POLITECNICO DI MILANO

Scuola di Ingegneria Industriale e dell'Informazione

Dipartimento di Energia

Corso di Laurea Magistrale in Ingegneria Energetica

Battery Energy Storage Systems for Ancillary Services Provision

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Anno Accademico 2016 – 2017

A mamma, Ale, papà. Sono proprio un ragazzo fortunato.

Alla bicicletta ed ai concerti con i poghi.

A Nico, Ste, Cippi. La mia squadra.

A Piacenza e a tutte le strane persone che la animano.

A Casa Botti e ai suoi magici abitanti.

Ad Eleonora e Fabri. Bellissimi.

Ad Ale Blaco. Catalizzatore di idee.

A Rovvy. Fratello matto.

A chi è lontano. Ma tornerà.

Ad Alessandra, che mi ha insegnato il meglio.

A Ludovica, che mi ha mostrato il peggio.

A Sara, la Gioia.

Extended abstract

Introduction

Global demand of energy will expand by 30% among today and 2040 [1]. The growth rate is decreasing compared to recent past, but far from stopping. In the same time horizon world population is expected to rise to 9 billion people. Growth in demand is due to both rise of population and increase in consumptions per capita: energy demand is usually related to wealth and social wellness, therefore its increase per capita should not be distressful. The concern should be in having clean power to feed that energy need. In New Policies Scenarios foreseen by International Energy Agency (IEA), new loads will be powered in large part by Renewable Energy Sources (RES) and predominantly by wind and PV. Since these are non-programmable intermittent sources, this scenario arises new issues for the security of power systems. Power systems needs to preserve a stable balance among production and consumption of energy. In AC systems, the most common type of power networks, main marker of grid balance is stability of frequency. Frequency must have average value exactly corresponding to nominal value (50 Hz in Europe, 60 Hz in US) and stay always as close as possible to this value. Larger share of RES in power networks leads to more unbalances due to their non-programmability and to possibility of forecast errors. Furthermore, rise of inverter-based systems as wind and PV generators causes a loss in inertia, affecting the capability of network to react to unbalances by keeping frequency variation small. Inertia of a network is proportional to the overall mass of spinning turbines grid-connected directly by transformers. Consequently, the energetic scenario evolution is going to be more and more bounded by an effective management of the so called Ancillary services. Ancillary services provide support in guaranteeing reliable operation of power network.

The scope of this study is to model a Battery Energy Storage System (BESS) able to provide multiple services in the framework of an Ancillary Services Market (ASM) and simulating its operation to provide both technical and economic analysis of the performance. ASMs have always been "conservative" environments and grid services have been only provided by large-scale conventional units. In fact, units suitable for providing power Reserves on ASM must be totally reliable and conventional units guarantee years of experience and 24/7 control. Nevertheless, in a system where RES increased, the size of necessary Reserves increased, too. The lack in new conventional plants to enter ASM obliged TSOs to refine the rules of ASM in many ways with the purpose of attracting new actors in it.

Since the interest of the study is both in modeling the battery system and introducing it in a market, a deep analysis on both the modeling of the complex electrochemistry of the battery cell and the structures and evolution of ASMs is one of the peculiarities of this work.

Battery modeling

Modeling a system means approximating its operation using a mathematical representation considering all relevant aspects of that system. Several models with different degrees of accuracy are in place for batteries: accuracy is usually directly proportional to computational effort. This study will focus on electric and analytical models, whose accuracy and computational effort stay halfway in the panorama.

Electric models

Electric models simplify batteries considering that useful parameters for describing their operation are the ones that can be seen at the terminals of electric circuit: a potential difference and a current. Consequently, they depict battery as an equivalent electric circuit (Equivalent-Circuit Models, ECM) with a voltage source (or a capacitor) and an impedance in series. By performing experimental campaign, a value for every circuital element is found. The number of the circuital elements defines the level of approximation of the model: the more elements are present, the more every element can be representative either of a phenomenon or of an element of the electrochemical cell. Outputs of interest are: terminal voltage (V), current (i) and Open-Circuit Voltage (OCV). This last output is used to compute State of Charge (SOC), the operating parameter that indicates the amount of energy still present in a cell with respect to total energy. In particular, a passive impedance-based model developed in Politecnico di Milano has been adopted for this application. Passive means that it presents a capacitor as non-ideal voltage source for measuring OCV. Impedance-based means that the experimental campaign to characterize its circuit used diagnostic techniques in frequency-domain. The model is implemented in a MATLAB® Simulink® tool called BESS4PCR [2]. This model was built after an experimental campaign on the cell Swing® 5300 by Boston-Power. This is a Lithium Nickel Cobalt Oxide (LNCO) battery. The equivalent circuit of this model is presented in Figure 0-1. It uses OCV for the approximation of SOC. Moreover, it implements a simplified Battery Management System (BMS) limiting the terminal voltage within a Safe Operating Area (SOA). When SOC gets close to saturation levels, power delivered by cell can be reduced to stay within the voltage window.

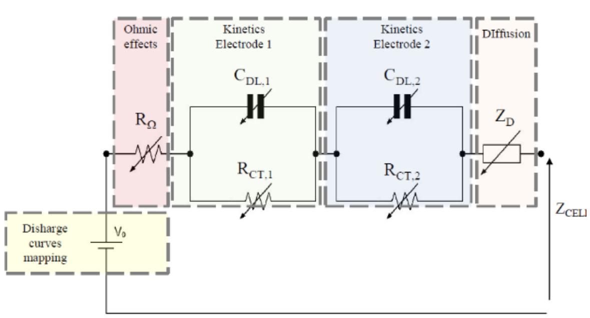


Figure 0-1 Equivalent circuit of BESS4PCR electric model

Analytical models

The huge amount of simulations performed during the study led to interest towards faster-computing models. Analytical models have been a tool largely widespread in battery modeling for years. They are based on equation no more dealing with physics of cell but just approximating its behavior mathematically. One or more equations are developed to model efficiency, voltage, OCV or SOC of the battery from experiments. Most widespread among this type of models are empirical models. They approximate steady-state operation of the battery: a value of each parameter of interest (OCV, V, i, efficiency) has been given for each condition experimented. Model is built on these measurements. Empirical models act runtime by computing the actual energy flow through the battery over a given time step to update SOC. Their accuracy becomes poorer when BESS perform long periods close to 0 and 100% SOC (SOC saturation limits), at high power requested or when operating conditions are far from experimented ones (low or high temperatures). With respect to electric model described before, the one selected for this study is not able to deal with voltage SOA. Therefore, some divergences in the behavior can be detected at SOC close to saturation. Despite lower accuracy, empirical models are the most widespread tool for battery sizing, thanks to their velocity.

State of Health

Scope of battery models is estimating not only State of Charge but also State of Health (SOH). This latter is useful to compute battery lifetime. SOH definition for this study (many are valid) is the ratio among battery capacity at time *t* and initial battery capacity. Lifetime definition in this study is the moment in which battery reaches 80% of SOH. Batteries undergo cycle ageing, when charging and discharging, and calendar ageing, when idle. For cycle ageing, this study used a diagram fitting Swing® 5300. 12 years have been selected instead as maximum lifetime due to calendar ageing, following data from study

[3]. Therefore, in the study, lifetime will be selected as the minimum among cycle-ageing lifetime and 12 years.

Ancillary Services Market

Ancillary Services Market (ASM) is the electricity market where power Reserves to face unbalances of grid are gathered. Marker of balance of grid is the frequency: average value equal to nominal value and as small as possible deviation are requested. Three main Reserves, managed by three main Ancillary Services, are always present in markets. Primary Reserve is associated to Primary Control Regulation (PCR) and pairs the unbalance to lead frequency back to a steady value. Every unit involved in PCR follows a control law requesting a power output proportional to frequency variation with respect to nominal value. This control law is called droop control curve, since droop is the value of the ratio among frequency variation and required power output: it is the absolute value of slope of line in Figure 0-2. Secondary Reserve is linked to Secondary Control Regulation (SCR) and creates temporarily an unbalance in opposite direction with respect to the one solved by PCR, to take back frequency to nominal value. In Italy, TSO is sending a signal (Segnale di Livello) each minute containing the fraction of regulating band to be used by each unit selected for provision. Tertiary Reserve is providing Tertiary Control Regulation (TCR) to restore the margins of Secondary Reserve that gets ready for next eventual unbalance. ASM is evolving since its importance

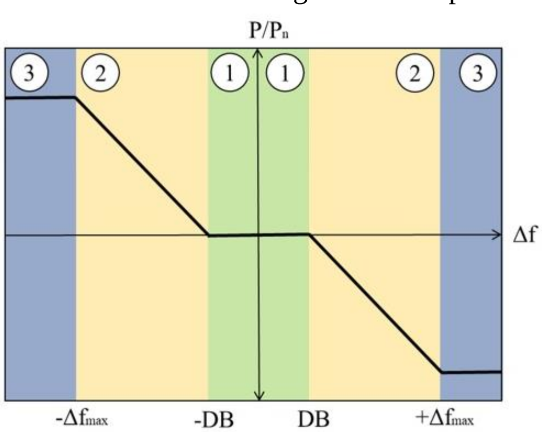


Figure 0-2 Droop control curve

is increasing. Evolution is in the direction of involving *New Actors*, to increase the size of the Reserves. The introduction of *New Services* can be then of interest, to exploit qualities of these Actors. BESS present higher precision in following steep power ramps and sudden setpoints, therefore enhanced services can be designed. On the other side, BESS limits must be taken in account. It is the case of Enhanced Frequency Response (EFR) in UK: it is exploiting fast-response of BESS while allowing SOC restoration. SOC restoration is the operation of taking back SOC to a target value (usually 50%) when SOC is getting close to saturation limits. Asymmetry of services is another valuable feature for ancillary services. This term defines the possibility of offering different regulating bands for positive and negative Reserves of same service. This would allow batteries to better manage regulating band offered with respect to SOC.

Multiple services provision

Multiple services provision is indicated in studies as the main road to provide positive economic return for investment on BESS operating on ASM [4]. This allows in fact to increase the power cycled by batteries, increase cash flows per month and decrease time idle. With convenient combination of services, also SOC restoration can be provided by grid services with no energy flows on purpose.

Methodology

The methodology proposed is simulating a period of 30 days of Ancillary Services provision. The simulations have been performed in Simulink environment. The outputs of simulation were then fed to a spreadsheet and elaborated. The work of the Author included the construction of the controller of the Simulink model for implementation of grid services; the choice of the services to provide within the simulation; the sizing of the battery; the evaluation of performance and of economic return of the battery in the context of two ASMs. Italian ASM was used as reference case, German one was used for economic return comparison. The scheme of the process includes the reception of inputs necessary for simulation (frequency data for PCR, regulation signal log for SCR), the simulation performed by the BESS model, the collection and elaboration of outputs. The process is presented as flow chart in Figure 0-3.

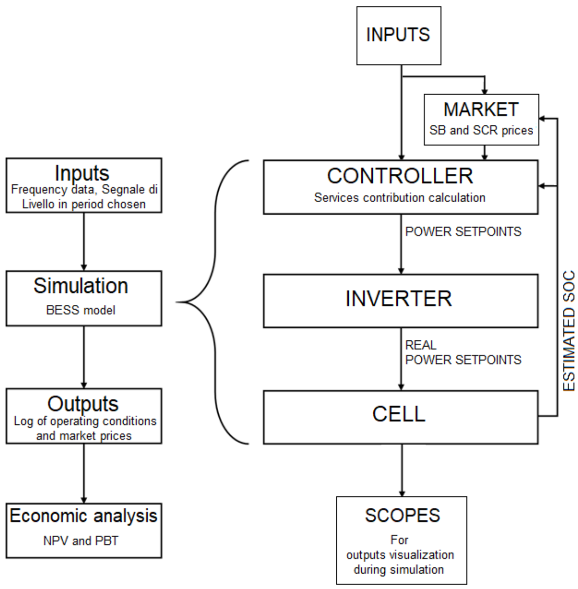


Figure 0-3 Flow chart of the process utilized in the study

Inputs

Frequency data were measured directly in Politecnico di Milano without interruptions in 2017, in the period February 15 – March 16, in framework of the IoT-Storage Lab. Frequencies were stored in a 1 Hz sampling-rate array. Regulation signal for SCR in Italian framework (Segnale di livello) was taken by Italian TSO website. Data for markets come from the Italian energy markets manager website.

Simulation

The electric model receives as input the power setpoint requested and updates SOC level as a function of its OCV. It gives as output updated SOC level. During the development of the study, the large number of simulations to perform foster the interest in use of a faster-computing model. Validation of that model entered the aims of the study. This empirical model comes from a campaign of experiments on same Swing® 5300 cell and operates by assigning a variable efficiency as a function of power requested in per unit. The roundtrip efficiency formula is a polynomial of degree 3 whose coefficients *a*, *b* and *c* come from experiments. Instantaneous efficiency is the square root of roundtrip efficiency:

$$\eta_{cell\ emp}(\Delta\dot{P}) = \sqrt{1 - a\,\Delta\dot{P}_{req} + b\,\Delta\dot{P}_{req}^2 - c\,\Delta\dot{P}_{req}^3}$$

Eq. 1

Real power in per unit is therefore obtained as:

$$\Delta\dot{P}_{real} = \begin{cases} \Delta\dot{P}\ \eta_{cell\ emp}(\Delta\dot{P}) & if\ \ \Delta\dot{P} < 0 \\ \Delta\dot{P}\ /\ \eta_{cell\ emp}(\Delta\dot{P}) & if\ \ \Delta\dot{P} \geq 0 \end{cases}$$

Eq. 2

And SOC update is consequently:

$$\Delta SOC = \frac{\int_t^{t+1} \Delta\dot{P}_{real}\ P_n\ dt}{E_n} = \frac{\int_t^{t+1} \Delta\dot{P}_{real}\ \ dt}{EPR}$$

Eq. 3

Where Energy to Power Ratio (*EPR*) is the ratio among nominal energy and nominal power (P_n). The two models deal with SOC estimation, but neglect SOH estimation. SOH estimation is computed, in terms of capacity-fade only, after simulation, by using an empirical diagram tailored on same cell and linking capacity-fade

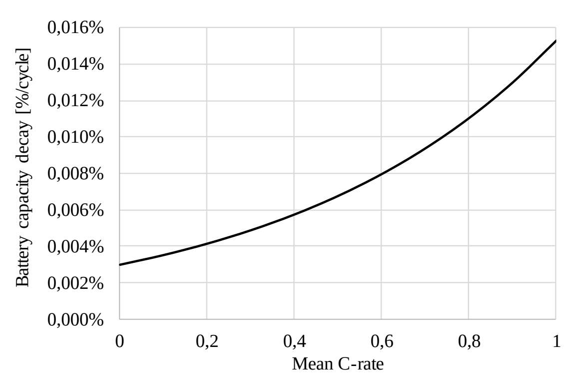


Figure 0-4 Empirical diagram for capacity-fade estimation

per cycle with average c-rate in the period (Figure 0-4).

Both cell models are completed with Inverter model, introducing its efficiency, and Controller. The Controller is the section of the model where implementation of services is active. Implementation of services and therefore Controller construction has been developed during this study. Ancillary Services present similar characteristics and needs. Their modelling can be done by defining a common process, to be fitted then on the specific characteristic of each service. A comprehensive procedure was described and then implemented as a tool for multiple services provision in Simulink: it is the Controller of the model. It receives as input all data for the provision of the service. It returns the power output requested from grid to BESS every instant. It is presented in the scheme in Figure 0-5. It is based on the functional blocks here described:

- In Band Management block is implemented the strategy for building the regulating bands for the service. The output is the value of regulating band (battery side).
- In Efficiency Computer block the efficiency of the system is estimated. The output value of this block is multiplied to the output of Band Management block, to obtain regulating band offered on market (grid-side).
- Market Time-period block allows just a single update of regulating band value at the beginning of each market session.
- In Allowing block the market is simulated. The output of this block is a Boolean value: 1 if unit is selected by market, 0 if rejected. Allowing switch works as door for regulating band: if result of market is positive (1), then regulating band is transmitted downstream the switch. Otherwise, 0 is transmitted.
- Input Management block is the block receiving the inputs for the provision of the service. These inputs define share of regulating band asked to unit by network each instant. Output of this block is exactly that share, and it is multiplied by regulating band to obtain power setpoint requested to BESS.

Outputs and analysis

After simulation, outputs are collected to files and analyzed. Analysis of performance aims to define the security guaranteed by BESS in grid services provision. The index used is Loss of Regulation (LOR), returning the share of energy not provided (E_{np}) on the total energy requested (E_{req}) for each service. Definition of LOR for service *i* is:

$$LOR_i = \frac{E_{np,i}}{E_{req,i}}$$

Eq. 4

Economic analysis has been implemented using Net Present Value (NPV) at 20 years, Payback

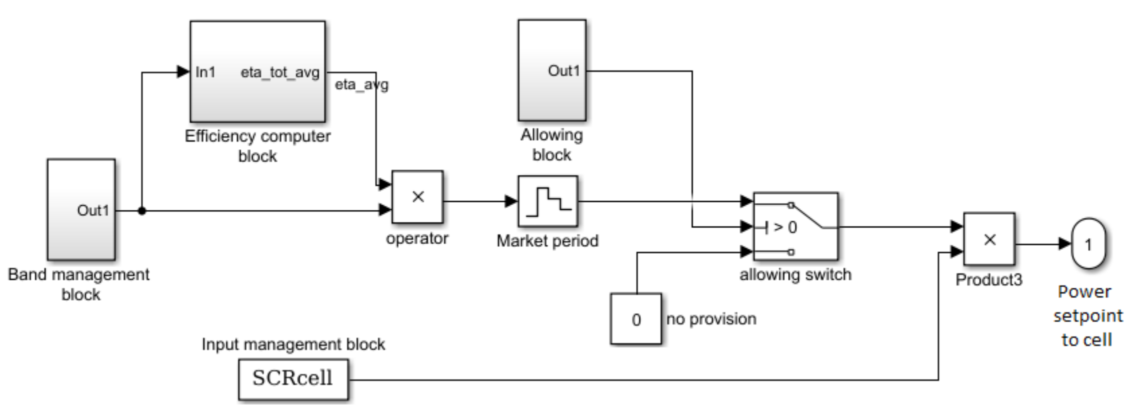


Figure 0-5 Controller layout on Simulink, based on comprehensive procedure for multiple services implementation developed

Time (PBT) and Profitability Index (PI) as main indexes. NPV is the sum of Net Cash Flows (NCF) for each year added of Residual Values (RV) of goods at year 20 and subtracted of cost of investment of batteries (C_{inv}):

$$NPV[€] = -C_{inv} + \sum_{y=0}^{20} \frac{NCF(y)}{(1+r)^y} + RV(20)$$

Eq. 5

PBT is the first year in which NPV is positive, while PI is the ratio among NPV and C_{inv}.

Services implementation

The core of the work is the implementation of Ancillary Services in the Controller of the model. They are implemented based on Italian Grid Code.

Primary Control Regulation

First implemented grid service was PCR. PCR follows fixed droop control law, that provides a unique correspondence among frequency variation from nominal frequency and power requested to cell. There is no market since PCR is mandatory in Italy. Recalling the layout of Controller (see Figure 0-5), the input of Input management block is the measured frequency, samples are detailed each second. To get the output, droop control curve in Figure 0-2 is used. Dead band is ±20 mHz. Maximum power output is regulating power ($P_{reg,PCR}$,in per unit). Droops value used during simulation are function of $P_{reg,PCR}$:

$$droop[\%] = \frac{[0.03 - 0.075]}{P_{reg,PCR}}$$

Eq. 6

These droop values have been selected to comply with the Italian Grid Code requirements (2-5% of droop on 0.015 regulating band in per unit), just rescaled on actual regulating band. Regulating band is a constant value subject neither to market nor to market period: the output from Allowing switch is always that constant value of user's choice. This band coming from Allowing switch is then multiplied by power requested, obtained from droop relation by frequency.

Secondary Control Regulation

SCR is implemented in the model following Italian rules. It is a symmetric service traded on market every 4 hours for next 4 hours. It is regulated by regulation signal sent by TSO, updated every minute, indicating the share of regulating band to be provided (*Segnale di livello*). Band Management block is less trivial here. Band offered is updated every 4 hours and is aimed to avoid hitting of SOC saturation limits in next four hours. Since there are two SOC saturation limits (0 and 100%), there will be two bands (respectively $P^*_{reg,SCR+}$, $P^*_{reg,SCR-}$) as output of Band Management block. They are obtained by dividing the energy contribution needed for hitting each of the thresholds in 4 hours:

$$P^*_{reg,SCR+} = \frac{(SOC_{init} + variation_{+} - SOC_{min})}{100 \bullet avg_{segnale\ di\ livello+}} \bullet \frac{EPR}{4}$$

Eq. 7

$$P^*_{reg,SCR-} = \frac{(SOC_{max} - SOC_{init} - variation_{-})}{100 \bullet avg_{segnale\ di\ livello-}} \bullet \frac{EPR}{4}$$

Eq. 8

Where SOC_{init} is SOC at the beginning of the 4 hours and the * is present since these values must be updated with system efficiency. *Variation*$_{+}$ and *variation*$_{-}$ are the contribution to SOC variation from PCR provision in the 4 hours. $Avg_{segnalde\ di\ livello+}$ and $avg_{segnalde\ di\ livello-}$ are the maximum 4 hours average values in direction of either positive or negative contributions that the regulating signal for SCR can have. Both couple of values come from statistical analysis performed during this work on historical data of frequency and *Segnale di livello*. They are utilized to better exploit the SOC margins while setting regulating bands. These outputs are multiplied by Efficiency Computer block output and just the minimum one is offered on market:

$$P_{reg,SCR} = \min\left(P^*_{reg,SCR+} \bullet \eta_{sys+}, \frac{P^*_{reg,SCR-}}{\eta_{sys-}}\right)$$

Eq. 9

This is the limit of symmetric service that are not exploiting the whole ΔSOC residual in the two directions taking instead the smaller one for defining regulation band (red bars in Figure 0-6). The SCR market is simulated in the Allowing block of the Controller. It uses real prices from Italian ASM market session in the simulated period and sets price offered each hour, for each Reserve (positive and negative). BESS is selected for the provision of service in positive and negative Reserve if its bid is lower than the maximum accepted on real market for both Reserves. To bid consistently, a statistical analysis was performed on prices in February-March 2016. Allowing block acts each hour by returning a 0 or a 1. Input Management block output is the regulating signal expressed as share of regulating band. It is multiplied by the band of the correspondent Reserve selected in that hour to obtain power setpoint requested from grid to cell.

Relaxing (in order to simulate viable market conditions for BESS) the hypothesis of symmetry on SCR provision, asymmetric SCR is implemented. The procedure is the same as for symmetric SCR, but the bands offered on market are:

$$P_{reg,SCR+} = P^{*}_{reg,SCR+} \bullet \eta_{sys+},$$
$$P_{reg,SCR-} = \frac{P^{*}_{reg,SCR-}}{\eta_{sys-}}$$

Eq. 10

The exploiting of SOC margins in this case is reported in Figure 0-6 with green lines.

Two Allowing blocks manage markets for each Reserve, and each one returns 1 or 0. Regulating signal is multiplied by positive band if requiring positive power, and vice versa.

Simulations and results

The aim of performing simulations with the described model is finding a satisfactory setup of PCR and SCR provision guaranteeing simultaneously security to grid and economic return of investment. A battery of 1 MW of

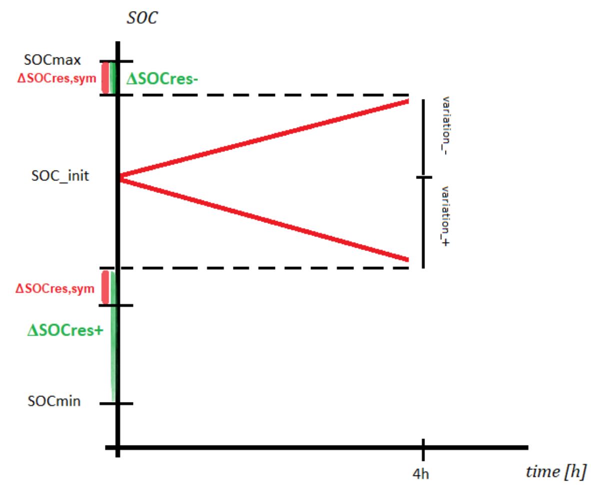


Figure 0-6 SOC residual margins exploiting comparison (red for symmetric, green for asymmetric SCR)

nominal power and 2 h of Energy to Power Ratio (EPR) was selected. 1 MW is an arbitrary choice, useful to provide a significative term of reference and to be scaled up. EPR is the ratio among nominal energy and nominal power in a battery. EPR must reflect relation among energy and power requirements of services provided. The aim is exploiting both energy band and power band to maximize performance. A statistical analysis has been performed for a battery offering PCR and SCR and the range found for EPR consistent is 1.03-1.93 h. The value 2 h used is taken as upper limit of this interval. It is a conservative value to endorse security of grid on return of investment: a larger cost of investment (investment is proportional to nominal energy) is justified by lower LOR expected (larger energy band implies SOC more stable). Droop value is 0.075%/P_{regPCR}, upper limit of interval shown in Eq. 6, selected following same reasoning.

First simulation (CASE A) involved just PCR provision, with P_{regPCR} = 1. It highlighted high LOR (13.2%) and NPV highly negative, due to low remuneration of PCR in Italy. Regulating band for PCR can be increased, but this would lead to higher LOR.

The second simulation (CASE B) implemented simultaneously provision of PCR and of symmetric SCR, following requirements by Italian Grid Code. Since SCR is more remunerative on Italian ASM than PCR, SCR band was set larger. The simulation on PCR and symmetric SCR took to results similar to previous ones in terms of LOR. LOR is high since SCR band is large when far from SOC saturation. It brings SOC far from 50% fast, towards either 100% or 0. In following market session regulating band offered to SCR decrease to zero for both reserves, because of SOC. Since $avg_{segnale\ di\ livello+}$ and $avg_{segnale\ di\ livello-}$ are both around 0.4 and maximum variations of SOC for PCR provision statistically expected in 4 hours in the two directions are

$$variation_{+} = \frac{-23.6\%}{EPR} \cdot P_{regPCR}, \quad variation_{-} = \frac{26.2\%}{EPR} \cdot P_{regPCR}$$

Eq. 11

SCR band offered, computed as in Eq. 9, gets to zero if either $SOC_{init} > 93\%$ or $SOC_{init} < 6\%$. Therefore, SOC gets fast to limits and then behaves as CASE A. LOR value is above 11% and still there is no PBT within 20 years. The multiple service provision with symmetric services only resulted an unviable strategy for BESS since no one of the services is providing SOC restoration. A SOC restoration dedicated strategy would be necessary. This would mean energy purchased and sold on market with the purpose of getting SOC back towards 50%, when

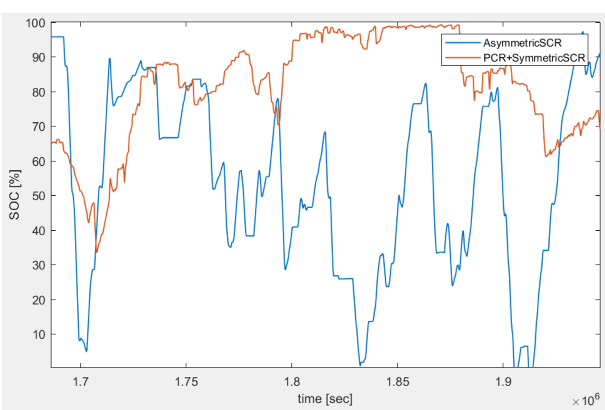


Figure 0-7 SOC evolution in CASE B (red) vs CASE C (blue)

it is close to saturation. SOC restoration dedicated mechanisms imply:

- More costs for energy purchased.
- Regulatory issues since the BESS operates as consumer and producer of energy.
- Increased average c-rate due to new energy flows, and consequent increase of cycle ageing and decreased lifetime.

Therefore, SOC restoration dedicated mechanisms are not considered during this study. Instead, asymmetric service provision is introduced.

Third simulation (CASE C) is provision of asymmetric SCR only. This CASE took the first result of interest. SOC restoration provided by asymmetric service worked and the simulation took to good results: LOR at 4.5% and positive NPV. The battery is well exploiting energy band: SOC log highlighted repeated cycles featuring large Depth of Discharge (DOD), that is the difference among maximum and minimum SOC within same cycle. With respect to CASE B, energy exchanged is doubled and LOR is less than halved. The comparison among SOC evolution is found in Figure 0-7, where the difference among the exploiting of SOC margins can be checked.

Fourth simulation (CASE D) has been dedicated to multi-service provision (providing both PCR and SCR). PCR is in fact mandatory in Italy for large-scale programmable plants. Furthermore, the main trends in ASM over Europe are leading towards an increasing importance of Primary Regulation, also presenting improved versions of it as EFR in UK. PCR and Asymmetric SCR provision were performed simultaneously. This setup gave satisfactory results with very low LOR (<2%) and positive NPV. Asymmetric provision of SCR worked as passive SOC restoration mechanism: SOC is restored when it gets close to saturation limits without implying costly energy flows but using the provision of service itself.

This setup was taken as reference for many simulations aiming to verify possibility for increasing economic return without penalizing performance. These many simulations required faster-computing model. In this framework, validation of empirical model became necessary. Performances of this model in terms of elapsing time for the simulation are outstanding with respect to electric model (15 minutes vs 12 to 14 hours): a certain decay in accuracy is accepted in order to exploit this speed. Several cycles with different setup of services provision were simulated with both electric and empirical model. In all these simulations, energy exchanged over period was checked and SOC and LOR log were inspected. Difference among gross energy outputs over periods on real-operating cycles were always below 4%. Even a test cycle on a square wave power profile was performed (c-rate = 0.5, 5 times more than average c-rates during services provision). After 2 hours, difference among energy cycled was 6% and final SOC value diverged of 1% (Figure 0-8). Empirical model accuracy has been consequently considered sufficient for the scope of the study.

