs.	There is no legal requirement for the TSO to own the BESS.	No	No.

a need for a minimal amount of storage systems and in particular of BESS?						
Question 15. In your opinion, which are, if any, the main barriers to BESS participation in ancillary service supply in your country? E.g., technological ones (too strict requirements for connection, too long time availability for service supply…), economic ones (high investment costs, lack of incentive mechanisms, poor remuneration …), other barriers?	The business case in Austria for storage is not very clear, unlike in other neighbouring countries (Germany comes to mind). Among other barriers, prequalification of devices is not clearly specified in documents and many interpretations are needed. Also, requirements lack flexibility to account for the particularities of BESS. In my opinion, a very interesting approach is the one followed by Terna in Italy, where the BESS is only required to provide a certain product at given times (known ahead), which facilitates multi-modal operation and collection of multiple revenue streams.	costs for capacity	For frequency containment reserve, there are no critical barriers for BESS participation in my opinion. However, regarding ancillary services in distribution grids, there is currently a lack of regulation / incentives for DSOs to make use of the BESS' flexibility.	Two main challenges are the regulatory framework and economical investment. There is no remuneration for fast response ancillary services in Germany not like in the USA; therefore the BESS cannot compete yet with the conventional options in the market. The BESS is at the early stage of the market adoption which require technical requirement and regulatory framework the enhance the competitiveness in the market. https://www2.deloitte.com/content/dam/Deloitte/bg/Documents/energy-resources/gx-er-challenges-opportunities-global-battery-storage-markets.pdf battery solution providers in Germany are increasingly setting their sights on the secondary reserve market	Prequalification schemes, lack of support for aggregators, unclear rules regarding accepted profit per bid, profitability since main freq. regulation is conducted by cheaper hydro units.	The barriers are mainly economic. There is a lack of incentives and little remuneration, which makes the economic case difficult.

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