With possibility of performing faster simulations, the search for an economic optimal in multiple services provisions opened two new directions.

A set of simulations allowed a study on remuneration of PCR feasible to pair the NPV of multiple service with the one of asymmetric SCR only. PCR has lower remuneration per MWh with respect to SCR in Italy. If Primary Regulation is getting more and more important, it is necessary to give consistent price signals to BESS owner in

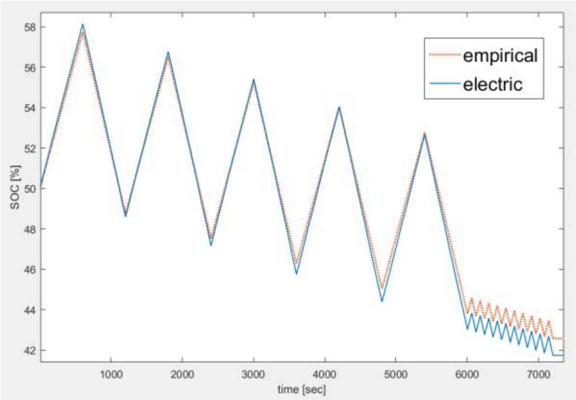


Figure 0-8 Empirical vs Electric SOC on square wave power

Energy	ASCR only	PCR + ASCR	PCR + ASCR min droop	
Droop	-	0.075%/P_{reg}	0.030%/P_{reg}	
PCR positive	0.00	19.44	36.14	MWh/mon
PCR negative	0.00	20.64	38.64	MWh/mon
PCR positive remuneration	-	**114.44**	**96.11**	**€/MWh**
PCR negative payment	-	**0.00**	**0.00**	**€/MWh**
PCR net revenues	0.00	2225.21	3473.00	€/month
Net Cash Flow	9228	8392	8598	€/month
PBT	12	12	12	Years
NPV (20 years)	**298.6**	**298.6**	**298.6**	**k€**

Tab. 1 PCR remuneration for investment attractiveness

direction of PCR. Tab. 1 provides the PCR remunerations necessary for pairing NPV of asymmetric SCR only provision, with different droops for PCR. Two were selected and reported.

Last analysis for Italian framework was the optimal sizing for battery. As stated at the beginning of Paragraph, EPR of 2 h was a conservative choice: it was meant to minimize LOR, even if causing larger investment cost. Investment cost of batteries is by far the largest negative cash flow in a BESS investment. Sizing properly a battery, therefore setting convenient EPR for its application, means saving large amount of money, since investment cost is proportional to nominal energy. The cost used in this study is 400 k€/MWh, considered today an average cost for the whole BESS system. A set of simulations was used to define the optimal EPR in terms of NPV, PI and LOR. The services provided were PCR (0.5 per unit) and Asymmetric SCR (0.8 per unit). Results are shown in Tab. 2.

Following this analysis, best EPR in both terms of LOR and economic return is 1.5 h (CASE E).

EPR[h]	1.03	1.25	1.50	1.75	1.93	2.00
LOR total [%]	**3.75**	**2.54**	**1.57**	**1.30**	**1.39**	**1.60**
NPV (20 years) [k€]	-15.7	37.3	182.1	76.8	71.1	122.5
PI	**-0.04**	**0.07**	**0.30**	**0.11**	**0.09**	**0.15**

Tab. 2 EPR comparison

Last step of the study aimed to give a comparison among Italian reference case and a similar market: German ASM. Power system of Germany is similar to Italian one for two main factors:

- Large non-programmable RES penetration.
- Same synchronous area (Central Europe).

And prices of Italian (CASE E) and German (CASE GER) market were applicated to a simulation of PCR and Asymmetric SCR provision with EPR = 1.5 h. PBT with German revenues is 3 years, 14 years with Italian.

Complete summary of the simulations is presented in Tab. 3.

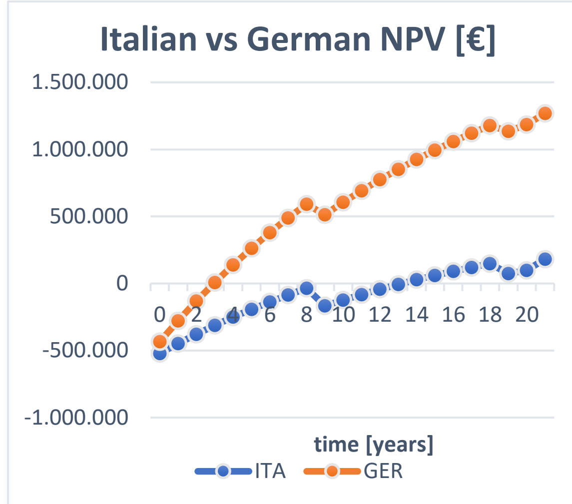


Figure 0-9 NPV in Italian and German framework for PCR + Asymmetric SCR provision

Conclusions

The aim of the study was inspecting the behavior of Battery Energy Storage Systems while providing grid services in an Ancillary Services Market framework. Furthermore, Authors were looking for an optimal setup in terms of regulating band splitting among grid services and sizing. This setup was the one guaranteeing lowest LOR and highest economic return. Many simulations have been carried out on this purpose using an electric model and an empirical model, on a simulation period of 30 days, checking battery operation and analyzing model outputs quantitatively. Validation of empirical model was performed during the study through simulations on both real-operation cycles and test cycles. A comprehensive procedure for the implementation of Ancillary Services was developed. Based on this procedure, a tool in Simulink has been developed to be used as Controller of battery model. Implementation of PCR, symmetric and asymmetric SCR was performed and tested. Other services can be added following same procedure and using the tool, in case of extension of study on BESS. Positive outcomes have been found in terms of quality of regulation, discovering the role of asymmetric services as passive SOC restoration mechanisms. LOR is lower than 2% in case of simultaneous provision of PCR and SCR, without any dedicated energy flow just aimed for restoring SOC. On the other side, economic return of investment is not outstanding when remaining in Italian framework. Minimum PBT found is 12 years, for provision of asymmetric SCR only. By moving to Germany, situation changes in terms of economic outcome. Even if the two power systems have been defined similar (highly RES penetrated, part of same large Synchronous Area) remunerations on the two ASM market are much different (Germany is largely using capacity payments, Italy has only energy-based payment) and have different weights (German prices are higher than Italian ones and PCR is much more remunerated than SCR, oppositely to Italy).

	CASE A	CASE B	CASE C	CASE D	CASE E	CASE GER
PCR band (per unit)	1.0	0.5	0.0	0.5	0.5	0.5
max SCR band (per unit)	0.0	symm 0.8	asym 1.0	asym 0.8	asym 0.8	asym 0.8
LOR [%]	13.2	11.5	4.5	1.6	1.6	1.6
NPV [k€]	-813.	-465.5	298.6	122.5	182.1	1268.6
PBT [years]	-	-	12	18	14	3
PI	-1.02	-0.58	0.37	0.15	0.30	1.59

Tab. 3 Summary of simulations

Contents

Abstract

The scope of this work is simulating behavior of a Battery Energy Storage System (BESS) providing grid services in the context of an Ancillary Services Market (ASM). BESS are nowadays involved in several pilot projects for Ancillary services provision around the world. This is because they have some characteristics of interest with respect to conventional power generators that are usually the only providers trading on ASM. Specifically, the extremely high ramp rate and the precision in following power setpoints can provide extreme benefit for security of today's power network, facing the integration of non-programmable and unpredictable Renewable Energy Sources (RES). The methodology proposed is the simulation of provision of multiple services on a 30-days period using an electric and an empirical Li-ion battery model implemented in a Simulink tool. The work included the development of the controller of the model, the analysis and the development of a complete and replicable procedure for accurate representation of grid services, the validation of the empirical cell model and the simulation of different combination of services provision, namely different layouts of Primary and Secondary Control Regulation. Results of the simulations were investigated and elaborated by both the points of view of the assurance of provision (the point of view of the Transmission System Operator) and of the economic return (the point of view of the investor). Simulations showed outstanding performance by BESS in providing the power requested. In the best case, power non-provided was less than 2% of the overall power requested. This result was achieved by exploiting the favorable characteristics of asymmetric Secondary Reserve provision. By the side of economic return, when inspecting the Italian ASM framework, results showed Payback Time (PBT) of at least 12 years. When analyzing German framework, PBT decreased to 3 years.

Keywords: *BESS, ancillary services market, empirical cell model, primary regulation, secondary regulation, asymmetric reserve*

Sommario

Lo scopo di questo lavoro di tesi è la simulazione del comportamento di un sistema di accumulo energetico a batteria, nella fornitura di servizi di rete nel contesto di un Mercato dei Servizi Ancillari. Gli accumuli a batteria sono al giorno d'oggi coinvolti in vari progetti pilota in tutto il mondo per la fornitura di servizi ancillari. Questo accade perché questi sistemi presentano alcune caratteristiche di interesse rispetto ai generatori elettrici tradizionali, che usualmente sono gli unici soggetti autorizzati a prendere parte al mercato dei servizi ancillari. In particolare, grazie al gradiente di potenza estremamente elevato che riescono a fornire e alla precisione nel seguire setpoint di potenza che li caratterizza, gli accumuli elettrochimici possono portare grande beneficio alla sicurezza della rete elettrica odierna, che affronta l'integrazione di Fonti Energetiche Rinnovabili non programmabili e aleatorie. La metodologia proposta è la simulazione della fornitura di molteplici servizi di rete su un periodo di 30 giorni, utilizzando un modello elettrico ed uno empirico per una cella agli ioni di litio implementati in Simulink. Il lavoro comprende lo sviluppo del controllore del modello, l'analisi e lo sviluppo di una procedura completa e replicabile per la rappresentazione accurata di servizi di rete, la validazione del modello empirico e la simulazione di varie combinazioni di fornitura di servizi, ossia di differenti schemi per la Regolazione Primaria e Secondaria di Frequenza. I risultati delle simulazioni sono stati esaminati ed elaborati dal punto di vista della certezza della fornitura (punto di vista dell'operatore della rete di trasmissione dell'energia) e del ritorno economico (punto di vista dell'investitore). Le simulazioni hanno mostrato notevoli prestazioni del sistema di accumulo nella fornitura del servizio richiesto. Nel caso studio migliore, la potenza non fornita è stata meno del 2% sul totale della potenza richiesta. Questo risultato è stato raggiunto sfruttando le caratteristiche favorevoli della fornitura di Riserva Secondaria in maniera asimmetrica. Dal punto di vista del ritorno economico, analizzando il caso del Mercato dei Servizi di Dispacciamento (MSD) italiano, i risultati hanno mostrato un tempo di ritorno di almeno 12 anni. Nello studio del contesto tedesco invece, il tempo di ritorno scende a 3 anni.

Parole chiave: *sistema di accumulo elettrochimico, mercato servizi di dispacciamento, modello empirico di cella, regolazione primaria, regolazione secondaria, riserva asimmetrica*

1 Introduction

Global installed capacity of battery energy storage systems (BESS) at utility-scale is exponentially increasing [5]. There are reasons for this growth. First, global demand of energy will expand by 30% among today and 2040 [6]. World population is still rising, and it is growing also consumption per capita. Second, the world is going towards a further electrification: many loads and compartments are switching their energy conversion system from oil & gas-based to electricity-based. It is the case of automotive and residential heating sectors, with the diffusion of electric vehicles and heat pumps. From 1970s to today, electricity's overall share on total energy demand has risen from 9 to 17%. Electricity is necessary to foster the decrease in Greenhouse Gases (GHG) emissions to meet COP21 requirements and scenarios. In fact, most of Renewable Energy Sources (RES) are electric (RES-E). In all scenarios so far proposed, the share of electricity with respect to overall energy consumption climbs up at least to 25% within 2050. 40% in the growth of global energy demand by 2040 will be electric. Global electricity consumption will therefore double. Large differences between regional growth rates will be present (in non-OECD countries, electricity demand is expected to increase by factor 4) [7]. In some world areas, power system will arise and expand at impressive speed. Third factor, increasing share of RES-E leads to less programmability and control in electric system. Electric system works only in presence of a regulated balance among producers and consumers of electricity. If producers (and prosumers: users providing energy for grid and requiring energy for their own loads at the same end-point of the grid) become less accurate, forecastable, programmable, deployment of equipment able to delay or mitigate the unbalance by injecting or withdrawing power at request from network could avoid curtailment of non-programmable RES-E – such as wind and photovoltaic – and increase security of grid [8].

The function of guaranteeing balance among producers and consumers every instant is provided in every national electric network by ancillary services. Ancillary services are necessary even when the system is well managed and totally programmable. Ancillary services are traded on Ancillary Services Market (ASM). This is a particular segment of the electricity market, that usually takes place after Day-Ahead Market (DAM), the main market session. Most of energy is traded in DAM [9], but this market ignores some of the constraints of the network and neglects possibility of faults and errors by generators selected to sell their energy [10]. To guarantee security of network, some reserves of power (capacity) must be found. These reserves are offered in following ASM sessions by generators which have still capacity available after DAM. The majority of ASM are not open for BESS yet. Regulatory framework of most of these markets – Italian one (Mercato dei Servizi di Dispacciamento or MSD) included – are tailor made on conventional programmable generators. These generators offer and provide, after being selected, a schedule of power setpoints following orders by Transmission System Operator (TSO) who is managing the grid. The units allowed to participate to ASM must be programmable and reliable with very low uncertainty. They also must comply with energy and power requirements of every service. These are in fact bought and sold on the market as a product which has strict parameters. For instance, products request power reserves for a specific time, that can be of some weeks or few hours: given the particular situation of the grid, this available reserve can correspond to a higher or lower (positive or negative) cumulative energy contribution. There are products only requesting positive reserve (more power from unit to grid with respect to DAM schedule) or only negative (less power from unit to grid with respect to DAM schedule). There are products requesting mandatorily the same amount of positive and negative reserve. These products are built to be feasible for conventional units. Since batteries have fundamental differences with respect to conventional generators, a market open to them must verify if BESS are feasible for providing some products or modify those. Many markets in Europe are defining new rules or experimenting projects and products to enlarge the range of units participating markets. In Italian case, pilot projects for participation in ASM of aggregators and demand response are in place [11]. This happens because regulation services need is usually proportional to share of non-programmable RES-E capacity installed in a system [11]. Since the share of wind and photovoltaic generators is increasing, but just conventional units (the ones respecting some parameters) can enter ASM, there will be in next years a shortage of reserves for main grid services that could be faced by introducing in ASM new actors.

The scope of this study is to verify the opportunity for BESS of providing grid services, from both technical and economic point of view. Multiple services provision (Multi-service) has already shown interesting results in terms of return on investment with respect to single service provision, and technical feasibility [4]. The project here proposed evaluates BESS integration in the ASM framework. In particular, the analysis focuses on Li-ion BESS, which is the most widespread electrochemical storage device. This kind of devices has two main parameters and limitations: a nominal power (P_n) and a nominal energy (E_n). This means a battery can be designed with two main degrees of freedom, one related to maximum power can be injected or withdrawn from grid each instant, the latter defining which is the maximum amount of energy can be stored in a battery. Speaking about the more common State of Charge (SOC) index, nominal energy is the delta in energy contained between 0 and 100% of charge. This limit on energy is the main difference among conventional generating units and BESS while approaching to ASM participation. A power injected or withdrawn for a too long time interval could lead to saturation of the battery: maximum SOC or minimum SOC can be reached, making impossible to continue power exchange in same direction (from battery to grid or vice versa).

A model of the battery must be found and validated. In literature, several models have been proposed for simulating BESS behavior. The core of the model is the electrochemical cell model. Cell models differ for the nature of the equations implemented (electrochemical, electric, empirical, stochastic) and for the complexity. The complexity of the model is usually proportional to its accuracy in representing the larger variety of phenomena characterizing batteries. The model to be selected must show accuracy in representing the states of the battery performing power cycles simulating services provision. Cell model receives as input a power setpoint each instant, and gives back an efficiency of energy conversion process, an update of SOC and voltage state for the cell. The model of the BESS also includes the rest of the system linking battery to grid and managing the battery. In detail, it must include: a Battery Management System to simulate the software verifying operation of battery; a controller to compute power setpoints requested by TSO to battery; an inverter modelling AC/DC conversion. To prove accuracy of outputs by cell model, different models must be tested in same simulations, undergoing same power cycles.

The peculiar characteristics of the cycles approximating services provision must be studied and correctly replicated. To do this, an analysis of the main grid services is needed in order to choose the ones that are feasible for BESS and bringing larger revenues. After the choice has been made, data about resulting power cycle must be fed to the model.

Since the aim of this work is to deal with products traded on a market, a simulation of the market itself, even if simplified, is necessary. Actually, modeling a service means both selecting the input data needed for power setpoint arrays creation, writing the function linking these parameters to the power requested, modeling a market to evaluate when battery is selected for provision and must follow setpoints during the simulation of the whole period.

Once services have been chosen and market have been designed, battery must provide services simultaneously. Since there is a nominal power not to overpass (or that can be overpassed just in a limited share of time), every service must have a dedicated power band (regulating band, P_{reg}) as a maximum threshold. Splitting of regulating bands among services is next step in designing battery operation and offers on ASM. It will be done, once more, following economic and technical criteria. The result of this analysis will be a mix of services provided, each one with a fraction of nominal power as regulating band, managing a fraction of the total capacity.

BESS presence in ASM is particularly of interest since a BESS is not a generator. Battery would not be able to sell a relevant energy quantity on DAM since it would fully discharge reaching quickly saturation of SOC level. BESS would only be able to provide power for a service (or a sum of services) which have null net average power. So, oppositely to conventional units which work mainly on DAM and offer residual regulating bands on ASM, BESS can have all the nominal power dedicated for services provision on ASM, that would be its main market. On the other side, Multi-service strategy should aim to perform SOC restoration by having balance among services. SOC restoration is the operation with which SOC value is brought towards 50% every time it gets close to saturation limits. If different positive and negative bands can be sold on markets at least for one of services inserted in Multi-service strategy, that service can work as SOC restorer. This introduce the need for asymmetric services: negative regulating band offered on market would be higher than positive in case of SOC level higher than a predefined setpoint, and vice versa. Target of Multi-service is managing SOC without purchasing or selling energy to grid on purpose. The objective is reducing to zero energy flows dedicated to SOC restoration, using instead asymmetric services provision for that intent.

Finally, since aim of the study is verifying the possibility for BESSs to have a role in ASM, in the core of the work there is the definition of the modifications ASM – starting from Italian setup – would need to guarantee technical and economic feasibility for batteries. As already mentioned, TSOs could be interested in making easier for BESS admission in the market. In this thesis, the goal is staying as stuck as possible to reality and perspectives, proposing modifications that are already in place or in discussion in other electricity markets. These proposals pass also by the simulation of variations of the services traded on ASM: batteries have peculiar characteristics that will be highlighted in this study and that can enhance stability and control of the network with respect to nowadays situation, giving also life to new versions of grid services in place today. One of these characteristics is the very high ramping capability and ramp rate (MW/min) achieving by adopting BESS technology [12]. This peculiar characteristic have already been taken in consideration for services as virtual inertia [13] or Enhanced Frequency Response [14] in place in UK. These services require ramp rates only achievable with power electronics and hardly with conventional units (gas turbines or combined cycles).

Results presented try to highlight: economic return of the investment – by using indexes such as Net Present Value (NPV) and Payback Time (PBT), use and ageing of the battery – by defining average c-rate (c-rate is ratio among current and nominal current of the device), cycle and calendar ageing (the two main types of degradation of cell) and equivalent cycles per period (a measure of the total gross energy exchanged by BESS).

In conclusion, there will be a proposal for an optimal mix of services (P_{reg}), managed by a BESS designed on purpose (E_n, P_n), used in a convenient way (in terms of average c-rate, equivalent cycles per period, cycle ageing) for preserving it for a decent time, to reach as high as possible revenues (NPV and PBT) in a market with specific rules.

1.1 Thesis layout

A Battery Energy Storage System (BESS) aiming to provide grid services has to be eligible in the Ancillary Services Market (ASM) for offering regulating power bands (P_{reg}) for each service chosen. For entering ASM it must comply with requirements set by Transmission System Operator (TSO). In performing multiple services, the maximum power threshold must not be overpassed. There is also a limit on capacity/energy to be considered. In fact, it is a peculiar characteristic for batteries having power and energy both defined by the device design. To study the whole operation avoiding having a test bench, an IT model is needed. The model must be validated in approximating well all the operations of the BESS in services provision.

It becomes clear the need for a literature review focused on the two topics of the battery modeling and of the ASM. A battery model should be suitable for its application. To understand the requirements of this application the comprehension of the framework is necessary. Only after this review, the methodology selected and proposed for the study will be described in detail. Finally, results of the simulations performed and outcomes for performance and economic return evaluation will be analyzed and commented.

The structure of this thesis is the following.

Chapter 2 presents what a Battery energy storage system is, what parameters characterize its design, what limits and differences can be recognized with respect to a conventional unit (a gas turbine, a combined cycle, a nuclear power plant, generally speaking a thermoelectric generating system or a hydro plant), what are the positive features of a Battery and why it can be interested for innovation of electric network. Then it will move towards description of types of models approximating battery operations. The many kinds of models will be listed, clustered and briefly described, to focus then on the types of the ones adopted for this study: electric and empirical models. Limits and qualities of these models in analyzing power cycles simulating services provision will be highlighted.

Chapter 3 describes Ancillary Services Markets, their recent evolution and their future trends. A description of main grid services is given, focusing on services considered in this study. A comparison among ASM rules as of today is then provided, with focus on Italian and German framework. There is then a description of main evolutions possible for ASM in next future. Some projects already in place are described. BESS future role and advantages of batteries in services provision are then highlighted. Finally, a focus on multiple services provision by BESS is reported, reporting advantages of this practice as of now recognized. An overview of studies and projects ongoing in this field is given.

Chapter 4 is dedicated to the presentation and description of the methodology proposed for this study. The description of the model and the reasons for the choice are included. The tools used are analyzed in detail. The comprehensive procedure developed and used for the implementation of services in the model controller is provided and explained. The grid services and the sets of parameters characterizing them are introduced and discussed. The Multi-service implementation and the strategy required for letting many services coexist simultaneously in a BESS are described and choices made are explained.

Chapter 5 contains the report of simulations and results found. It opens with the description of the study to get the economic indexes and parameters used for economic analysis of simulation results. The validation of the empirical model performed during the study is then presented for a check by the Reader. The setup of simulation is then explained in detail, in order to provide all the instruments to verify consistence of the results. All the outcomes are then reported in logical order, starting from the reference case to appreciate the improvement achieved in the following steps. Discussion of the results in terms of performance and economic return of the investment is proposed: the points of view of TSO and of investor are given.

Chapter 6 includes the conclusive recap of the work done and of the outcomes obtained, with a look to possible future steps.

2 Battery energy storage systems modelling

Battery Energy Storage Systems (BESS) are complex systems aimed to perform energy storage with a battery and providing its connection to the power network. Battery is the core. Battery is an electrochemical device. Electrochemistry is the part of chemistry dealing with relation among chemical change of species and electricity. Electrons can move among atoms chemically reacting and if they do, they arise currents proportional to rate of reaction. An electrochemical reaction provides potential difference among its reactants and its products. Battery energy is based on the potential difference among reactants and products stored inside itself. This potential difference is exploited as electric power while battery is discharging. BESS are becoming of more and more interest in last years for every type of applications. At small-scale, batteries are by far the predominant storage for portable devices. At medium-scale, batteries are under deep study and fast evolution thanks to their application in Electric mobility. This development brought with itself growth in performance and exponential decay in prices. These trends involved large-scale applications, too. Storage systems grid-connected are becoming of interest. Pumped-hydro (PHES) and compressed-air (CAES) energy storage systems for large-scale stationary applications grid-connected could see in next future their predominance be deposed. In this first part of study, the technology is presented by electrochemical and energy system perspective. Then, the study of modeling of batteries is presented. Different models for different applications are found. The two main performances to evaluate for selecting the convenient model are accuracy and computational speed.

Next Paragraphs provide an overview of process, of performance and of the parameters useful for BESS technology analysis.

Battery is a device able to store a finite amount of chemical energy and convert it to electric energy and back. It is a close system, since reactants and products remain stored inside it. Power and energy are both related to the device. Battery is a high-efficiency energy conversion machine: since it does not involve combustion process it has no thermodynamic cycles' efficiency limits. Its maximum work (reversible work) is the variation of Gibbs Free Energy of the process [15]. Moreover:

1. Roundtrip efficiencies can be averagely of 83% for Lithium ions batteries in real operations for 15-20 years [16]. This efficiency measures the efficiency of a cycle. What a cycle in battery operation is will be explained in 2.1. This number accounts for the efficiency of the whole system. The Li-ion cell analyzed on its own has higher efficiency, usually in the range of 95-98% [17]. The rest of the system decreases the overall outcome.
2. A battery can be used for multiple applications after end of first life, by accepting overall performances of about 80% brand new performances (in terms of both energy storage and power deliverable). A battery used first for portable applications can then be re-used for stationary ones.
3. Lifetime Greenhouse Gases (GHG) emissions of battery utilization are concentrated in production (more than 60% of total CO_{2eq} emissions), hypothesizing life of 20 years and one repowering during life for change in application after performances decay. This means this device is almost carbon-neutral during operation, and improvement in recycling or re-use techniques can increase largely this period of quasi-neutrality [18].

These facts define batteries as an interesting and promising technology in a sustainable energy system.

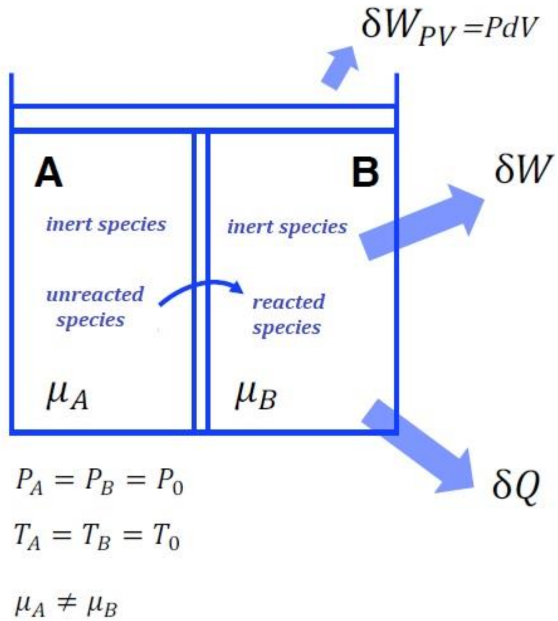


Figure 2-1 Closed System with semi-permeable membrane [15]

As mentioned before, batteries are not limited by Carnot efficiency, since they do not exploit a thermodynamic cycle. There are anyway thermodynamic processes happening in cell, that will be outlined here below to define limiting cases of its operation. For the system represented in Figure 2-1, divided in two subsystems A and B and with M species present at constant thermodynamic conditions (T, p), the limit of reversible work extracted is Gibbs' free energy:

$$dG = -SdT + Vdp + \sum_i^M \mu_{A,i}\, dN_{A,i} + \sum_i^M \mu_{B,i}\, dN_{B,i} \tag{2.1}$$

$$dH = TdS + Vdp + \sum_i^M \mu_{A,i}\, dN_{A,i} + \sum_i^M \mu_{B,i}\, dN_{B,i} \tag{2.2}$$

$$dH = -\delta W - \delta Q \tag{2.3}$$

$$dG = dH - TdS = -\delta W - \delta Q - TdS \tag{2.4}$$

$$dS = dS_{irr} - \frac{\delta Q}{T} \tag{2.5}$$

$$dS_{irr} = \frac{-dG - \delta W}{T} \tag{2.6}$$

$$if\ dS_{irr} = 0 \rightarrow \delta W = -dG \tag{2.7}$$

The electrochemical process happening in the battery aims to oxidize unreacted species present in the first subsystem and store them in the latter. This oxidation reaction implies the move of charged species, so production of electricity. To produce electricity, we need both a path for electrons and a path for positive ions. The system described before can be completed adding electrodes that can be linked to form an electric circuit (electrons' path) and a semi-permeable membrane to allow ions (and not mass) transport among subsystem (ions' path). Process is reversible, so a battery can both provide and withdraw electric energy. Since there is a circuit with flowing electrons, it will be measured at the two electrodes a voltage (ΔV) and in circuit a current (i).

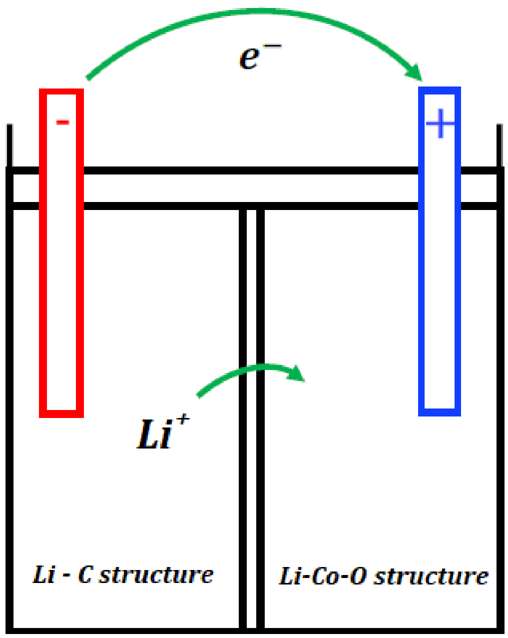


Figure 2-2 Li-ion battery during discharge process scheme [15]

The State of Charge (SOC) of the battery is a measure of the energy still stored in the device at each time of the use divided by the nominal energy (E_n) that can be stored in it. Theoretical definition of SOC involves Capacity instead of energy:

$$SoC = 1 - \frac{C(t)}{C_n} \tag{2.8}$$

Where C(t) is the capacity at time t and C_n [Ah] is nominal capacity. Since:

$$E_n = C_n \Delta V_n \tag{2.9}$$

And ΔV does not vary too much along with capacity, usually energy can be used instead of capacity using an average voltage value. Anyway, SOC cannot be computed real-time by using energy or capacity, but it must be estimated using Open Circuit Voltage (OCV).

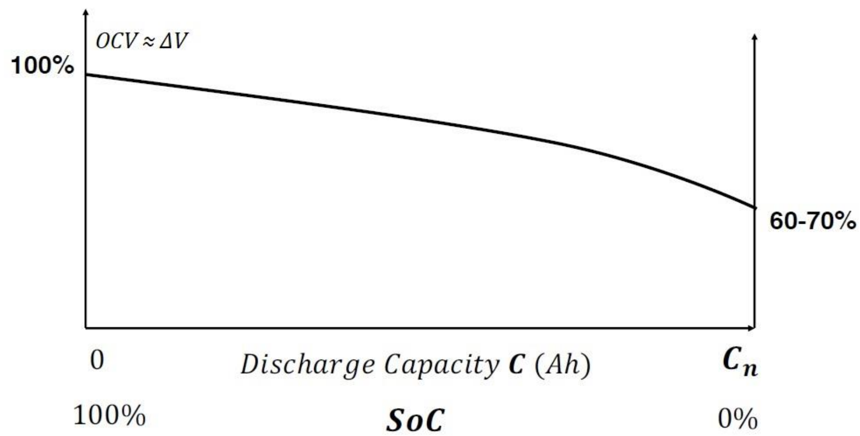


Figure 2-3 (SOC, OCV) diagram [15]

In Figure 2-3 it is clearly shown how voltage is decreasing slightly and not linearly, with a steeper slope close to low SOC. Voltage is constrained among minimum and maximum safety values. Within these values battery does not undergo carbon corrosion in the electrodes and other detrimental phenomena for the cell. Focusing on Li-ion cells:

$$\Delta V = [2.4 - 4.2]\, V \qquad 2.10$$

But usually producers use even narrower bars to furtherly prevent devices from damage (e.g.: 3.0-4.2) [19]. Carbon corrosion is among phenomena decreasing capacity and efficiency of battery during its life. Ageing phenomena and computation mechanisms will be explained later in this Chapter.

Furthermore, in Figure 2-3 OCV is approximated with cell voltage, that is the voltage measured at the electrodes. This is a very useful approximation since cell voltage is the only one can be measured in real-time. Since OCV is voltage would be shown at electrodes if current in circuit is 0, this approximation is only valid at low currents.

Even current is defined with respect to a nominal current i_n proper of the battery. The nominal current is the one able to discharge battery in 1 hour. It can be defined as:

$$i_n[A] = \frac{C_n[Ah]}{1[h]} \qquad 2.11$$

And every current is seen as a multiple of the nominal one through c-rate:

$$c - rate = \frac{i}{C_n} = \frac{1}{\Delta t} \qquad 2.12$$

Where Δt is the time for complete discharge (from SOC 100% to 0) at constant current i.

C-rate is important in the relationship among available capacity and cell voltage. At higher c-rates cell voltage gets far from OCV, so the voltage limits are hit before having exploited nominal capacity (and nominal energy), both during charge (Figure 2-4) and discharge (Figure 2-5).

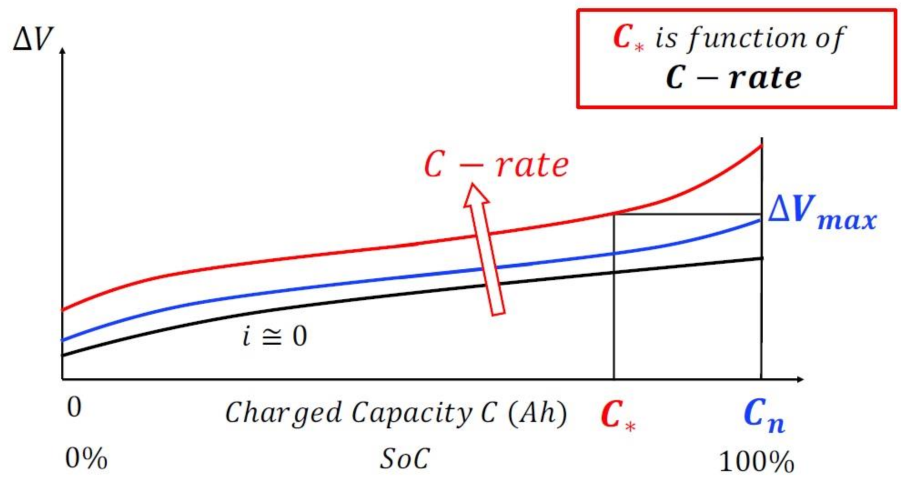


Figure 2-4 (SOC, V) diagram during charge with different c-rates [15]

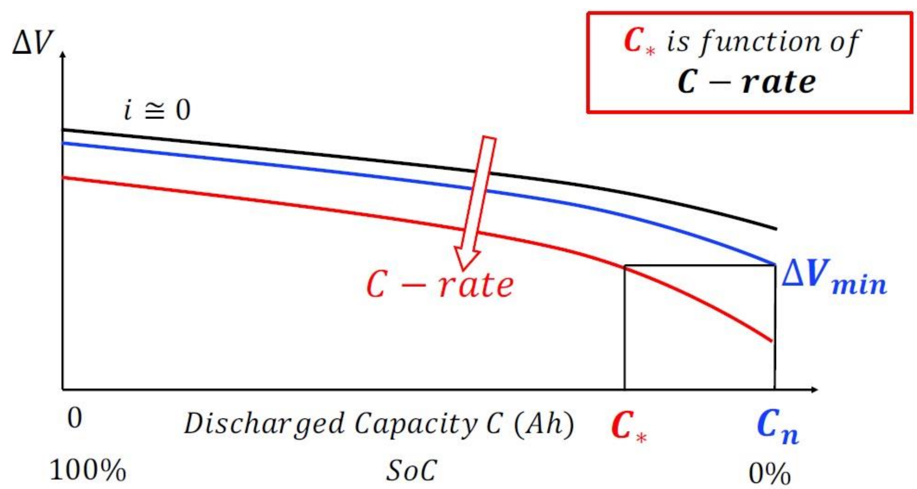


Figure 2-5 (SOC, V) diagram during discharge with different c-rates [15]

In Figure 2-4 and Figure 2-5, black lines represent OCV with respect to SOC, blue lines represent voltage at c-rate = 1 in charge and discharge defining nominal capacity. Actually exploited capacity C_* depends on actual c-rate of charge and discharge process. It is lower than nominal one for c-rate grater than 1 and vice versa. Given this, c-rate in batteries is better if lower. Thus, a battery is designed also with a limit in power (function of c-rate) even if the device could provide higher powers. As mentioned before, every power limit depends on voltage limits. For Li-ion batteries, range of ΔV allowed at terminals is usually the one presented in 2.10 or narrower.

This phenomenon must be taken in account when designing a battery. The Battery Management System (BMS) is the software controlling real-time the battery and preventing voltage limits saturation at every c-rate. If power required to or injected in cell is producing a current causing voltage to go outside the Safe

Operating Area (SOA) [20], power is limited by BMS. This can be done by having the measurements on ΔV and *i* in every instant.

2.1 Battery cycles

To complete definition of battery operations, a definition of battery cycle is necessary.

A cycle in a battery is every kind of process able to take battery from an initial SOC value to an equal final SOC value. This implies a charge process – where the battery withdraws energy from external source (negative power produced by battery) – and a discharge process – where battery delivers power to external loads or systems (positive power produced by battery). In this definition there are no mentions to power values in the process or to the fact that discharge and charge process must be continuous. Therefore, the processes shown in Figure 2-6 are both cycles since they have initial SOC equal to final SOC.

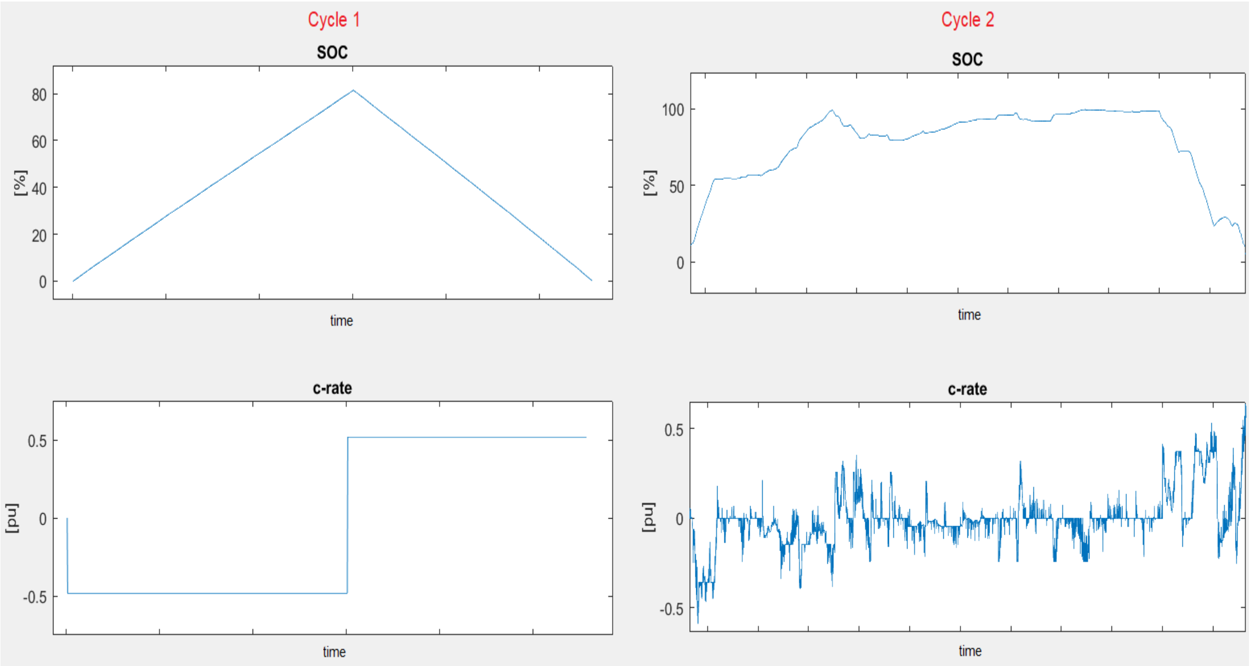


Figure 2-6 SOC and c-rate (in per unit) log of two battery cycles

Cycles can be very different. To better define them and characterize battery performance (for instance in datasheets) it is useful to add parameters to cycle.

1. Depth of Discharge (DOD): the SOC variation among maximum and minimum SOC level during discharge. It is a value in percentage (e.g.: if discharge process starts at 90% and ends at 10%, DOD = 80%)
2. Average, maximum or constant c-rate: this value characterizes the power output of the cycle. It can be an average value, for a variable c-rate cycle, a maximum value not overpassed, a constant value for specific cycles carried out at regulated power (e.g.: test cycles on a square wave, as in Figure 2-6, to the left).
3. Maximum or minimum SOC: since SOC levels close to saturation are more critical for the cell, a cycle can be described better by giving maximum or minimum SOC during process.

Moreover, detailed definition of cycle is useful for getting to some important index of performance for batteries, as listed in the following.

Efficiency of the cycle is a fundamental index for evaluating its performance. A first form of efficiency when it comes to batteries is Coulombic Efficiency (CE). It describes the efficiency with which electrons are transferred in an electrochemical system. It is physics-based and it considers all the losses internal to cell due to physical and chemical irreversibility in the process. A more common and easily-measured efficiency is Roundtrip Efficiency. It is energy-related, since it defines the amount of energy can be extracted by a cell with respect to energy input withdrawn by cell:

$$\eta_{RT} = \frac{E_{DIS}}{E_{CH}} \qquad 2.13$$

Where E_{DIS} is the total energy given to environment while positive power has been generated by battery in the reference cycle, while E_{CH} is the energy absorbed by battery during reference cycle. Since during operation voltage at terminals and current in electric circuit are always measurable, power can be computed and integrated to have energy flows. From now on in this study, roundtrip efficiency will be referred to as efficiency, and it will take in account of the whole system efficiency, since it will be measured at the inlet and outlet of the system, where it links to grid (AC/AC efficiency, see Paragraph 2.3 for vision of the system layout).

Lifecycle of battery can be described as amount of Equivalent Cycles before meeting a specific degree of decay in performances. Equivalent cycles are cycles exchanged a precise amount of energy: cycle with constant DOD. In this study, equivalent cycles will be defined as cycles with DOD = 100%:

$$equivalent\ cycles = \frac{E_{gross}}{2 * E_n} \qquad 2.14$$

Where E_{gross} is gross energy flown through battery taken with its absolute value (positive and negative energy furnish both positive contributions to this summation). At the denominator, we have energy flown in a standard cycle (c-rate = 1, constant) at DOD = 100%: two times nominal energy.

To define well what lifetime is and understand the role of equivalent cycles, ageing mechanisms and indexes detailed description is necessary.

2.2 Ageing and lifetime

Lifetime of a Li-ion battery is the time elapsed before it gets below certain performance thresholds. Usually these thresholds are on battery capacity and power. In fact, it has been shown in many studies how a battery decay with time in capacity it can store and power it can deliver due to multiple degradation mechanisms [21] [22] [23]:

1. Capacity fade: storing structure of the cell deteriorates due to many mechanisms such as Solid-Electrolyte Interphase (SEI) formation [24], leading to less room for Lithium-based storage or to Lithium consumption and less energy exchanged during each cycle.
2. Power fade: it concerns with increasing of resistances internal to cell, due to ageing mechanisms such as SEI formation and positive electrode loss in conductivity. Power fade can be also referred to as efficiency fade.

Usual thresholds utilized to define battery End of Life is capacity fade leading to available capacity of 80% of nominal capacity, and power fade leading to 80% of nominal power delivered (at equal c-rate) or 80% of original roundtrip efficiency.

Ageing is the ensemble of the mechanisms causing fades. It can be categorized in two main classes: Cycle ageing and Calendar ageing.

Cycle ageing describes degradation happening while the battery is utilized for charge or discharge processes. Cycle ageing depends on many stress factors. One of those is temperature of cell. It rises during operation, even non-uniformly across cell, and foster exothermal phenomena damaging cell. Also low temperatures, since they slow down kinetics of cell, should be evaluated carefully during operation. Another stress factor is c-rate. High c-rates can cause too low or too high terminal voltages damaging cell. Finally, SOC values kept for long periods close to saturation limits can be detrimental. Specific values depend on the device and they are related to voltage at terminals, too. Cycle ageing is a direct function of energy flows in battery, and therefore of equivalent cycles. A battery performing high cycling rate per period has greater share of cycle ageing on total.

Calendar ageing is referred to phenomena and consequences of storage, independently of charge and discharge processes. Stress factors are storage temperature (more detrimental if higher, since corrosion mechanisms foster) and periods at high or low SOC. Since it is not linked to battery use, it becomes more important if average c-rate is low, if environmental conditions are harsh or if there are long periods with no operations [25].

From each type of ageing, it can be derived a decay rate. The sum of these two contributions will define real lifetime of battery, when it reaches the minimum thresholds defined.

A brief overview of main ageing mechanisms could be useful to properly evaluate such phenomena. Main ageing mechanisms happen on electrodes and at the interfaces among electrodes and electrolytes:

1. Solid-Electrolyte Interphase (SEI) formation: at electrode-electrolyte interface. Mainly acting on negative electrode side, this mechanism forms a layer of solid interphase among electrode and electrolyte, composed by exfoliating graphite from electrode, particle cracking and gas formation. SEI is naturally formed in fist cycle of battery and serves as protection from corrosion for negative electrode. If it increases during lifetime, it can lead to both capacity fade due to dismantling of storing structure and increase in resistance to ions' transport [25].
2. Carbon corrosion: acting in composite electrode. Graphite in electrodes can corrode at high potentials. This happens at positive electrode at high SOC, since potential difference at terminals is high and so is voltage at positive electrode, and at low SOC at negative electrode, since low terminal voltage leads to higher voltage at negative electrode. Carbon corrosion leads to increase in resistances due to lower conductivity and higher tortuosity of electrode layers [26].

These and other minor degradation mechanisms lead to fade in capacity and efficiency of cells, that are modeled as will be explained lately in this Chapter. In particular, a quantity has been developed for defining State of Health (SOH) of the cell. SOH is a value in percentage, measuring 100% at Beginning of Life (BoL) and then decreasing, that can be related to many several variables: capacity, internal resistance, efficiency, voltages, etc. It is always defined with the same ratio. E.g.: for capacity:

$$SOH\ [\%] = 100 * \frac{C_n(t)}{C_n(BoL)} \qquad 2.15$$

Electrochemical cell's kinetics in operation could be represented by Butler-Volmer's and its logarithmic simplification Tafel's models. These two models deserve to be described at least briefly, since they are used and cited as basis for most of the studies on electrochemical cells.

Butler-Volmer equation is linking ionic current in an electrochemical cell with voltage at terminals, featuring an exponential for reduction reaction and one for oxidation reaction happening in cell depending on some other parameters, such as cell temperature and number of steps in electrochemical reactions. Voltage at terminals can be found only implicitly by hypothesizing ionic current in cell. Ionic current in cell is the flow of ions passing through electrolyte, that is always bound with a constant to current in electric circuit of cell [27].

Tafel equation is a simplification of Butler-Volmer's one, hypothesizing that at a high positive or negative current, just one out of two reactions is happening with fast and appreciable kinetics (by defining current as positive if battery is discharging: at high positive current only oxidation happens, at high negative current only reduction happens). In this way, voltage at terminals can be found explicitly by inverting Tafel equation [28].

Butler-Volmer model has proven its goodness in modelling electrode kinetics and defining voltage to current relation [29]. Thus, it is used as basis of models trying to represent totally or partially operation of BESS.

2.3 From electrochemical cells to BESS

Up to now the cell and all related parameters, indexes, variables, functions and processes have been analyzed. But the battery cell is just the core of a BESS, able to flow power in DC on the two directions, in and out (from environment and to environment), at a precise range of terminal voltages depending on cell. Since large majority of electric grids are in AC, at precise voltage, the cell needs several auxiliary devices to work.

The stack is a group of modular cells put in parallel or series, to achieve the desired voltage, capacity and power in DC required from application. It is the way in which cells are organized.

The Battery Management System (BMS) is an electronic system managing a rechargeable battery and controlling its operation to avoid going outside the Safe Operating Area [30], the area within the voltage, SOC and current thresholds already mentioned. It is able to compute all the quantities defining operation of battery and life, such as SOC, SOH, temperature, terminal voltage and current.

The inverter is the device aiming to perform conversion from DC to AC (power towards grid) and AC to DC (power from grid). It is a power electronics device. Usually it is in series with a transformer (grid side) to enhance potential to medium-high levels appropriate for Distribution and Transmission networks. While inverter's cost is usually in charge of battery owner, transformer, if needed, is already in place in grid, owned by Service Operator. Therefore, sometimes topology of grid influences the design and positioning of BESS systems.

Other auxiliaries can be present. They include HVAC systems for keeping temperature and air quality in BESS rooms, circuital elements for breaking currents and keep safety of the system, etc. The necessity of these devices must be taken in consideration when designing a BESS. Additionally, also DC generators, DC loads or other type of off-grid loads can be present.

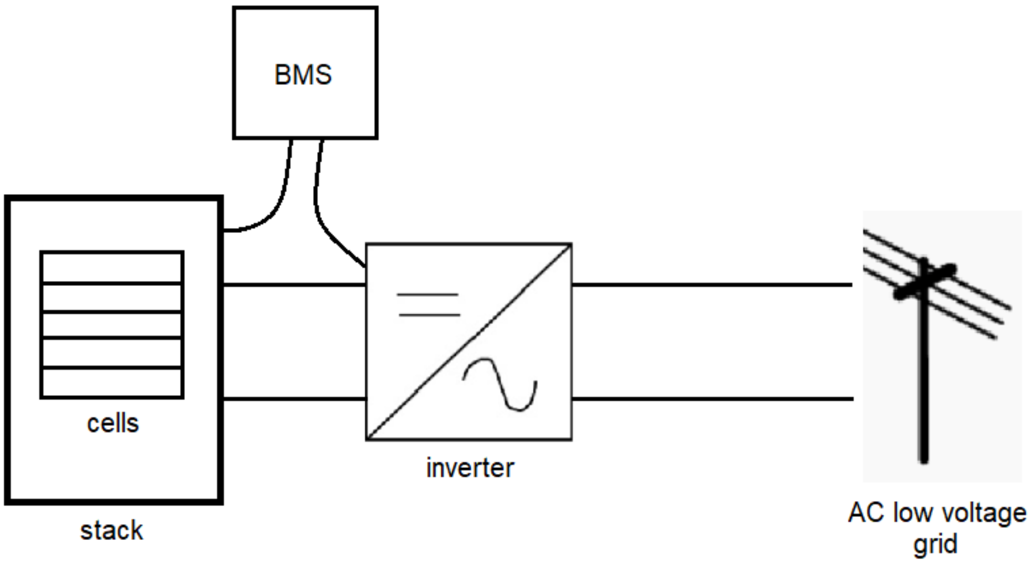


Figure 2-7 BESS grid-connected scheme

The whole vision of BESS system is important both for modeling (inverter is not an ideal machine, must be taken in account; BMS acts during operation setting limits) and for investment evaluations.

2.4 Battery modeling

As described up to now, processes involved in battery operation are complex, non-linear and a very wide variety. They include electric phenomena such as conduction in wires and electrodes, chemical reactions based on Tafel and Butler-Volmer electrochemistry equations, physical processes as diffusion and mass transport for ions, thermal processes such as temperature increase due to Joule effect.

Data provided by manufacturers are not sufficient to predict battery operation. They comprise efficiency, energy and power density, capacity and lifetime, usually given as constants or as nominal values in standard conditions. Actually, all of the parameters mentioned are heavily varying with operation and usage. They strongly depend on c-rate, SOC and type of cycle (current profile and DOD) [2]. This means that a large experimental campaign is needed to collect data for decently characterizing battery operation. Since it is impossible to experiment all the possible operating conditions a cell could undergo while working (which would mean every value of c-rate, SOC, DOD and current profile of each possible cycle) a model is necessary to simulate battery operation. This model will be built on experimental data, using equations depending on nature and complexity of model chosen as well on amplitude of system modeled.

The focus of this Paragraph is on Li-ion cells models, i.e. power electronics and regulators within a BESS are not discussed.

There are different types of model given the level of the system that is taken in account [2]:

1. Material level: system analyzed is the substance in which a particular phenomenon of cell operation is happening. Usually, this level does not include the whole cell but just the part involved in phenomenon studied – e.g.: SEI formation involves spacing between electrode and electrolyte.
2. Cell level: the elements of BESS are described by voltage shown at terminals. Mechanisms in cell are modeled one by one or as a whole but outputs of model show the overall effects at terminals.
3. Module level: several cells and the BMS are grouped. This system allows to study the whole operation of the cells during cycling, since the BMS is able to treat saturation cases in SOC, voltages or power that usually occur in battery cycles.
4. System level: complete stack of cells, BMS and inverter. All the system and its interface with external environment are modeled. This allows complete study of performance in common operation for BESS.

Nature of the system modeled defines the main categorization of model types. Four main types of model can be defined, listed here below from more complex and detailed to less:

1. Electrochemical models
2. Electric models
3. Stochastic models
4. Empirical/mathematical models

Last main division among models is based on which quantities they should evaluate.

1. Operating conditions: they are concerned in giving an approximation of operation of the cell while it is requested to provide a power output. Main quantity to estimate by these models is SOC.
2. Ageing: they are concerned in defining evolution of BESS characteristics along time, defining their lifetime based on their usage. Main quantity estimated is SOH.

Some models takes in account both SOC and SOH simultaneously, but most of models have focus on one of the two quantities, depending on their application.

In next Paragraphs there will be a view of the state of art of BESS models, focused on cell/module level, spanning from SOC estimating models to SOH estimating ones. Models of the four different natures defined before will be described, highlighting type of applications suggested for each type. As already mentioned, main parameters of interest in the choice of a model are accuracy and simulation time (computational effort). A model can deal simultaneously or separately with SOC and SOH. Moreover, a model can give major attentions to a parameter and relegate to background the estimation of the other one, depending if the application is an analysis of battery operation or of its lifetime. Since the aim of this study is more concerned in choice and validation of a SOC estimating model, more effort will be posed in describing this kind of models, giving SOH estimating model only a brief overview.

2.4.1 SOC modeling

SOC estimating model must approximate variation in SOC level while battery is interested by a power flow. Battery operation are always characterized by two main quantities: voltage and capacity. The product among them gives energetic content of the cell. Charge (negative power requested to cell) and discharge (positive power requested to cell) processes influence available capacity in battery and operating currents affect as previously mentioned voltage at battery terminals. Therefore, SOC estimation must take in consideration all these factors to give a reliable value. SOC is usually defined as a function of open-circuit voltage of the cell. Maximum and minimum threshold of SOC depend instead on terminal voltage, that is function of residual capacity and c-rate. This kind of models must be, depending on applications, more or less accurate in modeling electrochemical and transport mechanisms in cell, transients, SOC saturation conditions. These models are the ones implemented by real batteries' BMS in order to provide secure routine of BESS to users.

2.4.1.1 Electrochemical models

Electrochemical models aim to be as close as possible to real system by incorporating chemical and electrochemical kinetics and transport phenomena to produce prediction more accurate with respect to the other types of model [31]. To take in account of all the reactions happening in cell, they use mass, energy and momentum balances computed for each, species, phase and component. Typically, they involve system of partial differential equations to be solved in time and spatial dimensions [2]. There are different versions of these models, given the type of kinetics used and the spatial framework of reference:

1. Single-particle models [32]: cell is composed by electrodes and electrolyte which have no spatial extension and no potential difference at interfaces. The less complex among electrochemical models, using linear, Tafel or exponential kinetics and considering a 0-dimensional cell in which the electrodes and the electron are a sandwich with three layers of 0-thickness and same cross-sectional area. This model is neglecting ions concentration variation among negative electrode, electrolyte and positive electrode. Therefore, it is neglecting potential difference at interfaces and it has lower computational effort, but high accuracy just in case of low c-rates and thin electrodes.
2. Ohmic porous-electrode models [31]: cell still has no spatial extension, but there are potential differences at interfaces among electrodes and electrolyte. Linear, Tafel or exponential kinetics is assumed, and some additional phenomena such as dependencies of conductivities on porosity of layers at electrode-electrolyte interface are added [33]. Anyway, concentrations variation in spatial directions is still neglected. This model has an average accuracy and simulation velocity among the previous and the following.
3. Pseudo-two-dimensional (P2D) models: cell has spatial dimensioning, with potential differences among interfaces and concentration gradients in both electrolyte and electrodes. It uses Butler-Volmer kinetics and the system is composed by (from outer to inner layer) current collectors, electrodes and separator (electrolyte). It is called pseudo-two-dimensional since it has a real dimension on x-axis, in normal direction with respect to layers, and a pseudo-dimension of the spherical particle representing its radius: particles are no more 0-dimensioned. This model is by far the most widespread among battery researchers [31], when the aim is theoretical study and deep design of cell. It is less diffused in sizing applications and commercial studies due to its extremely high computational effort. In fact, this kind of models requires solving non-linear partial differential

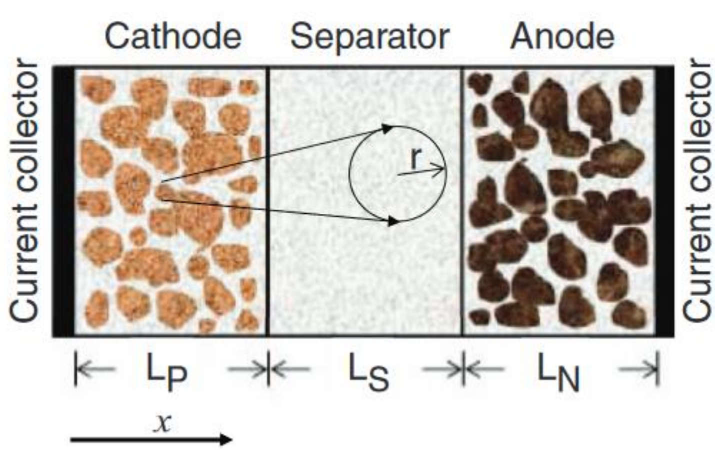


Figure 2-8 Spatial diagram of pseudo-two-dimensional models, with x and radial (r) directions highlighted [31]

equations (PDEs) in x, radial and time dimensions. A first version of this type of models is by Doyle et al. [34] in 1993, then many other improved versions have been developed to take in account of each particular mechanism in cell operation.

Beside electrochemical models, a mention is necessary for Multiphysics models. Electrochemical-thermal models can be of interest in more precisely represent effects of large variations of temperature during operation. Thermal models can be implemented in P2D in order to decouple cell thermodynamic computation [35] and stack thermal simulation [36] and sum their effects. This could lead to improvement in approximation of particularly high energy/power applications such as electric vehicles operation. Other very accurate models introduce stress-strain and particle size-shape distribution: to define well SOH of a battery, it is useful to take in account of:

1. Non-uniform expansion and contraction of material during reactions in electrodes' structure, leading with time to possibility of loss of active material, modification of tortuosity in graphite structure limiting Lithium diffusion or stress in electrodes' structure [37].
2. Change in dimensions and shape of particles in cell, e.g.: catalyst (Platinum), leading to variation of particle size distribution and consequently variation of specific area available and decay in efficiency of process [38].

2.4.1.2 Electric models

Complexity of electrochemical models (e.g.: P2D models) relegate them to a limited variety of applications, in which the extremely high computational effort is not an issue [39]. In the majority of applications, having a model slightly less accurate but faster is preferred. Therefore, with spreading of BESS in many commercial sectors, need for lighter models showing anyway a good fidelity with respect to P2D has risen. Electric models can answer to this demand. They are successfully used in large variety of research and commercial applications, showing high level of accuracy even if undergoing to very unsteady cycles or large temperature variations, e.g.: in prediction of electric vehicles' battery performance [40] [41].

Electric models can translate all the complex electrochemical and transport phenomena happening in cells in an equivalent electric circuit (Equivalent Circuit Models or ECM [42]). From this equivalent circuit, output is the terminal voltage, which is approximating the one of the real battery. Complexity of these models depends on number of circuital elements included. Low number of circuital elements is not able to approximate any electrochemical or transport mechanism, and these rudimental electric models are comparable with empirical ones. Anyway, every electric model is composed by two parts able to properly reproduce battery steady-states and dynamics:

1. A circuital element representing equilibrium voltage of the cell, i.e. OCV, that is reached at steady-state, with c-rate of 0. This element is the one approximating SOC as a function, as just mentioned, of OCV. In case this element is voltage source, the model is defined active electric model. Otherwise, if it is a capacitor, the model is a passive electric model. Passive electric models are more suited to represent real battery physics [2].
2. Other circuital elements representing the overpotential seen at terminals with respect to OCV.

Depending on the working principle of each model, electric models can be divided in [43]:

1. Thévenin-based models (time-domain models).
2. Impedance-based models (frequency-domain models).
3. Runtime models.
4. Combined models.

Thévenin-based models are developed in time domain based on Thévenin equivalent circuits. Thévenin theorem introduces Thévenin equivalent circuit as the circuit that can represent a complex electric circuit having a potential difference at its poles with a simpler circuit including a voltage source featuring the open circuit voltage at terminals of original circuit and in series the equivalent resistance of the passive original circuit (obtained by replacing all voltage sources with open circuits and all the current sources with short circuits) [44]. The simplest models are featuring one series resistance and one RC for predicting battery response at load transients [43].

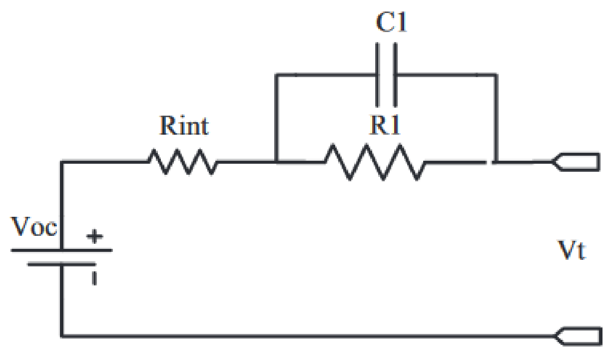


Figure 2-9 Basic Thévenin-based model [115]

Impedance-based models are developed in frequency domain by letting the BESS to be modeled undergo Electrochemical Impedance Spectroscopy (EIS) or other types of lab analyses. This test is meaning to define the impedance seen by a cell through the imposition of a variable frequency voltage input (potentiostatic mode). Usually frequency spans from 0 to 65 kHz [45]: each frequency is typical to stimulate a peculiar phenomenon in cells. The impedance seen at each frequency can be linked to one mechanism (e.g.: limited conductivity in wires at very high frequencies, kinetics in electrode at average frequencies, ion mass transport issues at low frequencies). EIS results are then transferred on the electric model by adding to circuit an equivalent impedance in series to the voltage source or capacitor aiming to represent OCV.

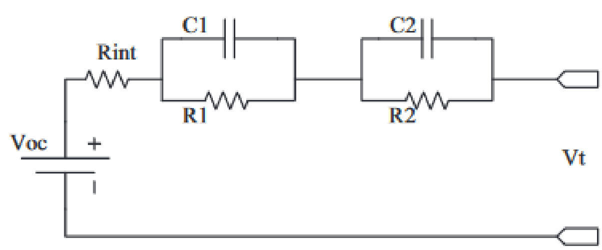


Figure 2-10 Basic Impedance-based model [115]

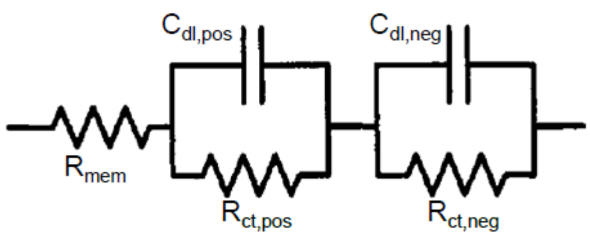
Model represented up to now are able to provide characterization of the circuit (OCV, voltage at terminals) at a particular condition of the cell: these models needs a power input (or voltage, or current) and the parameters of passive elements and give back the single result for relevant voltages at that condition. Runtime models add to previously described models the ability of updating operating condition of the cell to compute their evolution in discrete-time. Therefore, each time step operating conditions of battery are updated and the result is a log of them (e.g.: OCV, SOC, terminal voltage, power output) for the time frame of the simulation.

Combined models combine characteristics of interest of all the types of model previously described.

After having provided a panoramic view of the different variants of electric model, a standard of the resulting electric circuit can be given. This circuit aims to link not a single phenomenon to each element, but each element of the cell to an element of RC circuit.

1. Cables: they link voltage source and electrodes. They are purely resistive (R_{EL}). Usually this resistance is negligible with respect to the membrane's one.
2. Interface electrode – membrane: it is the part of battery in which is present the catalyst layer, linking anode or cathode and electrolyte. It can be modelled as a capacitor (C_{DL}: double layer approximation) in parallel with a resistor (R_{CT}: charge transfer resistance) for each one of the two poles.
3. Membrane: the electrolyte, usually formed by a solution of lithium salts in organic solvent, is affected by mass transport phenomena related to ions moving, approximated with a resistor by means of electric analogy (R_{MEM}).

This is how the equivalent impedance by the sum of this phenomena would look like:



$$Zeq = R_{mem} + \frac{1}{\frac{1}{R_{ct}^{-}} + j \cdot \omega \cdot C_{dl}^{-}} + \frac{1}{\frac{1}{R_{ct}^{+}} + j \cdot \omega \cdot C_{dl}^{+}}$$

Figure 2-11 Equivalent impedance in electric cell model [15]

2.4.1.3 Analytical models

Analytical models employ past experimental data to predict how a cell will work if undergoing same past processes and operational conditions. From data, one or more equations are developed to model efficiency, voltage, OCV or SOC of the battery. This or these equations are actually the model of the battery: there is no link among the equations and physicochemical mechanisms of cell, since these equations are just regression of experimental data, or even of manufacturer's datasheet statements. Polynomial, exponential, logarithmic, power law or trigonometric functions are usually used as analytical models. Every analytical model can just represent a single battery. Experimental campaign and equation fitting must be repeated from scratch in case of change in application. The computational simplicity of these models allows extremely quick simulations. But error can be large in case of particular operating conditions, difficult to experiment and fit (e.g.: c-rate high, operation at SOC close to saturation limits, operation at temperature or other environmental conditions far from standard or experimented values). This kind of models cannot be used for research and development on new batteries, since they are experimentally-derived [31]. Instead, they can be a useful tool for sizing of batteries or other commercial applications, that requires low to medium level of accuracy. Many analytical models are in use. They usually differ due to the quantity they use to characterize a battery: Peukert model uses capacity, Sheperd model uses directly voltage and current, as electric models do [46], KiBaM uses a ratio of "available" over "maximum charge", correlated with SOC. Given their low computational effort, they are the most used type of models in dimensioning tools [2]. Accuracy level from some analytical models for batteries has proven enough high also for studying stationary applications at university and company level. It is the case of KiBaM (Kinetic Battery Model) [47], one of the most diffused type of analytical models [48], that has found application in University of

Massachusetts' wind/diesel simulation codes [49]. Another model developed using Support Vector Machine (SVM), a regression algorithm, has shown error of 5.76% in dynamic state SOC estimation test [50].

Most used among this type of models are empirical models. Empirical models work on the steady-state operation of the battery. They compute the actual energy flow through the battery over a given time step to update SOC. There is no direct link with voltage and current, just a non-ideal system exchanging energy with efficiency lower than 100%. In these models, usually SOC coincides with State of Energy (SOE) [2]:

$$SOC(t) = SOE(t) = SOE(t-1) + \frac{\Delta E}{E_n} \qquad 2.16$$

Where t and t-1 are two subsequent time-steps in discrete-time simulation, and ΔE is variation of energy as a function of power requested to cell, time-step and efficiency of the cell. Efficiency can be a constant number or a function of c-rate and/or DOD. It is anyway defined experimentally as roundtrip efficiency (see 2.13). During experimental campaign, many cycles can be used to define the performance at different c-rates, initial SOC or DOD: roundtrip efficiency become in this way function of the parameters used. Having multiple values of efficiency, the empirical model can be represented by the curve interpolating all values. E.g.: if the efficiency is just defined as a function of c-rate, the equation modelling it could resemble the following:

$$\eta_{RT}(c-rate) = 1 - \sum_{i}^{n} k_i * (c-rate)^i \qquad 2.17$$

Where k_i are experimental coefficients and n is the degree chosen for approximating polynomial. Other versions of the model could implement more variables and/or different functions (e.g.: exponential or logarithmic). In this model there is no dynamic response considered. This means the efficiency at time-step t is not influenced by c-rate at time-step t-1. Modelling efficiency for operating condition estimation allows to predict SOC evolution over a period by just using data from manufacturer's datasheet or having a light experimental campaign on the chosen battery model. In the case shown by 2.17, the model has no dependence on SOC(t) and on cycle type. This can lead to large errors in some cases, since same c-rate is not feasible, for instance, at every SOC level in a real battery, due to voltage limitations shown in 2.10 not implemented in empirical study.

2.4.1.4 Stochastic models

These kinds of models are the least descriptive ones, but with their low computational effort they can be useful for some commercial application. Since their use is not of interest for this study, they will be just mentioned. They are based on discrete-time Markov chains. In the simplest form, capacity of battery (or nominal energy) is divided in equal units, each one representing amount of energy required to transfer a unit inside or outside the cell. Update on number of units in cell gives evolution of cell SOC [48].

2.4.2 SOH modeling

SOH estimation can be performed simultaneously with SOC estimation using physical equations evolving during battery lifetime or, more often, it is computed statistically as a function of operating parameters of the battery shown during applications. In latter case, estimation of SOH can happen runtime or after the end of the simulation. In case of simulations only involving brief time-periods with respect to lifetime of battery, a model estimating only SOC can be used, considering capacity-fade and power-fade null within the simulation. An equation can then compute the lifetime and the decay in capacity and power as a function of operating parameters shown during simulation (the stress factors described in Paragraph 2.2).

Usually, only detailed models used for design of batteries or for inspection at material level present equations updating with battery ageing. These equations are PDE if the model is electrochemical. They can update by considering the physical degradation of the elements of cell. In case the models are electric, they evolve by changing the parameters of the circuital elements based on experimental data on decay mechanisms. Just few extremely detailed models implement simultaneous SOC and SOH estimation [51].

More often SOH estimating models are analytical model based on experimental or statistical data. Accelerated stress tests are done on batteries and data on operating parameters are correlated with capacity-fade and power-fade. These correlations build up equations and diagrams used for lifetime estimation. Usually, this method cannot be performed in real-time. This second category of models is tailor-made on the single battery experimented and shows accuracy and reliability only if the data are collected in convenient amount [52]. In [53], an analytical model for assessing capacity fade in Li-ion cells for electric vehicles (EV) was validated by showing error lower than 5% on some test cycles. It dealt with both cycle and calendar ageing, using as stress factors for the first c-rates and temperature and for the latter SOC and temperature. These models based on statistical data work by receiving as inputs the operating parameters of interest (c-rate, SOC evolution, operating temperature) and returns the lifetime of the battery or the capacity and power-fade in a time-period.

3 Introduction to Ancillary Services Market

Previous Chapter offered an overview of what a battery is, how it acts and how it can be modeled. A battery model is fundamental to ease the study of BESS operation allowing not to use a test bench. In this study, the BESS must perform a specific task: it must provide Ancillary services to network. Merits to be measured are the quality of provision and the economic return. To verify the quality of service provision, rules of services must be clear. To evaluate economic return, market design and remunerations should be analyzed. Therefore, an analysis of Ancillary Services and of the market they are traded on (ASM) is necessary. Moreover, this study on BESS is motivated by an evolution of ASM. In last years, Ancillary services became more and more necessary to face larger unbalances caused by non-programmability of RES-E in power systems in which their share is growing. Transmission System Operators (TSO) responded to this incremental demand of power Reserves for grid services by opening the ASM to new actors and involving them in pilot projects. Aggregators, Diffuse Generation (DG), demand-response and in some cases BESS were the targets. Forecasting a further trend in direction of BESS, it is important to give panoramic view of evolutions of ASM and to discern what are limits and advantages of BESS for having a role in services provision.

3.1 Electricity markets

Electricity has become during years a fundamental good. To foster an economic competition, worldwide liberalized electric markets have been activated. The most common market model nowadays is made up by two main units. There is Day-ahead Market (DAM) for satisfying final consumptions, in which the product exchanged is Energy. And then there is Ancillary Services Market (ASM) for providing necessary reserves ready to face unpredictable events, opening after closure of DAM. Here the product exchanged is Capacity.

In DAM, sellers (producers) and buyers (consumers) put their offer in an Electricity Pool, that results as the central manager of market, the only counterparty for the market players. It acts as the only buyer for producers and the only seller for consumers. DAM is usually a clearing-price market:

1. Every producer offers for each contracted period a quantity (MWh) at a minimum price (€/MWh).
2. Every consumer requests a quantity at a maximum price.
3. All producers are listed in a cumulative supply curve from lowest to highest price proposed, vice versa consumers are listed from highest to lowest price offered in cumulative demand curve.
4. There will be a clearing quantity in which price for demand and offer equal. That intersection will define the price paid or received for every unit of energy exchanged, with marginal price system.

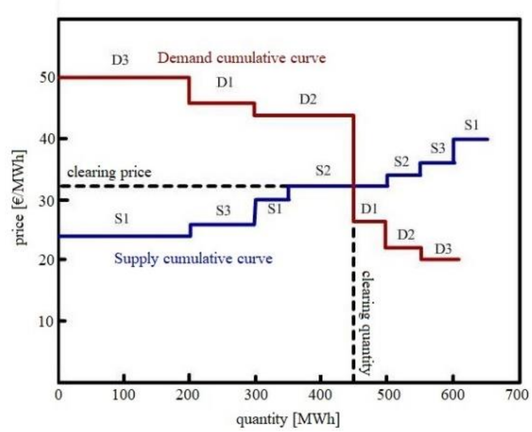


Figure 3-1 Day-ahead market cumulative curves

This market hypothesizes no transmission constraints (every seller and buyer is considered as if it is in the same place, without considering network topology issues) and a perfectly competitive market (every sellers bid its marginal cost of generation and every buyers offer its marginal value of energy purchased) [10]. Actually, topology of the network leads to local/nodal constraints not typically considered in DAM. Moreover, in Electricity Pool every producer and consumer are included. They sell and purchase based on forecast of what they can produce or consume next day. Some categories of participants to market cannot forecast with precision their production or consumption. For instance, non-programmable RES generation largely varies with respect to forecasts [54]. And even precise generators can undergo a fault: so, generally, production and demand fluctuate resulting in divergence among forecast and reality.

Given network constraints and fluctuation of demand and offer, DAM program is hardly ever respected and there is always need of ASM and real-time balancing. Trends show how the energy traded on ASM is increasing in years with respect to DAM's. ASM and balancing market (Mercato Bilanciamento, MB) in 2016 in Italy exchanged 32 TWh (while it was 25 TWh in 2014, +28.0%) [11] and DAM exchanged 203 TWh (it was 186 TWh in 2014, + 8.4%) [9]. Ratio among energy exchanged on ASM and MB with respect to DAM passed in 5 years from 13.4% to 15.8%. This trend goes along with increase in GW installed of non-programmable RES-E in Italy [11], as shown in Figure 3-2.

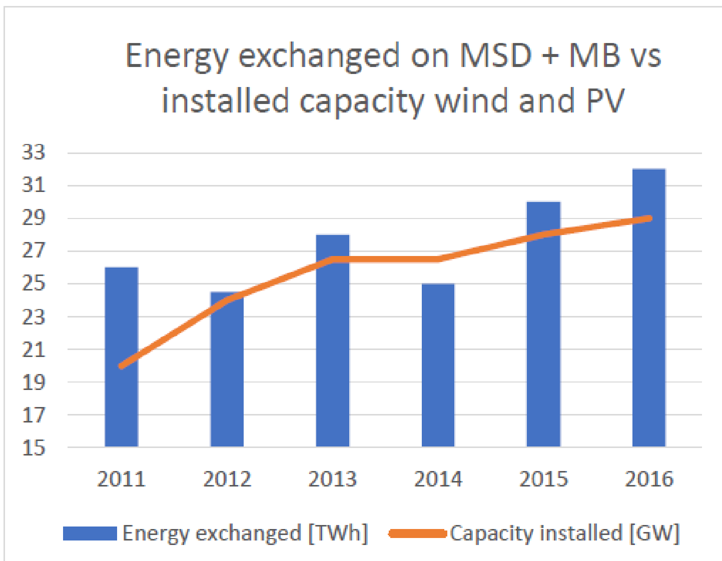


Figure 3-2 Relation among MSD volumes and RES penetration

Aim of ASM is the provision of necessary power Reserves for management and control of system. Before looking at ASM structure and possible perspectives, it is necessary to briefly present Reserves and relative services.

3.2 Main grid services: Power Reserves

Since main marker for assessing power quality in AC networks is the frequency, main reserves are defined with respect to their relations with frequency variation. Frequency behaves as follows:

1. If there is a positive unbalance ($\sum P_{producers} > \sum P_{consumers}$), it increases ($\Delta f > 0$).
2. If there is a negative unbalance ($\sum P_{producers} < \sum P_{consumers}$), it decreases ($\Delta f < 0$).

Frequency fluctuation is a phenomenon impacting on the whole of the connected grid: a grid operating under cooperating Transmission System Operators (TSO) working at same frequency is called Synchronous

Area [55]. Therefore, the value of the frequency is almost the same in every part of network, and perturbation of it due to an unbalance in a specific place of the network are propagated across the grid. The importance of keeping the nominal value derives from the narrow range of operation of rotating generators. But also some loads work by using the frequency of network as parameters [56]. Aims of Power Reserves are:

1. Restore a steady value after a transient, covering the unbalance and restoring equilibrium among producers and consumers.
2. Get back to nominal value (of 50 Hz in Europe), by producing a temporary unbalance in the opposite direction with respect to frequency variation.

Reserves are subdivided in different categories and different markets. Here below a detailed description of operation principle and aim of each reserve.

3.2.1 Frequency Containment Reserve: Primary Control Regulation (PCR)

This reserve is the fastest one. It acts quickly whenever Δf exceeds a dead band (usually ±20 mHz). The scope of this regulation is to contain the frequency variation within the maximum thresholds (±200 mHz). The ceasing in action of this reserve happens when frequency gets to a steady-state. To perform its action, PCR act as follows:

1. In case of under frequency, positive reserve injects power in the grid;
2. In case of over frequency, negative reserve withdraw power from grid. Actually, all relevant units inject less power than programmed in grid.

In any case, after PCR balance is restore in grid:

$$\sum P_{producers} = \sum P_{consumers} \tag{3.1}$$

This means frequency reaches a steady value.

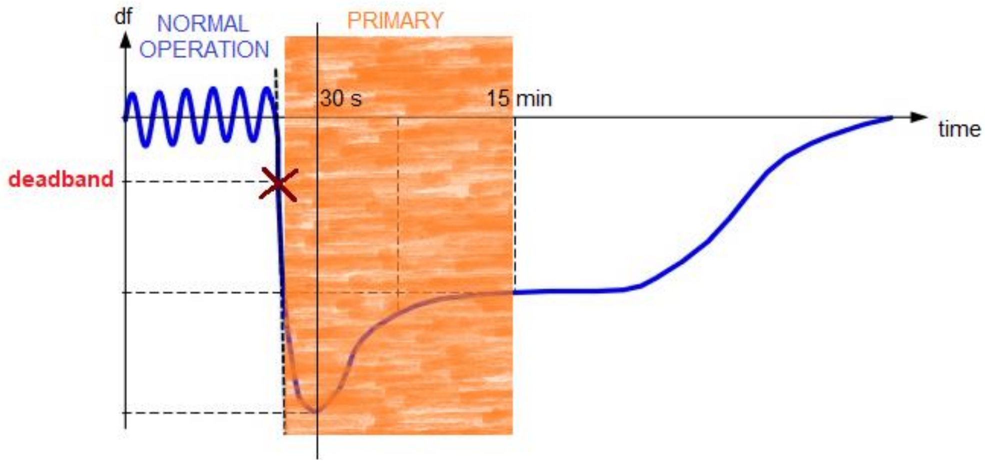


Figure 3-3 Primary regulation diagram

In Italy, PCR is a mandatory service provided by every relevant unit (Unità Rilevanti: > 10 MVA, programmable). It is not subject to ASM, but it has a remuneration that is function of zonal price of electricity.

To characterize and bind operation of units participating in PCR, a law of functioning called droop control law is implemented. This law links the variation in frequency with respect to nominal value to the variation in power output requested to generators. Droop means the ratio of a steady-state change of frequency to the resulting steady-state change in active power output, expressed in percentage terms with respect to regulating band offered (maximum power offered for reserve by each unit). The change in frequency is expressed as a ratio to nominal frequency and the change in active power is expressed as a ratio to maximum power offered for reserve by the unit. So, a single value in percentage chosen by TSO allow every unit to know the power output required in each moment of regulation. Usually a droop control curve features (see Figure 3-4):

1. A lower flat part, called dead band (power output = 0), where frequency variation is low and does not request any power regulation.
2. A part lead by droop law, in which power output requested increases (decreases) while frequency decreases (increases).
3. An upper flat part (power output = 100% of regulating band), in which power output is steady at maximum (minimum) since frequency is far from nominal value.

The equation for droop is:

$$droop\ [\%] = 100 * \frac{\frac{\Delta f}{f_{nom}}}{\frac{\Delta P}{P_{reg}}} \quad 3.2$$

Where f_{nom} is nominal frequency and P_{reg} is regulating band offered for service.

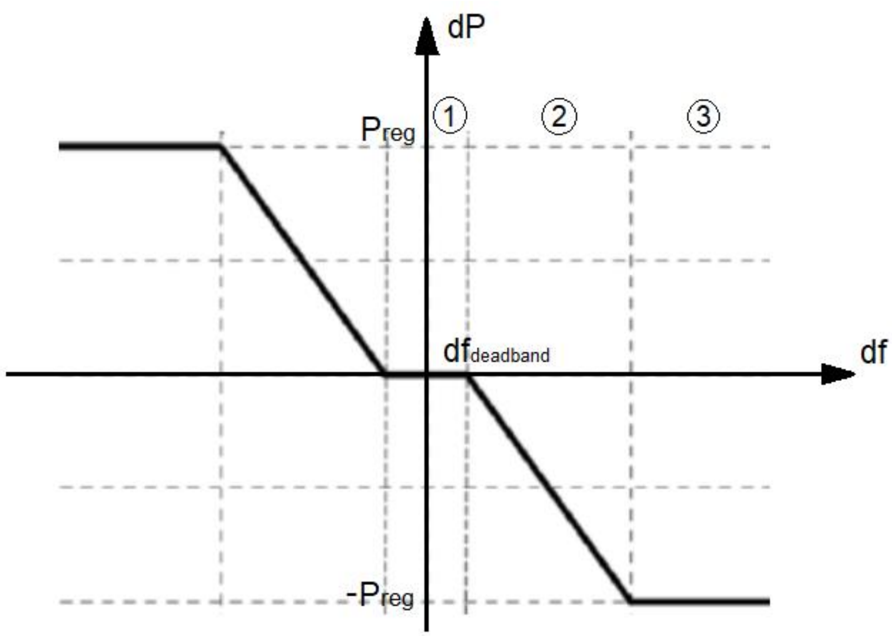


Figure 3-4 Droop control curve

The service specifications in Italy are:

1. 20 mHz dead band.
2. Fixed droop varying among 2-5% depending by type of unit.
3. Regulating band of ±1.5% of nominal power of plant (Symmetric Reserves).
4. Fully activation maximum delay is 30 seconds after dead band is overpassed.

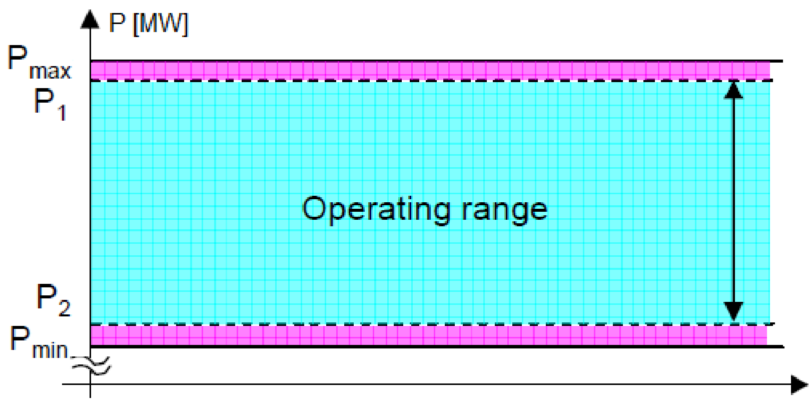


Figure 3-5 Scheme of maximum and operating range of a unit relevant for PCR. Pink bands are PCR regulating bands, limiting maximum and minimum power output

3.2.2 Frequency Restoration Reserve: Secondary Control Regulation (SCR)

Primary regulation does not restore frequency to nominal value. It just interrupts deviation and gets to a steady value that could be higher or lower than nominal value (50 Hz in Europe). SCR start working after PCR to reset nominal frequency. It acts causing an unbalance in grid for a certain period, injecting power if frequency is below nominal value and withdrawing it in case frequency is above nominal value.

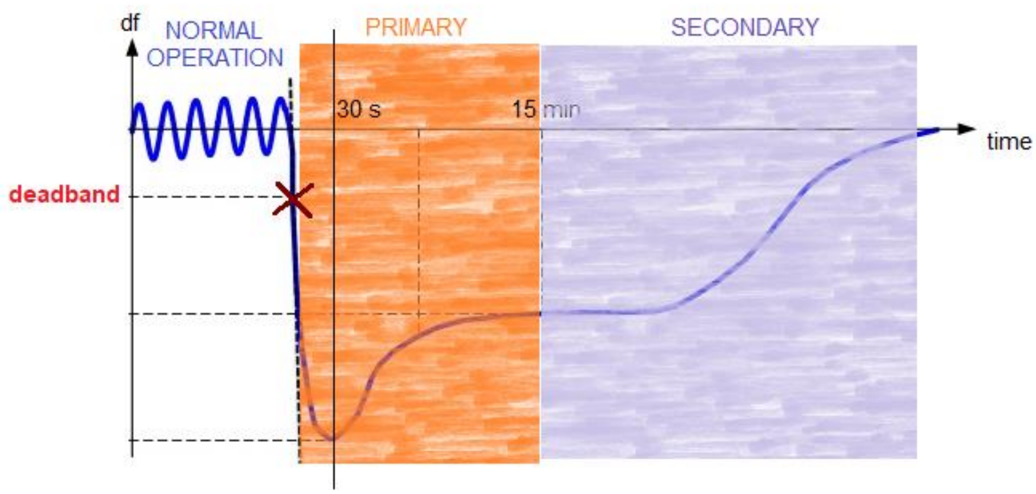


Figure 3-6 Primary and secondary regulation diagram

With respect to PCR, this service is less standardized and has more constraints. There are less actors, so larger power flows requested to each actor. Therefore, there can be topology constraints. Given the quantity of reserve available, output required to restore frequency must be computed by TSO and shared among generators. The result, for Italian case, is a common signal in percentage corresponding to power output requested to every generator selected in market with respect to its total capacity offered (regulating band). In Italy, Secondary Reserve is a paid service on MSD. Specifications of service on Italian market are:

1. Every unit willing to enter market must bid same power bands (Semi Bande: SB, in MW) in positive and negative reserve: symmetric service.
2. Selected units automatically follow setpoints given by Segnale di Livello for the whole period in which they are selected. Segnale di Livello is a value [0,100] given each minute by TSO and valid simultaneously for all plants selected for SCR, defining how much power output of unit must differ from its DAM program:

$$\begin{cases} \Delta P = +SB \ \ if \ \ Segnale\ di\ livello = 100 \\ \Delta P = 0 \ \ if \ \ Segnale\ di\ livello = 50 \\ \Delta P = \ -SB \ \ if \ \ Segnale\ di\ livello = 0 \end{cases} \tag{3.3}$$

   And all partial regulations are expressed by intermediate values.
3. Fully activation maximum delay is 15 minutes.

At the end of SCR, frequency is back to steady nominal value.

3.2.3 Replacement Reserves: Tertiary Control Regulation (TCR)

Since units providing SCR are plants with strong programmability and high ramp rate (ΔP/time), it is of interest to have them ready for new events. That is why Replacement Reserve enters the field after SCR to restore the Secondary Reserve. For instance, in case positive reserve of a plant providing SCR has been exploited, TCR provides positive power to grid allowing the plant enrolled in SCR to reduce its power output and get back to setpoint it was following before SCR. So, that power plant can be ready to give once more positive reserve. In Italy, Replacement Reserve is a service traded on MSD. It is not automatic, but manually activated by TSO if needed. It requires slower but longer action: therefore, slow ramp and large energy output. On Italian market, this requirement is translated in a rule asking that energy can be delivered by the unit in 24 hours must be at least four times the power offered on market [57].

3.3 ASM in Italy and Europe today

Reserves described up to now are generally traded on Ancillary Services Market. ASM, as explained before, is a market coming after DAM, necessary to control the network and face unbalances. Since the needs for security of each national network can differ, scheme, products and prices vary among different ASMs. Anyway, some characteristics are shared by most of countries: presence of many sessions during the day, three frequency Reserves, automatic and manual balances, remunerations per energy unit usually greater than in DAM.

PCR and SCR are the most widespread services and the ones with highest and more constant remunerations along years [58]. Italian market partially differs from common practices, specifically it has low remuneration of PCR. A comparison among Italian and German market on these main services, based on data 2013-2016, will be offered in Paragraph 5.1.1.

Both in Italy and in Germany SCR is a service traded on ASM. In Italy it is subject to a capacity market (units offer an amount of MW) generally every 4 hours of the day for the next 4-hours time-period. The remuneration is instead energy based: a positive amount of €/MWh for positive Reserve and a negative amount of €/MWh for negative Reserve are offered on market, that is pay-as-bid. On German ASM there are weekly auctions for different time-periods during the day, defined as peak and off-peak. Remuneration is both in terms of capacity offered (€/MW/week) and in terms of energy actually exchanged (€/MWh). Secondary Reserves are symmetric in Italy and asymmetric in Germany.

For what concerns PCR, there are larger differences. In fact, PCR is not traded in Italy but mandatory for a certain category of plants, called Relevant Units. These units show quality of reliable programmability and their nominal power is more than 10 MVA. These units must permanently provide 1.5% of their nominal power for PCR. There is a remuneration facultative (every plant must demand it and install a measurement system for controlling the provision), based on zonal price. The remuneration paid for positive Reserve is zonal price plus a half of a constant considering the differential among average SCR positive price and average DAM price of the year before. The payment requested for negative Reserve is zonal price minus a constant considering the differential among average SCR negative price and average DAM price of the year before. On the other side, Germany trades PCR with weekly auction and pays on capacity offered basis.

3.4 Evolution of ASM: what is already in place, what is coming and what to expect

As already mentioned, ASM is continuously increasing its share of total energy exchanged on electricity market. Correlation with Electric Renewable Energy Sources (RES-E) penetration has already been shown (Figure 3-2). Since renewables are expected to continue their growing trend at least to 2050 [59], also ASM can be expected to increase its energy volumes. Reserves could lack in the future, and already today this happens in certain conditions. For instance, in days with low load (holidays) and large generation by wind and photovoltaic (PV), it could happen that negative reserves are not enough, and that only base-load plants are active: slow in responding to solicitations and with minimum power constraints (they must deliver at least a minimum power, otherwise they must shut off). In these cases, reduction of import becomes necessary. If not sufficient, non-programmable RES are curtailed [60].

RES curtailment is not a solution to follow. Mainly, because the change in electricity production mix towards a larger share of RES-E is defined as a priority in all scenarios of decarbonization. From COP21 on, the need for investment in low carbon energy has become clear and stated: 60% of global investment in power generation in 2015-2030 should go for new renewable capacity [61].

To face the lack of power reserves for frequency regulation, many action paths have been studied, defined or put in place by several TSO and energy regulators. They can be divided in three main categories:

1. Opening of ASM to new actors or new categories of plants.
2. Introducing new services better responding to new needs.
3. Changing ASM (and DAM) structure, in the direction of increasing sessions and decreasing time interval among market session closing and delivery beginning.

These categories are not just a matter of different technical operations, but also of different philosophies and strategies aimed to different results. By opening ASM to new actors, the aim is increasing the turnout of members of market – and so the size of the Reserves. By introducing new services, the strategy is to vary and adapt Ancillary Services to the limits and qualities of the new actors of the market: Reserves size is the same but they are better utilized by exploiting peculiar characteristics of new members. By adopting new structure for market, the scope is actually decreasing the needs of Reserves. For instance, by increasing market session number, shorter forecasts allow narrower ranges of unpredictability and can – and really do, as will be described – reduce energy traded on ASM.

A brief analysis of each category will be given in next Paragraphs.

3.4.1 New ASM actors

ASM is traditionally open only to reliable, programmable and large power generation units. In a world with larger and larger RES penetration, while the size of necessary reserves increases, the share of conventional large-scale programmable units decreases. Therefore, new regulation allowing ASM participation also for other actors can represent a solution for lack of reserves. Specific categories of stakeholders or plants are interested in these years by pilot projects or studies.

1. Aggregator: a single market operator grouping units that are not relevant (small-scale) or well programmable and guaranteeing service provision by the aggregated capacity it manages. Units grouped can be of various types, usually can be defined generally as Distributed Energy Resources (DERs), both producing and consuming energy.
2. Demand response: opening of markets to loads, aggregated or not, is a way to decrease the unpredictability of their consumption profile.
3. Battery Energy Storage systems: since this kind of units has both limits on power and energy, ASM is the market suitable for them, with a zero or nearly-zero net energy demand over period [62].

These three groups are not separated but overlapping. In fact, aggregation can involve both demand response and BESS. But these latter categories deserve specific mentions since they are interested by specific projects and studies all over Europe.

Aggregation is the act of grouping distinct agents in a power system (consumers, prosumers, producers or any mix of these) to act as a single entity when proposing on markets: aggregator is an intermediary between Distributed Energy Resources (DERs) and the market manager imposed by market manager to allow security of system when dealing with DERs. Aggregation of power units and of loads allow better managing of them by market manager due to stochastic reasons and control strategies able to increase flexibility of DERs and sell that flexibility as dispatching services [63]. In Italy, a pilot project is acting since June 30 in 2017, introducing possibility for Demand and Diffuse Generation (DG) of participating in MSD (the Italian ASM, as described before), by grouping in aggregated topologically-based. A single counterpart will be seen from electricity market, offering the sum of the single generators' power bands: this market operator is called Balance Service Provider (BSP). The project aims to introduce gradually what Italian regulation calls Aggregated Virtual Units (Unità Virtuali Aggregate, UVA): first, aggregated of Demand (UVAC, UVA di Consumo), then aggregated of Diffuse Generation (UVAP, UVA di Produzione) and of storage, finally combined aggregated (UVAM, UVA Miste) that will overtake the previous division in UVAC and UVAP to remain as only actor in final market [64].

Demand response is the possibility for load to offer their flexibility on electricity market. A consumer can change its power consumption to match the needs of the supply. Demand response became of great interest in last few years, consequently to the change in Residual Load profile during the day. Residual load is defined in each instant as the difference between power demand and the generation of non-dispatchable and non-programmable generators (mainly photovoltaic and wind). With spreading of RES-E of new generation, peak power from them has become non-negligible: in some hours of the day – mainly on non-

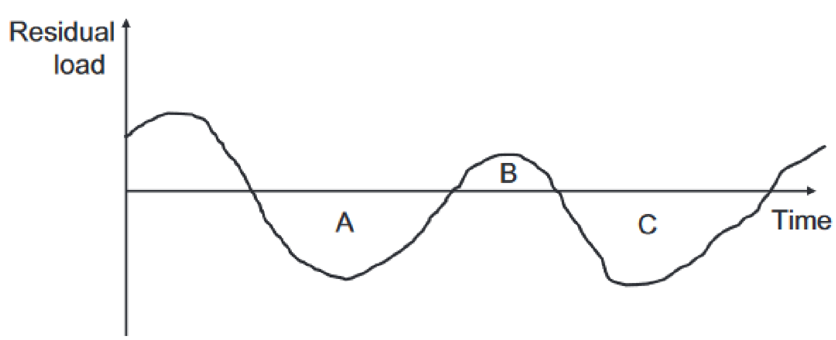


Figure 3-7 Residual load profile [115]

workday, mainly during light hours – residual load becomes even negative. The behavior of residual load during day highlighted in Figure 3-7 develop new requirements for activity of generators: a largely increased share of generators must comply with higher ramp rates (variation of output MW/min) since variation of residual load from off-peak to peak hours gradually increases. This more challenging behavior of network suppliers translates in need for larger secondary and tertiary reserve due to higher need of adjustments in real time. One of the aim of demand response is easing this burden to conventional generators by time shifting load from peak to off-peak hours. Demand response providers will be usually aggregated in a larger plafond and categorized (as relevant units for ASM do) due to their characteristics: response speed, frequency of intervention, period of intervention, programmability of recovery of demand curtailed. Demand response is more frequently provided by units with programmable and forecastable demand and/or with an autonomous power generation system such an Uninterruptible Power Supply (UPS) [11]. Different policies can be put in place to allow different orders of demand response: in France, Time-of-usage tariff (Tempo Tarif) involves 350 thousand residential customers paying different prices for electricity according to weather [65]. This is a kind of "light" demand response policy based on price signals. Consumers do not act on a market but choose a tariff that should lead them to behave, aggregately, by showing demand response to needs of network. In UK, specific demand response programs have been in place for some years, involving industrial and large commercial sector: these energy-intensive users can contract time of use or interruptible loads; on the other side, TSO can ask for load shedding as part of network balancing activities, following specific rules [66]. In Italy, a pilot project by TERNA, the Italian TSO, started in June 2017. It involves up to now around 300MW of aggregated virtual loads, with increasing interest and enrollment to the program [67]. It has been shown that 90% of enrolled consumers have their own generation system, usually CHP system. But studies have shown that in the future large interest in demand response could come from smart loads, such as public lighting, tertiary sector buildings, industry and residential buildings. Intelligent devices could be used if paired to demand response programs, in order to increase their value for owners. If market penetration of these solutions will be high, in the European Union area primary energy demand would experience 1-4% reduction, CO_2 emissions 1.5-5% reduction, investment costs for power generation expansion 2-8% reductions. If in demand response is included also Vehicle-to-grid (V2G) services provision, this number increase: V2G still need technology improvement, but according to trends of diffusion of EV [68] it can represent a massive benchmark of new and smart demand for next decades. There is Danish "Nikola Project" working in this direction, aiming to provide system-wide services (frequency regulation), distribution grid services (LV congestion due to fast EV charging prevention) and user added services by using EV charging management [69].

Battery Energy Storage Systems (BESSs) are fitting ASM due to characteristic of some services in this market of being "energy neutral": the cumulative energy inputs and the cumulative energy outputs requested for a service equal over a period (15 minutes period for fast frequency regulation, according to [62]). Since, as already mentioned, BESS have energy limits that difference them from conventional generating units, a market with lower requirements on energy-side is the natural workspace for them. Two different qualities define operation of batteries while providing grid services:

1. Precision advantage: due to ramp rate almost infinite, or at least largely overtaking the one from gas or steam generating units, a battery can precisely follow an irregular power profile as the one requested for frequency regulation (see Figure 4-7). In study [70], Authors defined that time response modifies Regulation Resources Value: 1MW of fast responding resource such as BESS can provide same service as 1.7MW of hydropower, 2.7 MW of gas turbine (GT), 27.5MW of a combined cycle (CC).
2. Duration challenge: the drawback is that energy storage can only provide some services for limited duration, due to finite ability of consecutively absorb or inject power [62].

Large-scale stationary BESS for grid services provision have been connected to grid in 2015 by Italian TSO in several critical zones of Italy. Critical zones were defined as zones with high non-programmable RES-E presence and low load (rural areas). In these areas, curtailment of wind power was not unusual, since local congestions of grid did not allow any other action in case of negative residual load or voltage threshold overpassing in transmission lines. Installation of large sodium-sulfur batteries was aiming to limit power curtailment and meanwhile providing PCR and SCR. Specifically, two different projects are working in parallel: the Storage Lab project is aiming to experiment different solutions for power intensive application of BESS and the Large-Scale Energy Storage project is working on local congestions and services provision in critical areas. Project is still operating and aims to define if there are economic possibilities for a private investor of having business providing both grid services and DG integration [71].

All three categories defined before are parts of the same intent of increasing plafond of actors operating, with different methods and possibilities, on ASM in Europe and in the world. New business models and positions will open in next years. Some actors will need new standards and modification of actual frameworks. Next two Paragraph will highlight trends for services and structure of ASM.

3.4.2 New ASM services

Since new actors and specifically BESS in ASM can have different characteristics from conventional ones, it may be of interest the introduction of new services or the modification of the existing ones. Study [72] highlighted main rules in defining products on the market hindering DERs entering ASM. Specifically: minimum bid size too high can prevent aggregators to deal with too small units; time period of products can be an obstacle for consumption units bound to habits of consumers; distance among reservation and service's delivery time (weeks, months, years), critical for groups in which units can be added or leave frequently; symmetry of products. The same study gives also a comparison among some countries' ASM nowadays in terms of accessibility for DERs. It does this by researching in these markets' PCR and SCR rules the hindering characteristics just defined. It highlights Danish ASM as best framework, followed by French one. German and British market, the other two analyzed are still backward. When it comes to BESS, they have peculiar characteristics and allow specific analysis:

1. Fast response of BESS to setpoints following. There are less constraints with respect to conventional units on ramp rates of the signals to be followed by BESS as services providers.
2. Limited continuous energy withdrawn/injection. Finite capacity of batteries limits their operation on a setpoint of same sign for long periods.

These characteristics immediately define two characteristics for modified or new services of an evolving services market more favorable to BESS.

1. Asymmetry of services: a service that can provide separately a negative and a positive reserve. In other words, the regulating bands offered by a unit trading on ASM can be greater in the direction of increasing power output and smaller in direction of decreasing power output, or vice versa. This is highly valuable for market users having thresholds in terms of energy content or capacity, as of BESS and demand response. If, instead, symmetric bids are required, the user will be obliged to offer on market the minimum among the upward margin and the downward margin, regardless of its overall capacity [72].
   The two situations can be synthesized in the following equations:
   a. In case of symmetric service:

$$P_{reg+} = P_{reg-} = \min(P^0_{reg+}, P^0_{reg-}) \quad 3.4$$

b. In case of asymmetric service:

$$\begin{cases} P_{reg+} = P^0_{reg+} \\ P_{reg-} = P^0_{reg-} \end{cases} \quad 3.5$$

Where $P^0_{reg(+,-)}$ are regulating bands computed before symmetry constraint, based only on margins available. Symmetric service implies always smaller or equal regulating bands with respect to asymmetric. The case in which they are equal is when SOC is exactly 50%. In the other cases, the farther SOC is from 50, the smaller both the bands are. In asymmetric service, the farther SOC is from 50, the larger is the delta among positive and negative regulation bands, one gradually increasing and the other gradually decreasing.

2. Enhanced response speed requirements: a service that requests higher ramp rates is feasible. Li-ion batteries, even at large-scale, are able to pass from positive power output of 1 per unit to -1 per unit and vice versa in less than 1 seconds [15]. Even if this is not at zero cost for efficiency and life of batteries, it can be said that batteries have ramp rates by far higher than every conventional unit providing services on ASM. This characteristic is actually a value on ASM, since, as already mentioned, it has been studied that in US ASM 1MW of fast-response frequency regulation can be evaluated up to 20MW of conventional regulation [62]. This is because in certain situations services faster-responding than PCR are needed: European network is undergoing a decay in inertia of the grid. Inertia is the ability of maintaining after a perturbation the behavior (or the setpoint) in place before the perturbation. Inertia in grid is provided by mechanically rotating generators (spinning metal) and is able to keep the frequency stable even in case of incidents. With the decrease in conventional turbine-based units and the diffusion of new generation RES (wind and PV), no more inertia is provided to network and oscillations of frequency become steeper. International power network is progressing from a synchronous machine-based system towards an inverter-dominated system [73]. This decrease in inertia is particularly experienced in smaller networks: UK has traditionally lower inertia, since is not a part of a large and interconnected synchronous area, and the decrease of inertia following RES diffusion created a problem. As inertia falls, speed of response delivery needs to increase [74]. BESS can provide this enhanced response.

Asymmetric services are already in place in [75]:

1. France, UK, Denmark, partially Belgium for Primary Reserve.
2. France, Germany, UK for Secondary Reserve.

Other projects and studies suggest a trend towards asymmetric Reserves: ELIA, Belgian TSO, is experimenting also Asymmetric Secondary Reserve since fall 2016; this study [76] tested large-scale wind power to provide downward Reserve for both Primary and Secondary Regulation; Swiss Grid, TSO from Switzerland, is planning asymmetric SCR introduction for 2018 [77]. Thinking of a future generalized switch to asymmetric Reserves, at least for PCR and SCR, is not a mirage.

Even for what concerns fast-response services there are project already in place and studies in this direction. National Grid in UK has introduced in 2016 an internationally leading service explicitly to take advantage of Energy Storage Systems (ESS) fast response capability: Enhanced Frequency Response (EFR) [78]. This service has been designed to allow SOC management between service windows, in order to be tailor made on batteries' energy constraints. SOC management requires a SOC restoration mechanism: this term indicates each strategy used for bringing SOC value towards a predefined setpoint when it gets close to saturation limits (0 and 100% SOC). The EFR service asks the providers to respond within 1 second to the frequency variations larger than ±15 mHz or ±50 mHz (variable dead band). The SOC restoration mechanism allowed is a variation of power setpoint within ±9% within dead band (dead band strategy). In Figure 3-8 the droop control laws admitted are shown: upper and lower lines are showing limiting cases for performing SOC restoration.

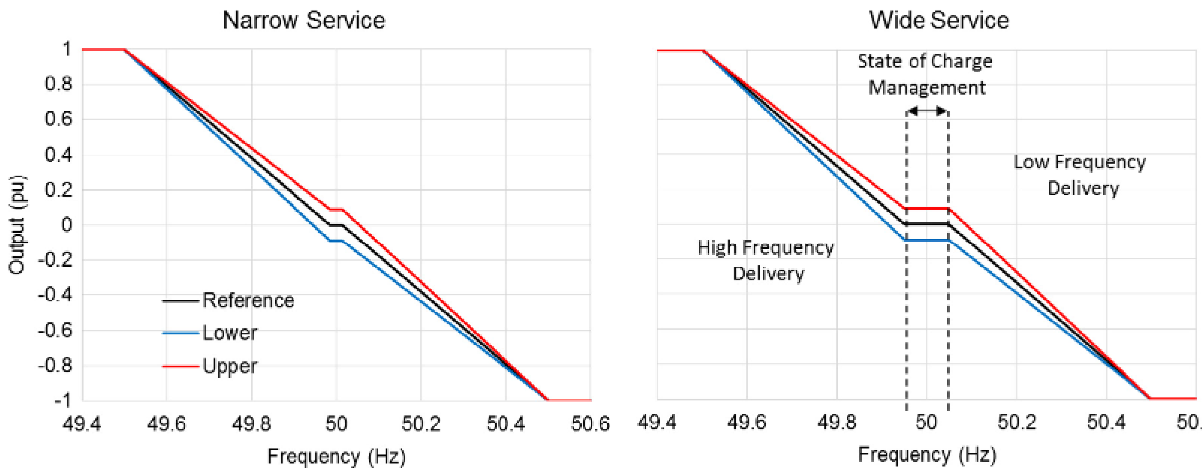


Figure 3-8 EFR droop control curves, highlighting variable dead band and SOC restoration mechanism

In US, Federal Energy Regulator Commission (FERC) ordered in 2011 to 755 grid operators to include in their ASM products related to frequency regulations a fast ramp-rate Reserve, in order to better remunerate providers able to comply with some speed requirements. One of the major operators, PJM, introduced in 2012 two different SCR signals to allow two different regulations:

1. Regulation A (RegA) is the slow-responding one, demanded to conventional gas, steam and combined cycles. It is designed for resources "with the ability to sustain energy output for long periods of time, but with limited ramp rates".
2. Regulation D (RegD, where D is for "Dynamic") is the fast-responding one. It was designed for resources "with the ability to quickly adjust energy output, but with limited ability to sustain energy output for long periods of time".

By substituting some RegA with RegD in global mix of Secondary Reserve, PJM was able to maintain original level of reliability by using less overall regulating power [62]. Moreover, RegD requires a quarter of the energy availability required to RegA with constant power offered on market (0.25 MWh/MW vs 1 MWh/MW) [79].

In Italy a study by RSE [11] has suggested debate on Fast PCR and Virtual Inertia introduction. Virtual inertia is the ability by inverters with specific control algorithms of appearing as synchronous machines to network, enhancing stability of grid [73]. No experimentations are in place as of now in this sense on Italian ASM.

New services, as described as of now, can respond to different issues: increased necessity of stability for grid, specific remuneration required for new categories of providers, delay in network reinforcement. If this would not be enough, a parallel evolution of ASM structure in the direction of better integration of increasing amount of non-programmable RES could be of interest.

3.4.3 New ASM structure

The growing importance of ASM is becoming clear since ENTSO-E defined in Network Code the final aim of creating an integrated European Balancing Market. In this framework, all European TSOs and market operators should uniform their regulations to a shared final code. In this scenario, Reserves will be European and shared. Reserves, as described as of now, should increase due to higher unpredictability mainly due to increase in penetration of wind and PV. An improved architecture of ASM could mitigate this rise.

Two main trends will be analyzed:

1. Local evolution of ASM: Distribution Service Operators (DSOs) collaborate with TSO for enhancing the communications among DG, DERs, aggregators and the market.
2. More frequent sessions and closer to delivery time: DAM and ASM increase their sessions and offering period gets closer and closer to time of provision of the service, allowing lower errors on forecasts and increasing accessibility for DERs to ASM and value of their energy on DAM.

DSOs can have larger role on services market in two ways. First, by acting as counterparty of TSO offering in the conventional ASM the capacities of production or consumption units of small-scale (non-relevant for ASM as of in Italian regulation) present in its distribution grid (connected on LV or MV). Second, by managing its own local ASM for local dispatching (ASM_D), in order to have cheaper prices and to solve easily local congestions and to take in account of local network constraints. This evolution can allow better managing of grids in which the number of provider increases largely (DERs are many and small) and TSO (or market operator) have issues in being the central and unique mediator [80]. Increased interaction needed will impact on communication and ICT infrastructure, therefore a change in structure of ASM will imply also an improvement and standard creation for technologies dealing with communications, signals and measurements [81].

Uncertain forecasts on wind an PV production cause large unbalances on network. If closing time of market sessions (both for DAM and ASM) gets closer to delivery time, then forecasts can suffer less unpredictability, range of tolerance by regulator can be set narrower, needs for Reserves decreases and even value of energy from RES increases [82]. Accuracy of forecasts heavily depends on the lead time which is required by market sessions, as shown in Figure 3-9.

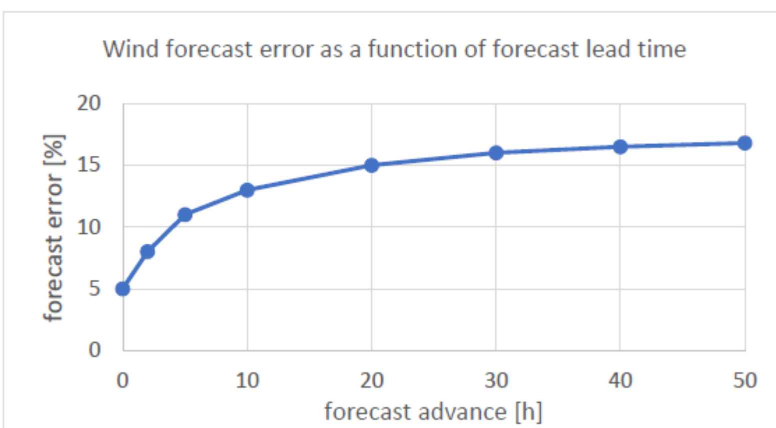


Figure 3-9 Forecast error with respect to advance [85]

Operating experience has shown that close-to-real-time and real-time markets are most interesting items by economic point of view for managing balance in a highly non-programmable RES penetrated network [83]. Many electricity markets have experienced in last years modifications and reforms in direction of better integrating RES also by introducing more rapid market operations, closer to real-time. It is the case of Electricity Reliability Council of Texas (ERCOT) in 2010. Studies showed that these reforms took to decrease in Reserves despite a large growth of DG share in Texas [84]. In New York State study by General Electric, 5-minutes scale has been recognized as the shortest period for human decision-making, planning and delivery of information, communications, dispatch orders and reviews of previous bid. In this case, forecast (nowcast, forecast with zero-time advance) can be accurate and define exactly market outcome. Therefore, variations in periods shorter than 5 minutes are faced by regulation, while for periods longer than 5-minutes thresholds, economic dispatch can be put in place (load-following), with small-bid products [85]. This kind of liquid market (a market is liquid if many actors can easily access and trade on it and if a single transaction does not influence the market too much) and close-to-delivery time approach can be a guideline for each market with large non-dispatchable RES share. In the case study, it was guaranteed to handle at least 10% wind penetration. In Europe, intraday market importance is growing due to needs of short-term adjustments due to greater penetration of non-programmable generation. According to European Commission "short-term electricity markets which allow trading RES-E across borders are key for the successful integration of RES-E into the market" [86]. Many of the national markets in Europe already introduced new market sessions, continuous trading or short-period products during intraday market. Interesting case is the 15-minutes intraday auction introduced by EPEX (exchange for power spot market in Germany, UK, France, Benelux, etc.) in Germany in December 2014. It was meant to substitute continuous trading that was not neutral to small-scale producers, unable to manage a 24/7 trading. It leads to larger participation to market and to reduced price volatility but also to increase in security and reliability of operation [87].

Not only an aim of market structure, but also technology is improving for getting to more reliable forecasts. In last years many operators switched from deterministic to probabilistic/stochastic methods. These forecasts are used even after market closures by TSOs and market operators to predefine necessary Reserves, accounting for errors in offers in DAM very accurately. Even if not decreased, Reserves can in this way cause lower costs for the system [88].

Example of a general modification of ASM structure leading to great decrease in Reserves' volumes and prices is German situation. Several refinements actuated in the period 2006-2012 lead to slight decrease of Primary Reserve volumes in 2006-2015 period, and strong decrease in Secondary Reserves in same period: 37% decrease for positive Reserve and 19% decrease for negative one. This result came due to gradual modifications in structure (from 4 different tenders to 1 overall national) and in services (decrease in minimum offered volumes, delay in market session closures, etc.). Renewable sources have been in this way accepted as an advantage instead of an issue, and analysts confirmed that the growing share of renewables, unexpectedly, helped decrease of prices of Reserves, since conventional generation capacity became abundant, moving outside DAM, and the opportunity cost of providing incremental Reserve significantly decreased [89]. Such a behavior has risen some interest, attentions and curiosity: it has been defined as "German Paradox" by Hirt and Ziegenhagen [90]. While in 2008-2015 in Germany non-programmable RES capacity has risen from 27GW to 78 GW (+189%) and energy output by wind and solar on total German demand grew from 7% to 15%, in the same period balancing reserves have reduced by 15%. This empirical fact is in contradiction with common sense and evidence of correlation among balancing needs and RES capacity, highlighted for Italian situation in Figure 3-2 and valid for many national frameworks. The situation in Germany is instead represented by Figure 3-10.

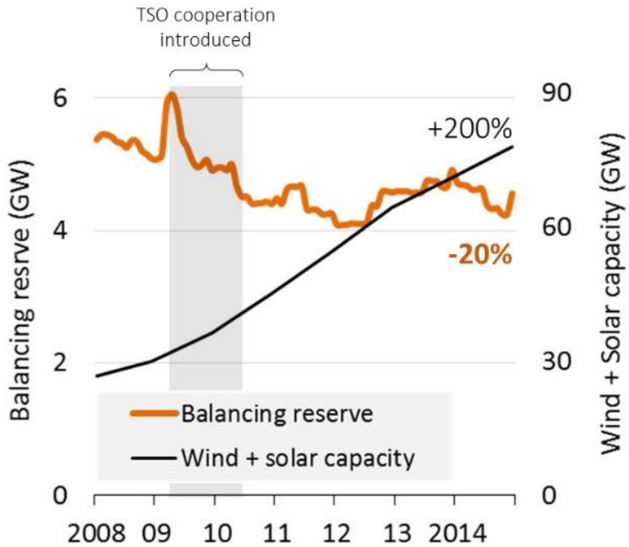


Figure 3-10 The German "paradox": Secondary + Tertiary Reserves with respect to Wind + Solar capacity [90]

In Figure 3-10 the TSO cooperation introduction from 2009 is highlighted. In that year the 4 TSOs previously present in Germany started taking joint auctions for balancing market. This can be one of the drivers of these well-managed transition. Other candidates, always according to [90], are:

1. Improvements on wind and solar forecasts.
2. TSOs cost-conscious behavior that lead to decreased additional "safety" margins. In other countries, RES penetration caused over-protection by TSOs.
3. Improved intraday market, increasing its liquidity and massively introducing 15-minutes trading just described, allowing different portfolios management.

Some other countries, such as Denmark, Spain and Portugal, showed no increase in Reserves even with high growth in intermittent RES penetration. Therefore, analysis of the RES capacity alone is not the best marker to predict Reserves' sizes. Study of grid services evolution requires in fact to put attention on many factors, as done in this Chapter. Last point to briefly repeat here, once more quoting Hirt and Ziegenhagen, is the positive impact of a larger balancing area (area in which ASM are connected and share Reserves) as a driver for avoiding rise in Reserves' volumes and prices. This technique has been developed in Germany, not only by letting TSOs cooperate in joint reserve sizing and activation since 2009, but also joining in 2012 "International Grid Control Cooperation (IGCC)". With Austrian, Belgian, Czech, Danish, Dutch, French and Swiss TSOs, this regional project acts by unifying automatic SCR provision, with a process called imbalance netting: Reserves are sized and remunerated separately, but unbalance to be covered is accounted on the whole area.

Studies and projects on each one of the three ASM evolutions described (new actors, new services, new structure) are promising and fast developing, consequently each one of these will introduce new variables in the behavior and possibilities for a unit targeting to provide grid services. The proposal that will be detailed in the rest of this work aims to enter this large and rising field of propositions and suggestions. Therefore, it will deal both with technical aspects related to BESS technology and with the regulation framework in which BESS is located. Since the reference is Italian Electricity Market, this will be the main target for the suggestions and analysis that will come from results.

3.5 BESS for multiple Grid Services provision

As already presented, the scope of this work is providing a study and a tool for assessing possibilities of large-scale BESS (BESS with some MW of nominal power and some MWh of nominal energy) of providing grid services in a regulated Electricity Market framework. Chapter 2 and first part of Chapter 3 have been functional to analyze the available tools for evaluating operating conditions and performance of the battery system and the rules of the framework in which this system should act. As shown, several battery models are available, fitting every kind of battery application. There is a large variety of theoretical basis validating their work and defining issues still present in their utilization. On the other side, Electricity Markets and in particular Ancillary Services Markets (ASM) are not a stable framework of reference for batteries yet. Rules change with time and countries, since products and structure of market are not yet consolidated, as seen, to work with new actors as BESS are. Anyway, drivers for the settling of a steady future situation in which batteries will be totally and maximally involved in services provision are already present. Batteries, in fact, feature some peculiar characteristics definitely suiting and interesting in the field of Ancillary Services. And, vice versa, ASM presents some mechanisms ad hoc for batteries: first among all, the fact of having, generally, null net energy balance over a period [62].

This Section comes as the natural consequence of the previous ones, defining the issues of battery operating in a market and presenting the state of the art of BESS multi-service provision with case studies.

3.5.1 Issues on ASM requirements

As already explained in Section 3.1, ASM has complex structure, many services different from country to country and demanding requirements for admission to participation. This last point is due to the fact ASM is the market dealing with safety and security of grid: faults, errors, low accuracy or lack of regulation in this market imply harsh consequences for the whole electric system. Rules are tailor made on conventional generating units. BESS are really different from those (first of all because they are not generators) therefore there are issues with some of nowadays ASM regulation aspects. Here below, main issues are briefly listed. Some of them have already been mentioned. Once more, principal framework is Italian ASM, but the aspect listed are generally shared by the majority of ASM.

1. Minimum size: most of the ASM accept to participate only units larger than a minimum nominal power (expressed in MW or MVA). In Italy, relevant units for ASM are larger than 10 MVA.
2. Constraints on energy with respect to power offered: some products sold on ASM require that provider must be able to sustain power output offered at least for a certain period of time. For instance, in Italy Secondary Reserve positive power offered must be sustained at least for 15 minutes, while Tertiary Reserve can be provided just by plants able to provide power offered at least for 4 hours per day [57].
3. Negative reserve is withdrawn: while for conventional generators (GT, CC, steam cycles, hydro, except for PHES) the only possibility is injecting power in grid, batteries can both inject and withdraw power. Withdrawn is what happens when they take part in negative Reserves. Conventional generators would have a program from DAM that is modified in various sessions of ASM and Balancing Market (BM): if they would take part in positive Reserve, they will increase their power output with respect to level set by DAM program; in case of negative Reserve provision, they would decrease their power output, staying anyway above zero. The two different behaviors are schematized here below:
   For conventional units:

$$\begin{cases} P_{afterASM} > P_{afterDAM} > 0 \;\; if \;\; in\, Positive\, Reserve \\ P_{afterDAM} > P_{afterASM} > 0 \;\; if \;\; in\, Negative\, Reserve \end{cases} \qquad 3.6$$

For BESS (and generally ESS):

$$\begin{cases} P_{afterASM} > P_{afterDAM} = 0 \;\; if \;\; in\, Positive\, Reserve \\ P_{afterDAM} = 0 > P_{afterASM} \;\; if \;\; in\, Negative\, Reserve \end{cases} \qquad 3.7$$

Two simplifications are done in relation 3.7:

a. A future participation of BESS also in DAM is not considered.
b. ASM is considered the market for every Reserve.

The difference among 3.6 and 3.7 is not leading to any type of change from grid point of view: the relative flow of energy in ASM programs with respect to DAM programs is remaining the same. This represent instead an advantage of batteries, able to perform reverse work. But from regulation point of view, it could require new definitions.

4. Programmability: the ability of being programmed for setpoint following is not an issue but an advantage of batteries, since, as already described, batteries have ramp rates by far higher than conventional units and this lead to high precision in following signals for frequency regulation (see 3.4.1)

To solve the particular issues in entering ASM (Italian framework considered), the parameters of batteries to be managed are:

1. Nominal power: as of now, minimum size for units relevant for ASM in Italy is 10 MVA. But trend towards products of smaller size has already been highlighted speaking about evolution of ASM. Therefore, this could be no issue for the future. For now, the constraint would lead to a BESS that has:

$$P_n > 10\, MW \qquad 3.8$$

That can be obtained with no issues with a large stack of cells. The only problem could be the investment cost for a system this large, due to the fact batteries are modular and imply limited scale economy [91].

2. EPR: energy to power ratio, as already described, is the ratio among nominal energy and nominal power of a battery. This index is linked by constraint of ASM rules with maximum power offered. Max power can be offered for service i is:

$$P_{maxASM,i} = EPR * \frac{P_n}{\Delta t_{min,i}} \qquad 3.9$$

Where Δt_{min} is time of continuous output required for each service. So, minimum EPR, as of now, for Secondary and Tertiary in Italy is:

a. Secondary ($\Delta t_{min,SCR}$ =0.25 h):

$$EPR_{min,SCR} = P_{reg,SCR} * \frac{\Delta t_{min,SCR}}{P_n} = 0.25 * \frac{P_{reg,SCR}}{P_n} \qquad 3.10$$

b. Tertiary ($\Delta t_{min,TCR}$ =4 h):

$$EPR_{min,TCR} = P_{reg,TCR} * \frac{\Delta t_{min,TCR}}{P_n} = 4 * \frac{P_{reg,TCR}}{P_n} \qquad 3.11$$

This allows to size the battery after chosen services and regulating band splitting among them.

This Paragraph showed that most issues related to ASM participation for batteries are matter of sizes. This is because performance of BESS in terms of reliability and speed of response is instead outstanding. The problem of the finite energy content remains. Besides, it arises a problem of investment costs. Multiple services provision can present some solutions to both economic return and energy content issues.

3.5.2 Approaches for multiple services provision

In previous Paragraph, the main questions to be solved when entering ASM with BESS were presented and, where possible, answered. Some problems are still unsolved. For instance, the investment cost for batteries is still too high. Trends towards lower prices are clear, but as of today there are strong doubts on convenience of batteries for stationary uses [92]. Second, SOC management has not been analyzed yet. In case of symmetric service provision, as already mentioned, sizes of regulating bands decrease as much as SOC is far from 50% (see 3.4.2). SOC values evolution would only be related to chances: if in the period, positive reserve has been called more than negative, SOC will be low. Vice versa it will be high. How often it gets to saturation values (100% and 0) only depends on grid situation. Aim of this Paragraph is to better analyze these two issues still present for BESS and try to solve them with the same cure: multiple services provision.

1. SOC restoration via asymmetric services

As described before, in case of symmetric services provision only, SOC evolution is just a matter of grid conditions and requirements. Previous studies from Politecnico di Milano have highlighted negative performance in case of single symmetric service provision. In study [93] from Politecnico di Milano, a BESS providing PCR often gets to SOC saturation limits and therefore cannot provide regulation for a share of 22% of total energy requested. It was necessary, in that case, to implement active strategies of SOC restoration able to take SOC back towards 50%. SOC was restored by overlapping to service provision some energy flows on purpose. Loss of Regulation (LOR) – energy share non-provided over total requested by regulation – astonishingly decreased from 22 to 2.2%, but not at zero cost.

a. C-rate increased due to larger use of battery for SOC restoration.
b. Lifetime decreased consequently.
c. SOC is no more just a provider of services, but also a consumer. This implies that some energy flows are not remunerated but paid and usually further issues on access to grid. In some framework, such as in UK’s EFR (see 3.4.2), this last point is not a drawback, since TSO also forecasts a SOC restoration mechanism accepted within regulation provision.

There is interest in finding a SOC restoration strategy to avoid drawbacks of having energy flows not paid and marginal battery degradation. Asymmetric services can work as SOC restorer. This is an element of originality in this study, since this strategy has been mentioned but not studied at a simulation-level by other studies, to the best of author’s knowledge. In Chapter 4.2 there will be a detailed description of implementation of asymmetric services in the model.

2. Economic return of multiple services

Investment cost of BESS is exponentially decreasing in last years. Main driver for this trend is the astonishing rise of interest towards these devices, led by Electric Mobility diffusion and by Renewable Electric Energy Source (RES-E).

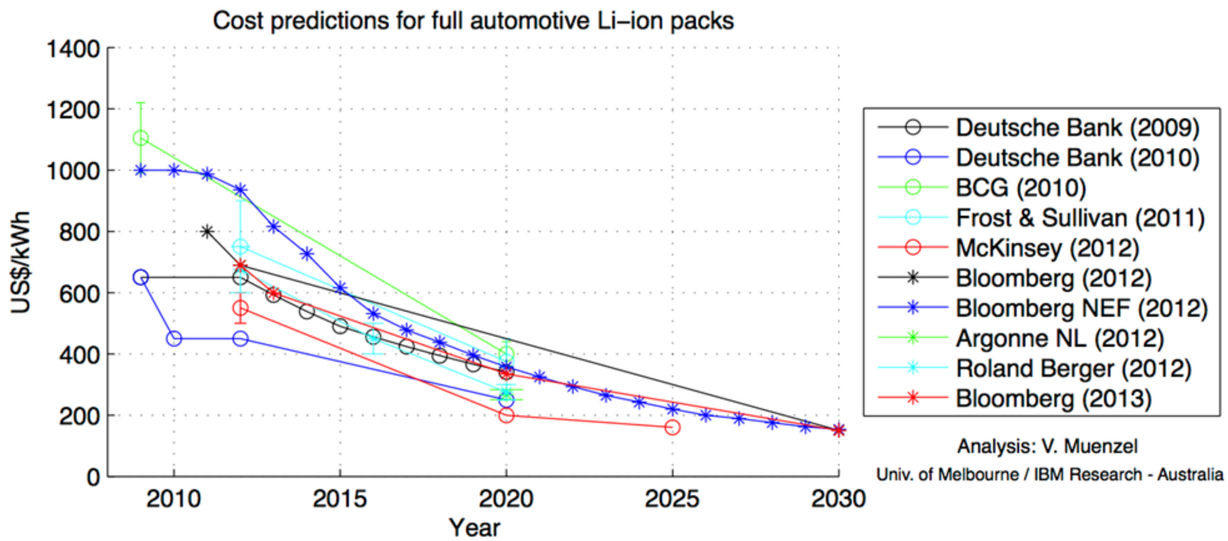


Figure 3-11 Different predictions for Li-ion batteries for automotive cost trends (2015) [115]

The most positive among the predictions talk about a price of 200 k$/MWh in 2020 [94]. Nowadays, a feasible price can be around 300-400 k€/MWh, with an exponential trend of decrease. Even once investors know investment costs, it is impossible for them to say how much multiple services provision can be remunerative before modeling this mechanism. Since investment cost is energy-bound, there is no possibility of linking revenues over a period and cost of investment without knowing precisely the size necessary for a BESS providing services. There are evidences that the investment attractiveness of batteries is still perceived as low, giving rise to call for incentives to foster their use. On the opposite side there are studies on the marginal gain of providing more than one service with the same battery. In this [4], considering German framework, the increase in investment economic viability of combining a Secondary Application (SA) to a Primary Application (PA), only operating while the latter is idle, has been highlighted. Providing SA only when PA is idle, there are no issues in power band splitting and no need for resizing the battery. Profitability Indexes (PI) of these investments (PI indicates ratio among NPV and investment cost) marginally increase among +0.05 and +0.95, passing sometimes from negative value to positive. Anyway, German situation has already been highlighted as one of the most profitable for grid services. And the approach of serving SA only when PA is idle is not always feasible. Qualitatively, the message is clear: combining applications allows to sum revenues and share investment risks. This mechanism can be explained by stating that, if the gain of an application is higher than the cost of battery cycling related to that application, the more equivalent cycles are performed, the more energy is exchanged for performing that application, the higher is the revenue. Filling idle periods with an operation creating positive revenue streams means apparently increasing revenues. Revenue from a cycle is positive if remuneration for that cycle is greater than marginal cost of that cycle. Marginal cost of a cycle in battery equals the cost of battery degradation (cycle ageing) caused by that cycle. In study [95], Authors proposed a detailed method for assessing Marginal Cost of Cycle of a battery. Ageing of each cycle was taken as a whole by considering depth of that cycle ($SOC_{max} - SOC_{min}$). Ageing was attributed only to discharge processes and accordingly multiplied by coefficients to account for all cycle. This was just to deal only with positive power output. Larger depth leads to larger ageing, through a linear or polynomial approximation. A SOC evolution profile over time was taken and divided in cycles using Rainflow Counting Algorithm. Then, for each cycle, ageing and cost of ageing related were computed. Marginal cost of the cycle is a function of Replacement Cost, efficiency of discharge, nominal energy of battery, incremental ageing of cycle. Equation resulted as follows:

$$CostOfCycle = f_1(ageing\ per\ cycle) = \frac{replacement\ cost}{\eta_{dis} * E_n} * f_2(ageing\ per\ cycle) \quad 3.12$$

If remuneration of cycle j is higher than its cost, then it is convenient to perform it. A reliable prediction of replacement costs becomes fundamental.

In [4] end-consumer arbitrage and self-consumption increase were presented as possible PA and coupled with PCR or SCR as SA. This detail opens a new way of use of batteries and of improving economic return of that investment not analyzed yet in this study: grid services provision can be coupled with end-user services. Next Paragraph will try to give an overview of what is already in place or studied.

3.5.3 Grid services and user services

If the battery is already owned by a private owner, the provision of grid services can be added to primary application of that battery to increase economic return. In [4] is highlighted that PI increases marginally by +0.98 in case of adding the service of increasing end-consumer arbitrage to PCR provision, with respect to providing PCR only. End-consumer arbitrage can be explained as the possibility of a consumer of having shaved its peak consumption by using the energy stored during off-peak, and therefore gaining differential prices of electricity. This can be made by large consumers (industrial or commercial) that have contracts with hourly pricing. As previously mentioned, in [4] the framework is Germany and SA (PCR and SCR) are taken as services to provide just when PA is idle. This do not take in account of ASM framework. But qualitatively, it indicates the possibility of reducing investment costs by using a BESS already in place for end-consumer purposes.

On the other side, maybe the most diffused private-owner large-scale application for BESS is the Uninterruptible Power Supply (UPS). For large or strategic industrial users, who have large losses by each interruption of their production or service, a UPS guarantees continuity of electricity provision over a certain time-period in case of fault in electric network. This service is defined as electric service reliability.

For assessing indicative values for batteries' owner of these end-consumer services, two main sources can be used: a report by SANDIA [96] and a paper by EPRI [97] both from 2010. They are only taken as indications, since they suffer of three main limitations: they are from 2010, with cost and benefits not scaled to outstanding development of last 8 years, they depict US situation, they are assessing general cases of batteries performing single service, they are not taking in account capacity limits of battery (no EPR of battery defined, numbers given as nominal power-based).

1. End-consumer arbitrage: lifetime Present Value is 395 k€/MW.
2. Electric service reliability: lifetime Present Value is 360 k€/MW, largely depending on type of user.

By hypothesizing an EPR of 2 and the investment cost previously defined as today's average (400 k€/MWh), one of these two services could lead to pay-back half of the investment in battery lifetime. There must be an assessment of whether an end-consumer service can be put in place with maintaining also grid services or not.

Italian studies for assessing economic return of a UPS also participating in TCR have been carried out [98]. It has been shown how a Lead-Acid BESS serving as UPS in a base transceiver station (BTS) can have PBT from 4 to 7 years depending of different policies of remuneration, in case of EPR = 2 and serving 0.42 per unit of regulating band for TCR. On the other side, PBT is around 8.5 years for a Li-ion BESS used as UPS in a data center while providing TCR. Lifetime of batteries in these applications is around 10-11 years.

Summarizing, even if it is very difficult to give values to end-user services, the real issue is defining if the coexistence of grid services and end-user services is possible in same BESS. There is still a lack of deep studies in this field. Anyway, provision of multiple services can certainly pass from private owners deciding to enter the market with their residual capacity.

3.5.4 Case study: Italian TSO's projects

Projects of BESS providing multiple grid services are not widespread yet. As of now, interest in battery industry and commercial field is focused on portable application as EV batteries or in residential applications to increase self-consumption or to provide off-grid solutions. In Italy some large-scale BESS projects for stationary application on grid have been present since 2015. Terna, Italian TSO, put in place three large-scale BESS in three sites to provide energy-intensive services (services in which the requirement on capacity overtake by magnitude the requirement on power) and two lab-scale projects power-intensive, where performances of different batteries from different technologies and firms is tested and compared. In this Paragraph the "Large-scale energy-intensive" project [71] will be described by technologic and operating point of view.

The interest towards "Large-scale energy-intensive" project arises due to Italian topologically heterogeneous RES penetration and due to network constraints present in some areas of the country. TSO has highlighted that some areas in the territory of Italy can be defined "critical areas" from network security point of view. These areas are the ones where the ratio of DG capacity over total loads is high:

$$k_{critical} = \frac{P_{DG}[MW]}{P_{loads}[MW]} \qquad 3.13$$

This situation is likely happening in rural areas with low population or industrial activities density, but large presence of wind generators. In these areas network is usually not ramified, but only present with main branches working as bridge across underpopulated regions. When DG presence in that area increases, main lines are solicited for transporting power produced by DG towards the larger urban centers far away from production site. In case of extremely low load in the area of production (at night, during holidays) and of large generation by DG, network constraints on maximum power over transmission lines are easily overpassed. This phenomenon is called local congestion. In this case, in absence of programmable plants available for decreasing their power output, the only choice is curtailment of wind power. Generators are simply disconnected from grid and mechanically braked, in order to get back below threshold on lines. In 2014 it led to 17.6 GWh of wind power curtailment.

The action of BESS is substituting network reinforcement. Local congestions highlight limits in the network in local area. New lines or reinforcement of existing lines would be necessary to face the larger presence of generators in critical areas. Since it would be costly, it would require time and effort, it would imply problems to grid during reinforcement work, BESS is now studied to define if it is a viable alternative. BESS is set up in a network node or close to a node, in order to act on multiple lines. Action of BESS in mitigation of wind production curtailment (in Italian it is called *mitigazione Mancata Produzione Eolica* or *mitigazione MPE*) is controlled remotely (in this case directly by TSO) and is implemented as follows:

1. When a local congestion (MV line constraints on maximum power flow overpassed) is forecasted in next hours on one of the lines feeding the BESS node, a signal (S1) is sent from the tele-control station to battery controller. It starts discharging at nominal power towards a SOC-objective value: usually zero. Meanwhile, provision of other grid services is suspended (with exceptions). When objective SOC is reached, battery stays idle.
2. When local congestion begins, battery receives another signal (S2) and starts charging up at nominal power, up to when congestion ends or when battery reaches SOC = 100%.
3. When congestion is ended, battery receives a third signal (S3) and get back to normal operation, restarting provision of other services until next S1 is sent.

As mentioned before, three BESS have been put on field for provision of this service, all insisting in the same critical area: it is a rural area in the province of Benevento, Campania region, in the peninsular south of Italy. These three BESSs are called Flumeri, Ginestra and Scampitella SANC. SANC is *Sistema di Accumulo Non Convenzionale*: unconventional energy storage system. They are unconventional storage for power network, since Italy largely use Pumped-hydro energy storage (PHES), but until this project no BESS. Also technology used is unconventional among BESS, since it implies NAS batteries: sodium-sulfur battery technology is a technology only feasible for stationary application. It is a high-operating temperature (>300°C) technology and it needs heating system to be always on to avoid solidification of sodium and sulfur present in electrodes as molten [99]. This is an issue for portable installations, due to high mass of the system, and intermittent operations, due to auxiliaries' consumption always on for heating.

Sizing of the three battery is almost the same.

1. Flumeri and Ginestra BESS feature:
    a. Nominal power of 12 MW;
    b. Nominal energy of 80 MWh;
    c. EPR of 6.7 h.
2. Scampitella BESS features:
    a. Nominal power of 10.8 MW;
    b. Nominal energy of 72 MWh;
    c. EPR of 6.7.

The difference is due to the fact Flumeri and Ginestra are made up by 10 batteries and Scampitella by 9, all featuring 1.2 MW of nominal power.

As already stated, the main issues of NAS technology is operating temperature. Since the battery needs always power for auxiliaries, the interest is towards permanent operation and permanent cycling: time-periods idle are a pure loss from energy and economic point of view. This would decrease the Cost of Cycle as defined in Paragraph 3.5.2, since the cost of staying idle is not zero.

Therefore, there is a major interest in multiple services provision. Terna defined a list of services given and a list of priorities for this project.

1. MPE mitigation: is the service with priority. But it is intermittent, as before stated. Battery operation can be divided in two main periods: when a local congestion is in the forecast or is acting, activation signals by remote control stop the normal operation and enter in emergency operation state. In this state, MPE mitigation is performed, as described before, with the system of signals S1, S2, S3.

2. Primary Control Regulation (PCR): this service is performed always when battery is on. It does not receive the stop signal while entering emergency operation. Anyway, it does not affect the prioritized service, since it does not involve large regulating band. Regulating band is not fixed by droop control law followed (see Figure 3-12), but power dedicated to PCR is most of the time less than 10% of nominal power. Fixed droop value used is 2%, half of the value imposed to hydro plants: this allows enhanced-response with respect to PCR provided by conventional units.

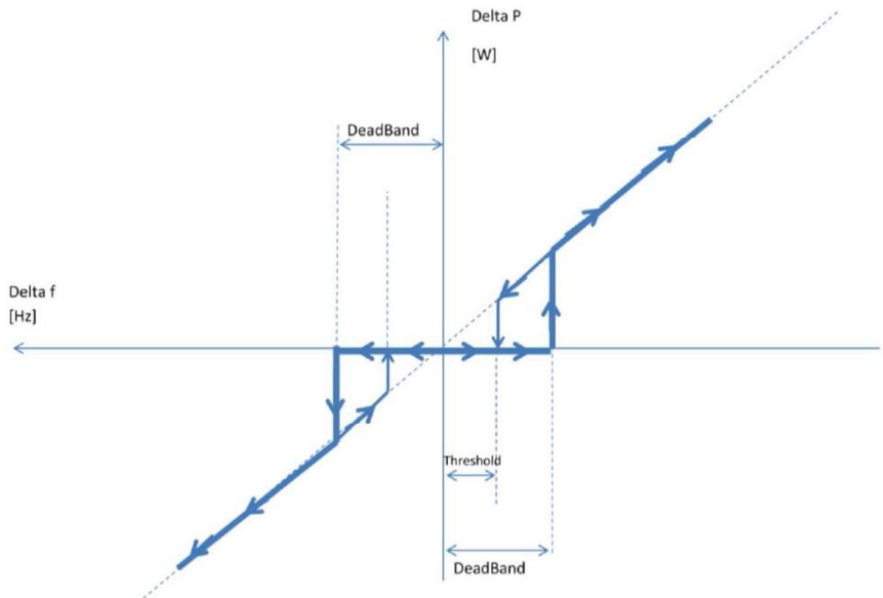


Figure 3-12 Droop control curve for PCR in Terna's project

3. Secondary Control Regulation (SCR): this service is performed only during normal operation, setting automatically to idle when emergency state is on. Regulating band is 20 or 100%, following inputs by tele-control. This service is not entering the market in MSD, but it is just expressed by receiving and following regulation level sent by TSO (Segnale di Livello). It includes a manual SOC restoration system, acting in case SOC goes close to saturation limits.

4. Tertiary Control Regulation (TCR): it has been predisposed, but never put in place until this step of the project.

The need for increasing number of services comes from need of increasing number of equivalent cycles to decrease share of auxiliaries' consumption on total energy exchanged. A minimum threshold of 150 cycles per year has been declared as feasible. In 2016, this threshold was just respected by Scampitella BESS: 156 equivalent cycles. Ginestra cycled instead 137 and Flumeri 129 equivalent cycles, as stated by Terna 2016 Report on project.

This project introduced a step forward with respect to study [4], already described in Paragraph 3.5.3: multiple services provision forecasts here the possibility of providing services simultaneously. This is even more an advantage for this technology due to auxiliaries' issue.

Terna's projects on BESS for grid services also put on field two "Storage Labs" where installing and comparing utility-scale BESS of different firms and technologies. These two labs have been installed in the islands: in Ciminna (Sicily) and Codrongianos (Sardinia). The islands are particularly sensible fields of Italian power network: since inertia of these network is historically lower (due to lower magnitude of synchronous area interconnected), constraints on, for instance, PCR are much larger than on the continent. Here every relevant unit connected to grid must provide permanently and mandatorily ±10% of nominal power for Primary positive and negative Reserves. Therefore, interest for studying and putting in place solutions power-intensive, able to fast-respond to issues in power grid, arises. In these two labs, test on standard operation cycles and on batteries' ageing are performed.

These two projects define an interest in Italy towards BESS' services provision. Results of these projects by technical and economic point of view could define a line of action for future changes in BESS market and Italian ASM. On this possibility, the study that follows will concentrate on Italian ASM framework and on its possible change in next future in order to integrate and have benefits from BESS participation to network control and security. Further analysis on the results of the energy-intensive project will be presented in Appendix A.

4 Proposed methodology

As already described, this study aims to discover how a BESS can play in an ASM as a provider of multiple grid services. The scope is simulating the activity of a BESS providing simultaneously more services in the framework of an Ancillary Services Market: Multi-service.

Multi-service is aimed to provide both SOC restoration and increased economic return with respect to single service provision. SOC restoration can be done by exploiting in a reasonable manner the different regulating bands offered on market in Asymmetric services. Since on MSD (Italian ASM) asymmetric services are not implemented, part of this study will be targeted to Italian TSO and market manager, to suggest some modifications to electricity market. Multiple services provision will be called for the rest of this study Multi-service.

Battery operation will be studied by point of view of its operating parameters. To do this, a model of a BESS and of its connection with the grid will be used. The model includes an electric and an empirical model for SOC estimation.

Main framework of the study is Italian ASM (Mercato dei Servizi di Dispacciamento, MSD). The importance of choosing the framework is the fact that ASMs over the world can significantly change. Even if the bases of network control and management are the same, different operating settings lead to slightly different needs and tolerances while defining ASM structure and services. This leads, on field, to different limitations to the markets, to different time-horizons of services and different types of payment and price signals. Services have been chosen and designed by respecting the products present in MSD market. BESS model has been chosen after an analysis of all possibilities which has been explained before in Chapter 2. Originality of this study is the approach to multiple services used: multiple service can be an effective way of managing SOC and increase economic return. The core of next Chapter will be the definition of the strategy used for implementing Multi-service, with the analysis of choice of all battery parameters.

This Chapter will present in detail what procedure has been followed and what tools have been used to reach the Results of Chapter 5. Topics described in this Chapter are listed here below.

1. The analysis of the models selected for this study is presented in Section 4.1. It will include the comparison among the electric and empirical cell models, highlighting advantages and limits of each one. The electric model is a passive impedance-based model. The empirical model is a cell model approximating efficiency of the system with a polynomial function. The whole BESS system includes also inverter and controller models. The indexes used to analyze the performance of the regulation are explained.
2. The analysis of the grid services modeled is presented in Section 4.2. The work starts from analysis of BESS performing PCR only provision. It has been already analyzed in Politecnico di Milano by [93]. It was analyzed both with and without dedicated SOC restoration strategies. In this study is taken as reference case, only without SOC restoration strategies.
3. The limits shown by PCR provision without SOC restoration in terms of both performance and economic return suggested to try provision of multiple services. Therefore, a group of rules to be used when implementing a new service are analyzed. A multi-service modeling tool is presented in Section 4.3.
4. The new service implemented following the scheme of the multi-service tool is SCR. SCR and PCR simultaneous provision as requested in Italian framework is explained in Paragraph 4.3.1.2. SCR is provided as requested by Italian ASM: it is a symmetric service traded on ASM with 4-

hours market sessions. Regulating band management for SCR is here presented. The aim is offering the larger bands possible to avoid hitting of SOC saturation levels within market period.

5. Asymmetric bands for SCR provision are introduced in Paragraph 4.3.1.3. The new regulating band selection criterion is explained. Asymmetric bands are a possible improvement to ASM for better integrating new actors such as BESS and aggregators. They allow a more effective management of bands and possibly higher economic return and safer SOC management.

The process used for the simulations is the one depicted in Figure 4-1.

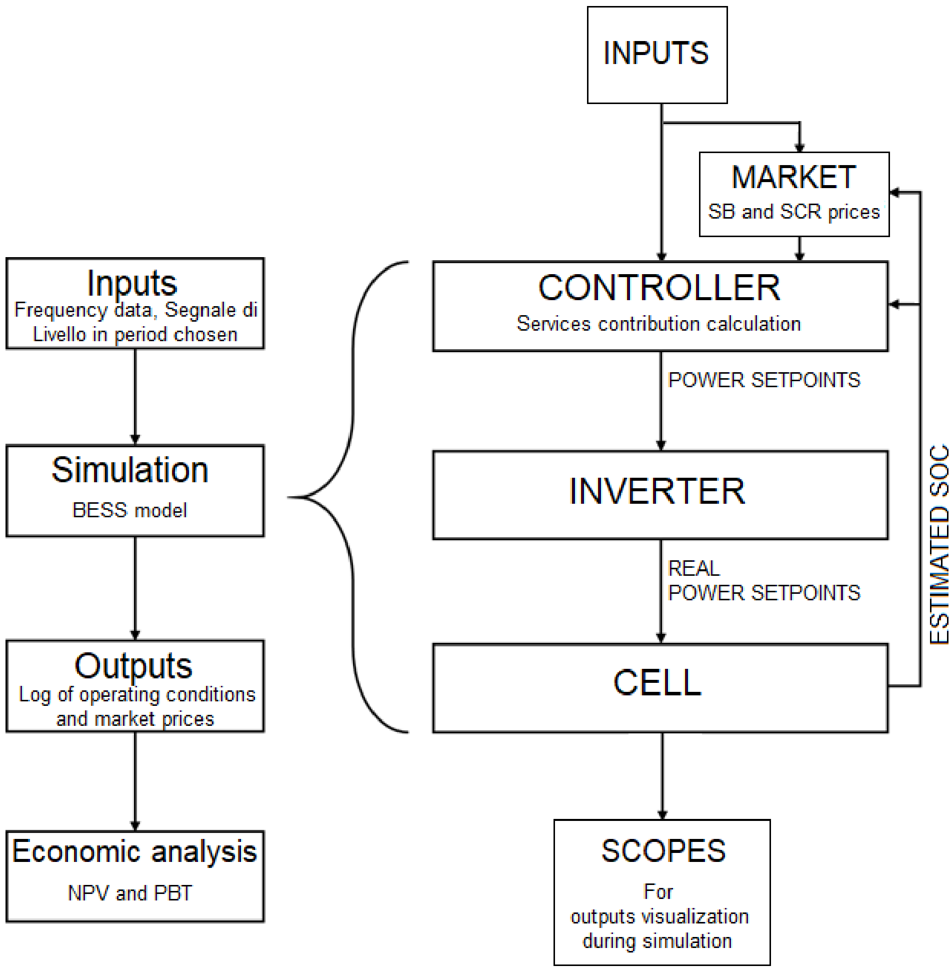


Figure 4-1 Process chart for services provision simulation and analysis

A series of Inputs, including all regulating signals for grid services provision and all market prices for computing revenues are fed to BESS model. Simulation starts. In the model, Controller uses Inputs to compute the setpoints requested to cell from grid side at each loop of the simulation. Inverter converts them to power actually requested to cell (by applying its efficiency). Cell takes as input power setpoints required and returns the update of its operating conditions (SOC, V) and real power flow. Scopes allow runtime visualization of outputs. Outputs are logged during simulation and then saved to file once simulation is done. Using a tool developed on spreadsheet, Economic Analysis is performed by using Outputs of simulation. Results are then elaborated and they will be presented in this work in Chapter 5.

All process was developed during the work for this study. Inverter and Cell model were taken as they were, analyzed and where necessary validated. The work consisted mainly of developing the system around that core. The environment used is MATLAB® Simulink®.

Inputs must be given to model before simulation. These include regulating signals and prices. For PCR, frequency log in the simulation period is necessary. Frequency log taken was directly measured in Politecnico di Milano in the framework of IoT-Storage Lab in the period 15 February-19 March 2017 without interruptions. PCR provision uses a control law linking each frequency variation from nominal value to the power output required as share of regulating band. For SCR, Italian TSO provides a regulating signal (Segnale di Livello [100]) that can be downloaded for the period of interest from TSO website. The regulating signal for SCR is common to all Italian peninsula and updated each minute. It contains the share of regulating band, negative or positive Reserve, requested each minute to every unit selected for the provision. Other data are market prices data for SCR, downloaded from market manager website for the period of interest [101]. Inputs include also battery data: EPR must be given as input as well as regulating band for each service. In case of PCR, band is constant throughout the simulation. In case of SCR, regulating band is variable and the value given as input represents the maximum value.

The analysis starts from BESS model. Specifically, from the two cell models chosen, in which type of cell is fixed and size of the battery can be modified. By collecting real network data as a basis to calculate services, the scope is find how a battery could work in terms of precision of regulation and economic return.

4.1 The BESS model

BESS model is implemented in a Simulink® tool. The system modeled includes:

1. Controller of the BESS, that receives as input state of the cell and returns as output power setpoints requested grid side to comply with services provision.
2. Inverter, introducing an efficiency on AC/DC interface among grid and battery.
3. Cell, the core of the process, receiving as input power requested battery side and returning State of Charge, Voltage and power output. It implements a BMS allowing its preservation.
4. Scopes to record results of simulations.

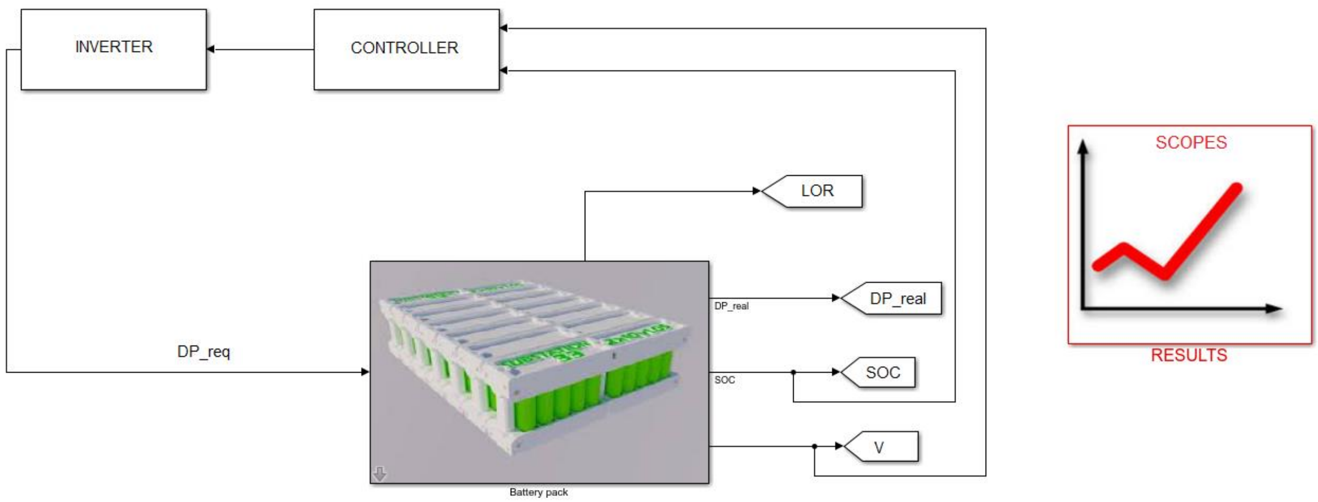


Figure 4-2 View of the electric model on Simulink desktop

The tool called BESS4PCR is a Simulink model including a cell electric model for SOC estimation, already proven as good for approximating grid service provision by the Author in [2], a cell empirical model for SOC estimation, an empirical model for SOH estimation, describing in particular capacity-fade due to cycle ageing. The battery modeled is Swing® 5300 by Boston-Power. On it, an experimental campaign has been performed. Decision to start from an electric model have been taken after analysis of all the possibilities. The literature review providing the theoretical basis for this choice has been detailed in Chapter 2. This kind of model guarantees a high accuracy and medium computational effort. Given the large amount of combinations of services, regulation bands division, battery sizing that can be studied while dealing with grid services provision, an even faster model would be appreciated. The validation of the empirical model for SOC estimation mentioned before is performed in this study. The model is presented in next Paragraph, after having explained in detail the electric one.

Electric cell model, as explained by Author in [2], has been first developed for BESS providing only Primary Control Regulation (PCR). Among the aims of this work there is implementing in the model other grid services (SCR in particular) and checking feasibility and economic convenience of the multiple provision. Implementation will take place in the Controller of the model, that has been developed from scratch in the context of this work. Its duties are the management of the inputs, their conversion in setpoints indicating the share of regulating band requested, the management of the regulating band offered for each service and the simulation of the Market. The output of the Controller is the power setpoint in per unit requested to battery from grid side. It is the input fed to Inverter.

This Section is dedicated to the detailed description of the whole process proposed. Starting from choice and selection of inputs. By inverting the logic order, model will be analyzed starting by cell since it is the core of the simulation process and requires choices. Accuracy level and computational effort depends in large majority on the cell, therefore it influences precision in results, simulation speed and time. A greater accuracy in study can be a drawback in a sizing study like this: the possibility of performing higher number of simulations in the same time is instead highly valuable. Thus, a part of the study has been dedicated to the validation of empirical model for SOC estimation to substitute the original electric one.

4.1.1 Inputs

Model requires as inputs:

1. Energy to Power Ratio (EPR) for battery, defined as the ratio among nominal energy and nominal power.
2. Saturation levels for SOC: SOC_{min} and SOC_{max}, Default values are 0 and 100%. These are the thresholds for empirical cell model. Thresholds for electric models are instead in terms of voltage and are already implemented in the model. Voltage thresholds cannot be modified since they come from experimental campaign on Swing® 5300. They indicate the SOA of the cell with a minimum and a maximum voltage limit.
3. One array at sampling-rate of 1 Hz for each service. It can contain directly the power setpoints for the whole simulation period or the signal from TSO or other operator giving information for computing in runtime the power setpoints.

4.1.2 SOC estimation: electric Model of cell

The electric model chosen is part of MATLAB® Simulink® tool named BESS4PCR [2] developed in Politecnico di Milano. This name is due to the fact the model was initially proposed for Primary Control Regulation application. Electric model is impedance-based. It holds a series of equivalent impedances able to represent main phenomena inside a li-ion cell of a battery. It is based on the real battery Swing® 5300 by Boston-Power. It is a passive impedance-based electric model (see 2.4.1.2) featuring:

1. $R_{EL} = R_{\Omega}$ for ohmic resistance in cables.
2. A series of impedances to model double layer behavior and charge transfer resistance in electrodes.
3. An impedance Z_D to model charge carriers' diffusion inside electrodes.

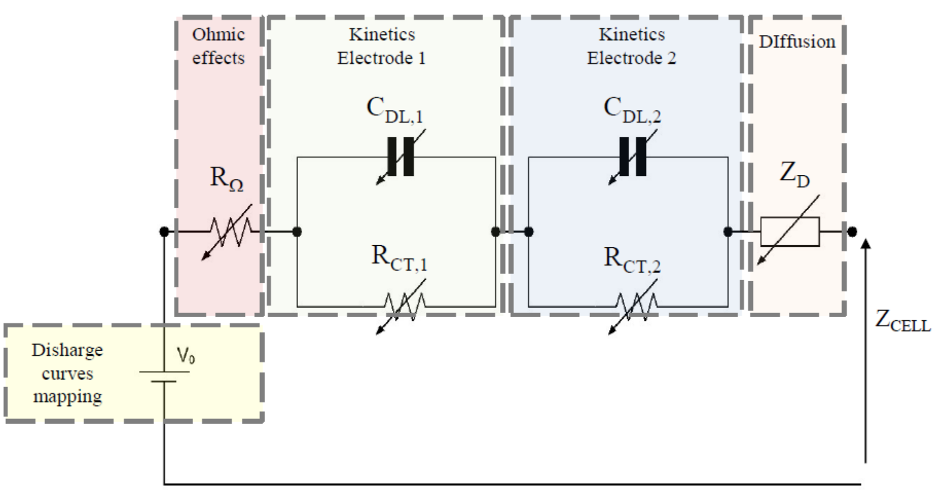


Figure 4-3 Electric model of cell used [2]

As described in 2.4.1.2, electric models approximate cell charge and discharge processes by defining an equivalent electric circuit. Their performances in terms of accuracy and computational effort should be an average value among electrochemical and analytical models.

Then, the battery is constituted as a stack of identical cells modeled as just described, connected in series or parallel to get desired voltage, energy/capacity and power. No modular basis (a unit with a specific ratio among nominal energy and power and a specific voltage at terminals) has been defined for this cell model, so every configuration of terminal voltage and capacity is available. The cell model takes as inputs the active power setpoints in per unit required each moment to BESS, after they have passed Inverter model. Inverter model allows conversion of power setpoints from power requested grid side to power that must be provided from cell. Inverter has in fact its own efficiency (as a function of power converted). Cell has a simple BMS (Battery Management System): it avoids cell to overpass maximum and minimum saturation limits on voltage, by limiting the power output if needed. In these cases, real power output is different from power requested to cell, with an absolute value in the interval among 0 and $P_{requested}$. The cell model gives as outputs:

1. Voltage at cell's terminals.
2. SOC of cell, estimated as a function of OCV.
3. Real active power output of cell.

By working at cell level, BMS can be simplified, since it does not include balancing and equalization of different cells present in the stack. This means every hypothetical cell is considered to work exactly in the same way, undergoing same SOC and voltage variations, having same efficiencies and same power outputs. This is a simplification fitting the aims of the study: this study is a sizing and a system study, not a design study for improving the cell.

Power of each cell is given by:

$$P_{cell} = \frac{C_{n,cell} * V_{n,cell} * \Delta\dot{P}}{EPR} \quad 4.1$$

Where $C_{n,cell}$ is the capacity of cell, $V_{n,cell}$ is the nominal voltage of cell and EPR is the Energy to Power Ratio:

$$EPR = \frac{E_n}{P_n} \quad 4.2$$

EPR must be given as input by user and it is an arbitrary choice. Each cell is assumed as a scaled representation of battery stack: this means EPR of the battery (given by data, user's choice) is the same of the one of the single cell. The product among capacity and nominal voltage gives exactly nominal energy. By dividing it by EPR, nominal power of cell is obtained. By multiplying it for the setpoint required in per unit, power requested to cell is found. It is linked by a constant to power requested to the whole battery. Given this assumption, from now on every term will be referred directly to battery instead of cell. EPR must be given as input to model. Model reacts by scaling power setpoints by itself on the correct c-rate. So, model will accept inputs in per unit, but it will give outputs based on c-rate. The integration in time of active power setpoints gives the energy requested to battery:

$$E_{req} = \int_{t=start}^{t=end} \Delta\dot{P} \, P_n \, dt \quad 4.3$$

As said, a simple BMS aims at preserving battery from overpassing saturation limits on voltages (remaining within SOA, see Chapter 2). When this event occurs, power output of battery can be lower in absolute value with respect to power requested, up to null output. In these cases, we have energy non-provided. The whole amount of energy requested to battery while V is outside saturation limits is considered as energy non-provided, even if curtailment is not total:

$$E_{np} = \int_{t=start}^{t=end} \dot{\Delta P}\ P_n\ dt \bigg|_{(V < V_{min})\ V\ (V > V_{max})} \quad 4.4$$

The index of Loss of Regulation (LOR) will be used to describe the ratio among the energy non-provided and the total energy requested to battery:

$$LOR\ [\%] = \frac{E_{np}}{E_{req}} \quad 4.5$$

Or we can compute performed service as real energy exchanged:

$$E_{real} = E_{req} - E_{np} \quad 4.6$$

LOR is one of the key parameters in the study: the aim is to minimize it since it will be linked to a penalty [€/MWh] and it will directly act on economic return. When entering the field of Multi-service LOR will be accounted to a service (it can happen that penalty for each service's loss of regulation is different). In cases with LOR different from zero, real power required to cell is different from power after inverter block. Real power is computed by cell model and it is the power used for SOC update. SOC is seen by external viewer as a function of OCV, computed internally by cell model (it is the voltage obtained at the terminals of capacitor, shown as V_0 in Figure 4-3).

4.1.3 A faster model: empirical Model of cell

The large majority of studies on BESS use analytical models (see 2.4.1.3). In particular, empirical models have proven their reliability even with their low computational effort. They do not relate on physics of the cell but just build equations approximating behavior of operating conditions as shown by a specific battery during experimental campaign. They work on the steady state of cell: many operating points have been tested by requesting a steady power output to cell and by measuring and recording operating conditions (efficiency, voltage, current, OCV, etc.) related to that working point. The model used is fitted on the same Swing® 5300 analyzed in electric model. It models efficiency of cell as a function of power requested. The model works by receiving each time-step the power requested to cell (the power expected as output battery side, built by Controller and passed through Inverter efficiency), computing the cell efficiency (η_{CH} and η_{DISCH}, as constants or functions of c-rate) and defining the real power in per unit to be requested to cell. $\Delta\dot{P}^0_{real}$ is then the real power that should flow in cell:

$$\Delta\dot{P}^0_{real} = \begin{cases} \Delta\dot{P}^0\ \eta_{CH}, & \dot{\Delta P} < 0 \\ \Delta\dot{P}^0\ /\ \eta_{DISCH}, & \dot{\Delta P} \geq 0 \end{cases} \quad 4.7$$

And $\Delta\dot{P}_{real}$ is the power that actually flows in cell, after verifying feasibility with SOC saturation limits:

$$\Delta\dot{P}_{real} = \begin{cases} \Delta\dot{P}^0_{real}, & if\ SOC_{min} < SOC(t) < SOC_{max} \\ 0, & if\ SOC(t) < SOC_{min}\ or\ SOC(t) > SOC_{max} \end{cases} \quad 4.8$$

Given the real active power flowing in battery, SOC is updated each time step as follows (no more relation with OCV but integration of infinitesimal power delivered or absorbed each loop):

$$\Delta SOC = \frac{\int_t^{t+1} \Delta \dot{P_{real}}\, P_n \; dt}{E_n} = \frac{\int_t^{t+1} \Delta \dot{P_{real}} \; dt}{EPR} \qquad 4.9$$

This approach is accurate in most of cases and characterized by low computational weight: quick simulation.

The limit of this approach, as already described, is the difficulty in simulating conditions at saturation. Since the model does not deal with voltages, there is no way to model the SOA on voltages. This model cannot recreate the conditions corresponding to SOC very high and very low, in which a partial power curtailment could be necessary in order not to overpass voltage limits (see Figure 2-4, Figure 2-5). Instead, this kind of model is only able to work as on-off controller: power given is exactly power requested (on) if $SOC_{min} < SOC(t) < SOC_{max}$, or power given is 0 (off) if $SOC(t) < SOC_{min}$ or $SOC(t) > SOC_{max}$. The equation for getting to energy non-provided and then to LOR is same as 4.4, but with different limits since there are not voltages but SOC as limits:

$$E_{np} = \int_{t=start}^{t=end} \Delta \dot{P}\, P_n \; dt \bigg|_{(SoC<SoC_{min})\, V\, (SoC>SoC_{max})} \qquad 4.10$$

The inaccuracy of empirical models can increase its impact when working at:

1. High c-rates.
2. With long periods close to saturation limits.

It will be one of the aims of following study to validate empirical models with the kind of simulations and battery managements utilized.

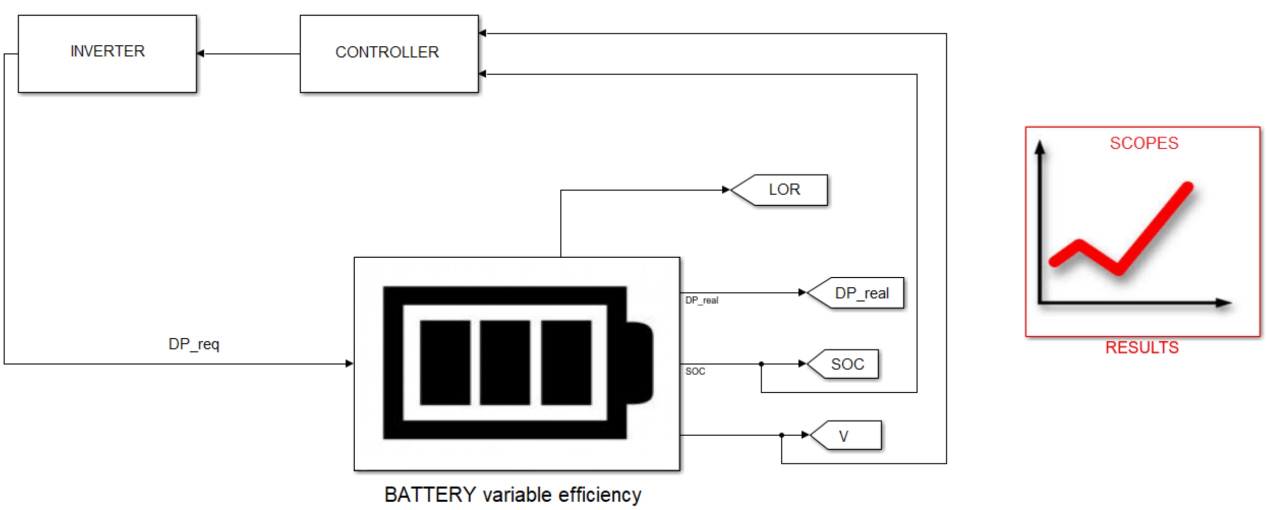


Figure 4-4 View of empirical model on Simulink desktop

As can be seen in Figure 4-4, the model is the same explained before, just with different cell block.

Cell model receives the same input of the electrical one, represented by power setpoint requested battery side. At each power is associated an efficiency, computed using a polynomial of degree 3 that approximate efficiency values of Swing® 5300:

$$\eta_{cell\ emp\ roundtrip} = 1 - 0.1397\ \Delta\dot{P}_{req} + 0.0314\ \Delta\dot{P}_{req}^2 - 0.0038\ \Delta\dot{P}_{req}^3 \qquad 4.11$$

$$\eta_{cell\ emp} = \sqrt{\eta_{cell\ emp\ roundtrip}} \qquad 4.12$$

Power requested is multiplied or divided by efficiency to find actual power output as in 4.7 ($\eta_{cell\ emp}$ is in that equation defined as η_{CH} or η_{DISCH}, depending if battery is undergoing charging or discharging process). Therefore, efficiency is variable as a function of power input (actually expressed as c-rate). Equation 4.9 for SOC update can be rewritten as:

$$\Delta SOC(t)\ [\%] = \frac{\Delta\dot{P}_{real}(t)}{3600} * \frac{100}{EPR} \qquad 4.13$$

Where 3600 is needed to convert from MW to MWh. Update of SOC is performed every second, following sampling-rate of inputs. And SOC is updated as follows:

$$\begin{cases} SOC(t) = SOC(t-1) + \Delta SOC(t) \quad if \quad SOC_{min} \leq SOC(t-1) + \Delta SOC(t) \leq SOC_{max} \\ SOC(t) = SOC(t-1) \quad elsewhere \end{cases} \qquad 4.14$$

In latter case, there is LOR (LOR(t) > 0).

Validation of this empirical model of cell for SOC estimation will be among the aims of this study. The rest of the model, described from now on, is the same for each of the two cell models. From now on, the description of blocks of the model will be in logical order: from Controller to Inverter. Cell is the closing of the loop, since updated values are then sent as inputs once more to Controller for the following loop<.

4.1.4 The Controller: power setpoints creation

As already said, a setpoint of active power must be fed at each cycle of simulation. Model requires power setpoints in per unit. It is able, as already mentioned, to deal with batteries with EPR different from 1 by scaling during simulation the setpoints to get to c-rates.

The battery modeled is aimed to provide grid services. So, the resulting power setpoint will be the sum of the single power setpoint required for each service. Every service has a periodical market. Market sessions can be every *n* hours, every week or on longer periods. If market period is shorter than one month, band offered must be updated during the 30-days simulation, once each market session. This is the case of SCR, that requires complex management of offers.

This complex strategy is not just something negative: the control strategy can be tailor made on contingent condition of battery (on SOC mainly) to use the grid service for providing restoration of optimal conditions (far from saturation limits). For instance, if SOC is closer to the upper saturation limit, services for discharging the battery will be offered at a more convenient price on the market, to be more likely accepted, and with larger regulating band, to discharge faster.

The strategy for deciding the power setpoint of each service will be defined from Section 4.2. In Paragraph 4.3, a complete procedure for getting from Inputs to power setpoints battery side will be implemented in the Controller to create functional blocks to be used as basis for each grid service added.

4.1.5 The Inverter: from grid side requirements to cell

After the setpoint for each loop is completed, it undergoes Inverter step. Inverter links battery (DC side) to grid (AC side). It is simply modelled as a first order low-pass filter, whose:

1. Gain is computed with a lookup table representing efficiency of inverter as a function of power in per unit. At each power requested by grid, the gain is 1/efficiency (if power must be injected in grid) or 1 $*$ efficiency (if power must be withdrawn from grid).
2. Time constant is 40ms.

Inverter equation:

$$Gain * \frac{1}{\tau \cdot s + 1} \qquad 4.15$$

Inverter is just an element of non-ideality in the study. The conversion from AC to DC and vice versa is just considered by energetic point of view as a loss. Therefore, inverter always at the interface among controller and cell: controller computes the requirements for services grid side, inverter defines losses of the system and update setpoints that are given as input to cell. Cell model then considers inputs (c-rate requested) and operating conditions (SOC and V) to define update of SOC conditions and real power flowing.

4.1.6 SOH estimation

The model up to now described does not take in account of any type of ageing. Therefore, during the simulation, nominal capacity is a constant. This is feasible an does not introduce a large error since the simulation period is short with respect to battery life. The decay of capacity in one month can be defined negligible. Lifetime computations are performed after simulation, to give life expectancy for the system and to introduce in economic simulation replacement costs. Decay in batteries, as described in previous Chapter, is both in terms of capacity-fade and power/efficiency-fade. In this study, only capacity degradation is modeled.

As described in 2.2, degradation of batteries is composed by two main ageing mechanisms:

1. Cycle ageing, describing utilization periods (function of utilization time) and depending on operating conditions such as c-rates, SOC, temperature variations due to operation.
2. Calendar ageing, describing total storage period (function of total time from beginning of life) and depending ambient temperature and SOC level during storage (during "rest").

Since in the study that will be proposed:

1. Average c-rates are low due to high energy requirements from grid services provision, that will cause choice of EPR values higher than 1.
2. There is no interest in maintaining SOC too close to saturation limits for long periods. Oppositely, the aim will be finding a strategy to have continuous exchange of energy and automatic systems for SOC restoration through service provision itself.
3. Temperature values of stationary operation can be considered constant or with limited variation to preserve battery life.

Cycle ageing should not be extremely heavy. Therefore, a simple empirical model can be enough to define cycle average decay in capacity. If cycling was more stressing, an improved model to take in account of cycle ageing would have preserved from major errors. Calendar ageing can be found in datasheets or in common studies on Li-ion batteries kept at ambient temperature, since it is not linked to operation.

Experimental campaign led to this diagram for cycling capacity decay on the Swing® 5300 [2] (an analytical SOH estimation model based on statistical data, see Paragraph 2.4.2), using as stress factor only average c-rate of whole period:

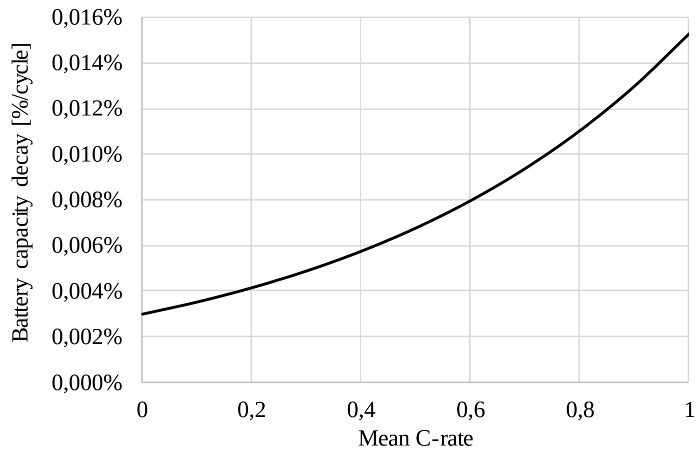


Figure 4-5 Battery capacity decay as function of mean C-rate

Once simulation is done, data are used as follow to define cycle lifetime:

1. Mean c-rate is computed:

$$c - rate_{mean} = \frac{E_{gross}}{EPR * P_n * \Delta t[h]} \quad 4.16$$

2. Since in this study, the only ageing modeled is capacity fade, lifetime is defined as the moment in which capacity becomes 80% of initial one, or at State of Health (SOH) of 80%. Since the information about decay is given in decay per cycle, it is a function of maximum cycles number to get to 80% of capacity and of equivalent cycles performed in a period (e.g. one month). By extracting from diagram shown in Figure 4-5 the *capacity decay per cycle* and transforming it from a percentage to an absolute value:

$$cycles_{max} = \frac{(1 - 0.8)}{capacity\ decay\ per\ cycle} \quad 4.17$$

$$lifetime_{cycle\ ageing} = \frac{cycles_{max}}{equivalent\ cycles_{monthly}} \quad 4.18$$

For modelling calendar ageing, these [3] data has been found describing a stationary application in which battery remains in natural environment with an average temperature of 25°C, seasonally varying. A Li-ion battery treated like this reaches 80% of SOH (on capacity) in 12 years, with linear capacity decay. This means in this study, maximum expected life for a BESS before replacement is 12 years. Lifetime of battery will be the lower value among cycle lifetime and 12 years and this will define End of Life (EoL) of the battery. At year of EoL, replacement costs will be taken in account in NPV.

4.1.7 Model outputs

Outputs of model are the results of each monthly simulation. They are in the form of logs with sampling rate of 1Hz (the same of Inputs). They gather:

1. SOC
2. Actual c-rate
3. C-rate requested for each service
4. LOR (total and allocated on each service)
5. Other additional information.

4.2 Services modeled

BESS modeled in this study must serve as services provider for network. Specifically, it must trade products on Italian ASM. It can be said the main aim of an economic study of battery providing grid services is the following optimization:

1. Minimize Loss of Regulation (LOR);
2. While maximizing revenues (NPV);
3. While requiring as low as possible (up to zero) energy exchange with grid outside the services given (lowest amount of energy purchased or injected to grid for SOC restoration purposes). Being only a provider and not a consumer for the market is valuable, since it implies less issues in connection with grid and metering. And less costs for energy purchased.

Different weights, usually given as price signals, can be attributed to each one of these three merit categories. In a system in which penalties for LOR are high, minimizing LOR will be the first aim. If instead there is a service highly remunerated, maximum band will be dedicated to it. It is consequently necessary to build a strategy for offering services. First, choosing what services to provide. Then, splitting the total regulating band among the services chosen. Different choices can lead to different decisions in sizing the battery. Specifically, the optimal or feasible EPR of battery depends on services provided and regulating bands splitting. In the model, the strategy influences the creation of the power setpoints fed to battery. The process is:

1. Inputs coming from grid (frequency, SCR regulation signals, etc.) are received and elaborated by the controller.
2. Regulating power bands offered on market for each service are decided.
3. Market acts, by accepting or refusing offers on each service: if an offer is accepted, the setpoint for that service are fed to model for the period in which the unit is selected by market. Otherwise, setpoint for that service is 0 for that period.

The period chosen for simulation lasts 30 days: from February 15, 2017 to March 16, 2017. Frequency data for that period are taken by laboratory measurements in Politecnico di Milano’s Department of Energy. Specifically, data have been logged with 10 Hz sampling rate with uninterrupted record for 1 month, within the framework of the *IoT-Storage Lab*. Sampling-rate has been decreased to 1 Hz when elaborating the inputs. This time-step has been considered sufficient to produce accurate simulation of services. In fact, the precision offered by this battery by following a setpoint each second is higher than the precision guaranteed by conventional generators [62]. Regulating signal for SCR (Segnale di Livello) and market prices for both positive and negative SCR provision are taken by website of Italian market manager: Gestore Mercati Energetici (GME) [101].

To briefly introduce layout of the Section:

1. The first step is the choice of first service to provide (Paragraph 4.2.1). The criterion used is starting from services with higher priority for Italian network. Primary regulation is mandatory in Italy for every programmable plant: it was chosen as first service to implement.
2. Then, the core of this study is introducing Multi-service (Paragraph 4.2.2): the multiple services provision. An analysis of all the constraints to respect while providing more than one grid service with a BESS is presented.
3. A comprehensive procedure for implementation of grid services in the model is presented in Paragraph 4.3. For the modeling of every service, same functional units are present. These

functional units divide the Controller of the in common blocks, that are modified by inserting the specific conditions of each service.

4. After having analyzed in general Multi-service rationale, the addition of another service is presented. This service is Secondary Control Regulation (SCR). It will be implemented first as it is in the Italian ASM (Paragraph 4.3.1.2). Then, the Italian product will be modified to better fit limits and characteristics of BESS (Paragraph 4.3.1.3), introducing one of the fundamental elements of this thesis: the use of asymmetric Reserves as "passive" SOC restoration mechanism. Asymmetric Reserves allow to define different regulating bands offered on markets for positive and negative power. Band management can be used for providing SOC restoration without purchasing on market energy flows on purpose, but with the provision of the service itself.
5. In Paragraphs 4.3.2 and 4.3.3, some of the criteria for setting battery parameters fitting provision of Multi-service will be introduced and analyzed, getting for each parameter (regulating power band, EPR) to feasible ranges.
6. In Paragraph 4.3.4, the mechanism used in analysis for allocating LOR on each service is explained.

4.2.1 Primary Control Regulation in the model

PCR is first grid service selected to be implemented. This choice was taken because of the importance that PCR has in Italy, being a mandatory service for most of generating units grid-connected in the country. Second reason to select it is the rising importance of Frequency Containment services in countries where share of non-programmable RES-E is increasing. It is implemented in the model following the principle of Italian grid code. Grid code imposes dead-band, fixed droop value and a regulating power of 1.5% of nominal power as described in 3.2.1. For the provision of this service, the choice has been to maintain the droop control law and relax the hypothesis of the 1.5% regulation power band, in order to increase the band offered and therefore the energy flows exchanged for this service. It is a natural choice, since grid services provision is the main aim of the BESS and not a secondary requirement imposed by TSO. The same scheme is therefore rebuilt on a different regulating band, chosen by user at each simulation and kept constant during the whole simulated period:

1. Dead-band is kept constant at 20mHz.
2. Droop is computed as follows, to remain within the span of the 2-5% regulation (that are the standard droops imposed by regulator in Italy to conventional power units):

$$droop = \frac{1.5}{100} * \frac{1}{P_{reg,PCR}} * n\% = \frac{[0.03 - 0.075]}{P_{reg}} \% \qquad 4.19$$

Where $P_{reg,PCR}$ is the regulating power band of the BESS offered for PCR in per unit, and *n%* is a number among 2 and 5 respecting Italian Grid Code (the smaller is, the more reactive is the control).

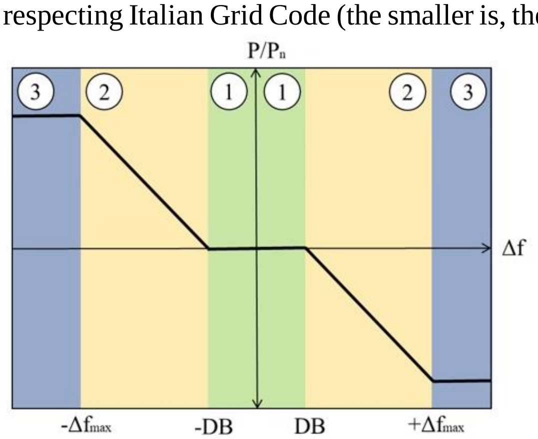


Figure 4-6 Droop control curve

In Figure 4-6:

1. $\pm DB = \pm 20$ mHz, dead-band.
2. $\pm \Delta f_{max} = \pm 57.5$ mHz in case of droop corresponding to 5%, ±35 mHz in case of droop corresponding to 2%, is the frequency at which we have the regulating power band saturation.

In Figure 4-7, a sample of frequency recorded ad used as Input for simulation. Blue line represents the PCR power requested, returned by Controller of the model.

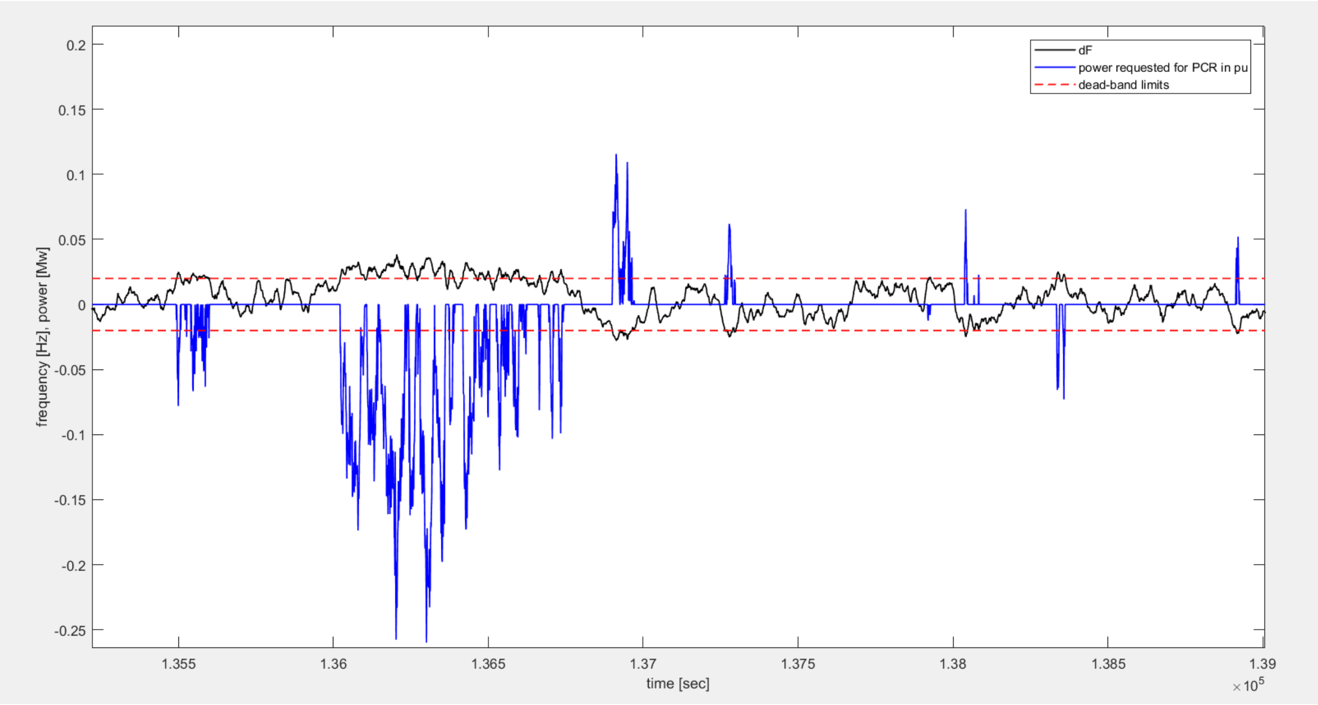


Figure 4-7 A sample of frequency variation from 50 Hz of network and consequently-computed monthly array of PCR setpoints sent as input of simulation

No SOC restoration strategy is related to PCR. Therefore, any power is withdrawn or injected in grid with the purpose of charging up or discharging the battery when it is getting close to SOC saturation limits ($SOC = SOC_{min}$, SOC_{max}) in this first setup. The already mentioned studies on Primary Control Regulation (PCR) by BESS show how BESS can provide constantly PCR with low LOR (less than 5%) only in case dedicated energy flows for SOC restoration strategies are implemented in BMS [93]. Otherwise LOR overpasses 20%. Dedicated SOC restoration strategies imply the main issues already mentioned, since BESS is also a consumer of the grid: it is subject to regulatory issues of being a producer and consumer, not only a service provider, and costs for energy purchased. Moreover, in BESS flows more energy than requested for the remunerated services, increasing average c-rate and decreasing both efficiency and life. A system should be found for performing SOC restoration avoiding energy flows on purpose. If there is a service whose power setpoints can help bring back SOC towards 50% (or, more generally, to a predefined SOC objective) and completely substitute dedicated SOC restoration strategies, then LOR will be low and the issues listed here above will be solved: BESS is no more a consumer for the grid and the incremental energy flows will be paid (higher c-rates but also higher revenues).

Therefore, next step becomes finding services able to balance the power requirements of the other ones. Or, in alternative, looking for services that can be offered on market only to request either positive or negative powers. Generally, the aim is finding services where regulating bands offered for positive and negative Reserve can be different in absolute value. The strategy on market will be, in this case, offering more regulating power in the direction which brings SOC far from saturation limits (e.g.: towards SOC = 50%):

1. Inject power in grid if SOC > 50%
2. Withdraw power from grid if SOC < 50%.

4.2.2 Multiple services provision for providing SOC restoration and increasing economic return

As described in Section 3.5, there are two main points still to solve while considering BESS as possible actors in ASM: SOC restoration mechanisms are still to be improved and low economic return is still rising doubts on the attractiveness of the investment. Multi-service can be a solution for both issues.

In [4], Authors highlighted the possibility of increasing NPV of investment on BESS when coupling a Primary Application and a Secondary Application, the latter acting while the Primary is idle. This approach finds its motivation in the principle assessing that a battery should increase its cycling rate and avoid time-periods idle. This is valid while the marginal gain of the service provided is larger than the marginal cost of the cycle related to that provision (see Paragraph 3.5.2). Marginal cost of the cycle equals the cost of the degradation of battery during that cycle: since in the SOH model used for this study cycle ageing is only function of average c-rate in the period, cost of the cycle is a function of c-rate average during period. Consequently, the optimization to perform to maximize revenues can be obtained by adopting some principles. First, the services better remunerated must be detected and larger power regulating band must be allocated for their provision. Then, time off must be avoided. Time in which gross power output is null should be minimized since calendar ageing is acting always and time idle is time with no revenues. Finally, c-rate must be kept low. A good strategy could be set the power in order to stay in the flat part of the SOH diagram in Figure 4-5: the point of maximum curvature in that diagram is actually optimal c-rate. The pursuit for optimal c-rate will not be stressed in the simulations since the SOH estimation model used is not particularly accurate. It just states a principle: lower c-rates are preferred. Average c-rates lower than 0.4 will be accepted.

For what concerns SOC restoration, it makes a fundamental difference if the service provided is symmetric or asymmetric. In case of symmetric service, no SOC restoration is possible and every SOC trend is just derived from network conditions. Actually, by only taking in consideration frequency control, if network suffers underfrequency, SOC will get close to lower saturation limit, vice versa in case of overfrequency SOC will get to upper saturation limit. If Reserves are asymmetric, the service provision can act as SOC restoration. The rationale is offering for each service regulating bands feasible with SOC margins before hitting saturation limits. These margins must be computed by considering the SOC variation caused by the other services coexisting on the battery. To be considered is also that the provision of one service during a period is not requesting always the maximum amount of power. There is a reasonable maximum of cumulative request over a period in both positive and negative direction that can be found. This can be done by performing statistical study on each service.

Hypothesizing that there is a periodical market for the provision of Reserves, every period will start with a SOC. In computing regulating bands for service i, the value of SOC at the beginning of market period will be called SOC_{init}, the SOC variation related to the other services except i will be called $\Delta SOC_{period,services\neq i}$, the maximum of SOC variation reasonable with respect to theoretical maximum will be called $ratio_{\Delta SOC,i}$, and the bands for service i will be offered as follows.

1. Band for positive Reserve of service *i*:

$$P_{pos,i} = P_{reg,i} * \frac{SOC_{init} - SOC_{min} - \Delta SOC_{period,services \neq i,+}}{100} * \frac{\frac{EPR}{t_{period,i}}}{ratio_{\Delta \mathrm{SOC,i,+}}} \quad 4.20$$

2. Band for negative Reserve of service *i*:

$$P_{neg,i} = P_{reg,i} * \frac{SOC_{max} - SOC_{init} - \Delta SOC_{period,services \neq i,+}}{100} * \frac{\frac{EPR}{t_{period,i}}}{ratio_{\Delta \mathrm{SOC,i,-}}} \quad 4.21$$

In the equations can be recognized two terms: the first is the term defining the ΔSOC available in positive or negative direction; the second is the term related to the service. In the equations:

- \+ and – are related to positive and negative Reserves.
- $P_{reg,i}$ is the maximum regulating band allocated for service i. It could be 100% of nominal power or lower.
- $\Delta SOC_{period,services \neq i,\pm} = \sum_{j \neq \mathrm{i}}^{n} ratio_{\Delta \mathrm{SOC,j,\pm}} * \Delta SOC_{max,j,\pm}$ is the sum of SOC variations expected due to provision of the other services in the period among two following market sessions, considering that the battery is providing *n* services.
- $ratio_{\Delta \mathrm{SOC,i,\pm}}$ is a coefficient among 0 and 1 defining the statistical ratio among the expected energy contribution for a service in the period among two market sessions and the theoretical maximum (it is based on the principle that the Reserve will not be used all the time at 100% requirements in the period among two markets. See Paragraph 4.3.1.1 for detailed explanation of the computation of these coefficients).
- $t_{period,i}$ is the time-period among two following market sessions of service *i*.

This relation is aimed to offer different bands for positive and negative Reserves, function of initial SOC at beginning of market session and of the contribution of the other services to SOC variation in the period among markets. The two results obtained by following the strategy are:

1. Perform SOC restoration via offering larger band for either positive Reserve (in case of SOC_{init} > 50%) or negative Reserve (in case of SOC_{init} < 50%).
2. Offering bands suitable to avoid hitting of SOC saturation limits in the time-period before next market session due to provision of the service itself.

In Chapter 5, many simulations are presented in order to validate this approach. The detail of the mechanism just briefly introduced here above will be detailed and applicated (mainly to SCR provision) in next Paragraphs.

As can be understood by reasoning explained before, SOC restoration does not actually deal with Multi-service, but more with asymmetric services. The best choice to get larger economic return in Italian framework is to exclude PCR provision and only provide asymmetric SCR. The interest in keeping PCR among the BESS priorities is that is a service highly valuable for the network, even if not remunerated enough in Italian rules. Moreover, interest towards enhanced version of PCR is rising in RES-penetrated network due to loss of inertia (see 3.4.2). BESS, thanks to their high ramp rate, can provide this type of services better than conventional units. Therefore, an evolution in structure and remuneration of this service also in Italy is likely happening in next future.

4.2.2.1 LOR allocation on each service

Talking about priorities of services, next issue in definition of a strategy for simulating Multi-service arises: LOR must be allocated on each service, for both measuring security of provision and for penalties computation. In the model, LOR has value different from zero each time power requested to cell is different from power delivered. In electric model partial curtailment of power is possible, therefore real power delivered can be a value among 0 and P_{req}. There could be several cases, leading to different LOR allocation strategies. Cases presented here below refer to a BESS providing two grid services, but can be extended to more. One of the services is defined Service with Priority. The other one is without Priority. When LOR is different from 0 ($|P_{real}| < |P_{req}|$), situations can be:

1. Power requested for one of the services has sign different from P_{req} sign. In such a case, LOR is allocated only on the service that has sign equal to P_{req} and value of LOR is equal to power requested for that service.
2. Each service has power requested of same sign and the magnitude (absolute value) of P_{real} is larger than absolute value of power requested for one of the two services and lower than absolute value of power requested for the other. In such a case LOR is only accounted for the latter service, and its value is the value of power requested for that service.
3. Each service has power requested of same sign and the magnitude of P_{real} is larger than each single absolute value of power requested for a service, but lower of their sum. In such a case LOR is accounted only on service that is without Priority, and its value is the value of power requested for that service.
4. Each service has power requested of same sign and the magnitude of P_{real} is lower than each single absolute value of power requested for the services. In this case, LOR is allocated to both services and its value is for each service the value of power requested for that service.

4.2.2.2 Band splitting criterion

Batteries have not a stringent limit on maximum power that can be delivered. There are instead constraints coming by requirements of the system and by criteria of preserving the battery. System constraint is given by inverter: maximum power usually admitted by inverter can be set to 130% of its nominal power. Nominal power of inverter is set equal to nominal power of battery in this work. Other limits can be set to guarantee cell preservation. This whole power band should be allocated on the services provided, in order to offer on market convenient bands. Regulating band for each service is given as input for simulation. It represents a constant value for PCR during all the simulation. Regulating band is instead variable for SCR and will change during simulation. A different band will be offered in each market session according to SOC management criteria.

After setting maximum band available, band splitting is decided to follow a criterion of remuneration: larger band for more remunerated services. Some other constraints can be useful or necessary sometimes. For example, in case only one service is provided, maximum band is set to 1.0 per unit. This is because it is less frequent that two or more services require at the same time, in the same direction (positive or negative), the maximum amount of regulating power. Instead, a statistical analysis showed that more time close to 100% of regulating band is present if the service provided is just one. Therefore, in next simulations the sum of the regulating power will usually be 1.3 per unit (the maximum usually acceptable value for inverters). And the number of instants above 1 per unit will be recorded and checked, to avoid too much stress to system. This analysis on maximum power output led to select also a minimum band for each service. Below that band, the situation is comparable to single service provision for what concerns maximum power. Therefore, below that threshold less overall band is exploited.

To give a general rule for minimum band of each service, if Pmax is the maximum power acceptable in per unit (e.g.: 1.3 per unit):

$$P_{reg,i} \geq P_{max} - 1 \quad (4.22)$$

Where $P_{reg,i}$ is the regulating band for service *i*.

Other thresholds can be found or tailor made for the peculiar behavior of each service.

4.2.2.3 EPR choice criterion

Energy to Power Ratio (EPR) choice is fundamental since it directly influence investment cost and so economic return of the investment. EPR should be convenient for the utilization of BESS. It should reflect the ratio among requirements in terms of SOC variation during a period and power offered on market in that period. This ratio is something similar to the already introduced $\Delta SOC_{period,i,\pm}$. For each service i a maximum SOC variation for the provision of that service in the time-period among two market sessions, can be computed. The maximum value can be theoretical or statistical. A statistical value is more useful to better exploit BESS power. The value selected will be divided by the regulating power band offered, to have a relation among energy in the period and power useful to set EPR.

Theoretical maximum ratio among SOC variation and power results:

$$\frac{\Delta SOC_{max,i}}{P_{reg,i}} = \frac{t_{period}}{EPR} * 100 \quad (4.23)$$

Where $t_{period,i}$ is time-period in hours among two sessions of market for service with more sessions during the day.

The statistical maximum ratio is:

$$\frac{\Delta SOC_{stat,i,\pm}(EPR)}{P_{reg,i}} = \frac{t_{period}}{EPR} * 100 * ratio_{\Delta SOC,i,\pm} \quad (4.24)$$

Obtained by multiplying the ratio found in 4.23 by the ratio among statistical maximum and minimum average value of output for service *i* and maximum output in absolute value for the service i. E.g.: in case of PCR, with SCR as secondary service, there will be an analysis to perform over long period on distribution of average SOC variation in 4 hours for provision of that service (that will be function of the standard deviation of frequency in 4 hours). Having a plethora of average values, they will be approximated with a normal distribution and on this there will be computation of the two tails at a chosen confidence level (95% is the default for this study). The ratio among these values and the maximum values of SOC variation theoretically achievable will give $ratio_{\Delta SOC,PCR,\pm}$. + and – as subscripts are present to indicate the value can be different for positive and negative Reserves.

EPR ideal will be the one allowing to reach 100% SOC variation maximum once chosen $P_{reg,i}$ for every service:

$$\sum \left(\frac{\Delta SOC_{stat,i,\pm}(EPR_{optimal})}{P_{reg,i}} \right) * P_{reg,i} = 100\% \quad (4.25)$$

It can be find by applying an iterative procedure.

4.3 Model implementation for Multi-service

This Paragraph aims to give a comprehensive procedure for implementation of grid services in the model. This will result in a scheme that can be used as general frame and tailored to the necessities (to specific service requirements). This procedure is explained at this point of dissertation since it is useful to explain the implementation of next service, subject to a market and to variable band. For PCR in Italian context, controller can be modeled in trivial way, as already described. In the end of the Paragraph, PCR implementation will be repeated using this framework, to better understand why this procedure was considered pleonastic for explaining that grid service as regulated in Italy today. This procedure will be then validated by using it to implement other services in BESS4PCR model used in this study. The aim of this Paragraph is staying as general as possible, to allow:

1. That most of services can be modeled by using this process as a basis, in the vision of performing other simulations on this model in the future.
2. That the procedure can be used also by other researchers even outside of MATLAB's Simulink framework. The scope is providing a scheme of how services and BESSs work, based on experience gained in this study, to give a guideline for others approaching world of services provision through batteries and prevent them to commit main errors and to forget steps in building their own models.

This procedure receives as inputs all the operating conditions of battery and the regulation signals by network operator or by private owner of BESS system and returns as result the power setpoint in per unit that can be required to BESS from grid or from loads connected (in case of end-consumer services). It will substitute the Controller Block of the model presented in 4.1.

The tool has been implemented in Simulink. In Figure 4-8 the view from Simulink desktop can be seen, representing all main units/blocks of the tool. Two of these tools in parallel can better manage asymmetric Reserves, as will be explained in the end of this Paragraph.

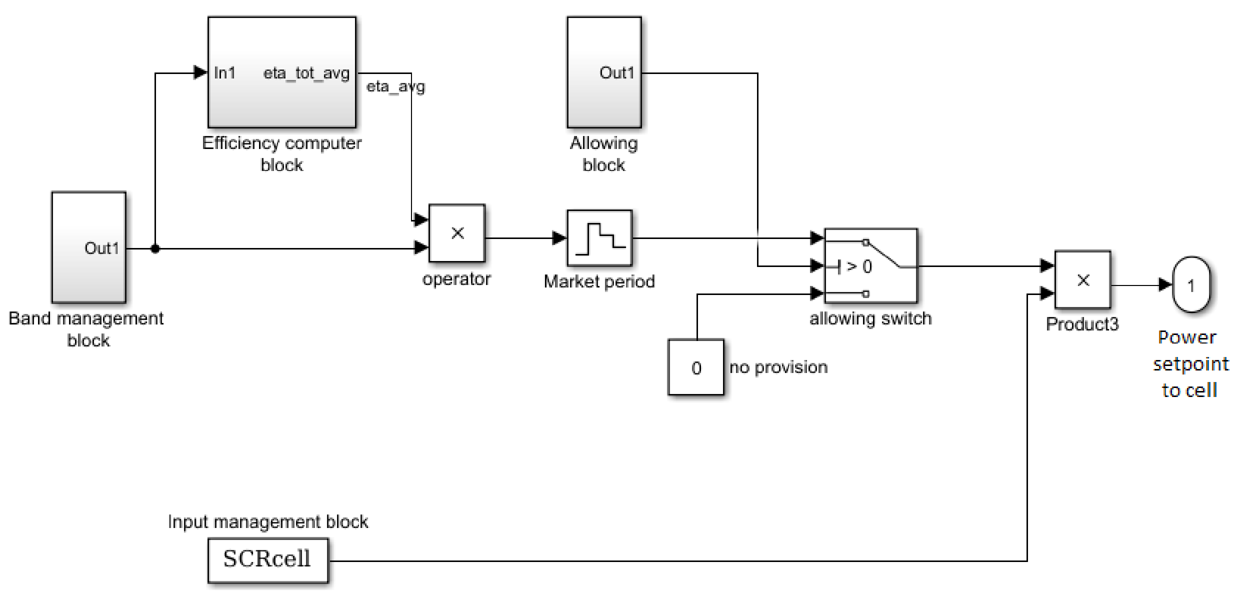


Figure 4-8 Service implementation tool as seen by Simulink desktop

Each part is functional to create the setpoint and can be of various nature, depending on characteristic of grid service itself. The units of the tools are the following.

1. Band Management block

It is the block defining the regulating power band of the service as it will be seen by cell. It implements the strategy chose for bid, if any. Most of services will require this block since they will be asked from TSO of an offer featuring a capacity (in MW) and a price (€/MWh and/or €/MW/unit-time) requested for guaranteeing that capacity. The strategy for choosing the capacity can be complex or essential (a constant value). There could be many criteria for setting this band: priority of service, operating condition of the cell, hour of the day, etc. These all must be defined in this block. Main management will usually account for the following variables.

a. Operating parameters of the cell: many services can be offered with thresholds on capacity dependent on the way the battery is working at that moment or in the recent past, or even in next future. The most representative example is SOC value. SOC is a fundamental variable for determining band magnitude to avoid saturation in next market time-period. Furthermore, SOC is fundamental for services aiming to provide SOC restoration. Other criterion could be temperature: larger power band implies larger c-rate required to cell, and therefore temperature rise. Even the hour of the day could be of interest: prices of services vary during the day. It could be of interest to offer more or less power for a service that is better remunerated in a specific time-frame.
b. Requirements of other services: there are thresholds depending on the other services the battery is providing at that moment. For instance, usually there is a limit on maximum power output for the battery. If other services are likely to saturate that limit, then no more band can be allocated for the service in analysis. Oppositely, there could be several services imposing power setpoints in the same positive or negative direction. The band in that direction could be saturated, but there could be room for offering band in the opposite one. Priorities can be given to services: when a service is already in place, the power band offered for the non-prioritized one will be lower. This can happen only in one direction or both, only in some hours or always. For instance, in the case of end-consumer arbitrage with priority: if during the day this service is aiming to discharge the battery, then negative Reserve can be exploited (or must be exploited) by other services to avoid lower saturation limit or power limit hitting.

The block ends anyway with a quantity (usually in per unit) defining the power band feasible for the time-period of next market session. This band is the one available on battery side. It is not yet the one (grid side) that will be offered on market and will be seen by TSO or by load (in case of end-user services). This is because the band is established following criteria linked to battery operating conditions, therefore battery side. For converting it to grid side and to the real band to put on market, there is Efficiency Computer block.

2. Efficiency Computer block

Having obtained the regulating band on battery side and willing to obtain a setpoint from grid side, the number must undergo efficiency of the system. The BESS is usually made up by two main non-ideal machines: cell and inverter. They both introduce an efficiency. These efficiencies can be usually multiplied and give a single number defined as system efficiency. This number will be multiplied to band coming from Band Management block in case power is injected by battery in grid (on grid will be offered less power than the one actually leaving battery: case of positive Reserve); the inverse of system efficiency will be instead multiplied to band in case power is withdrawn by battery (on market, more band will be offered than actual power absorbed from battery: case of negative Reserve). This happens in case of asymmetric service.

In symmetric services, the smaller bands among the two will be offered in both directions (positive and negative):

$$P_{reg,grid\ side,symm} = \min\left(P_{reg,batt\ side+} * \eta_{cell} * \eta_{inv}, \frac{P_{reg,batt\ side-}}{\eta_{cell} * \eta_{inv}}\right) \qquad 4.26$$

Efficiency to be used must be selected. There could be multiple choices since it is an estimation. If model has constant efficiency, there is no choice. Otherwise, since in next market time-period (that can vary from hours to weeks) the system will undergo different situations and operating conditions, therefore different system efficiencies, a choice should be done:

a. A prudential choice is to take minimum efficiency of the system, or anyway a value of efficiency for sure lower than the ones will be experimented during the whole period. This will lead to undersized regulating bands.
b. A common choice could be to take an average efficiency, for instance the efficiency correspondent to the average c-rate expected for the whole simulation (this value could be extracted by previous simulations or by guess).
c. If bands are set in terms to manage SOC evolution and avoid hitting of saturation limits, as it is this study, the choice could be: the efficiency of the system chosen is the one of the correspondent constant power output (positive or negative) to get to the saturation value exactly at the end of time-period in which this band is offered. E.g.: if the target SOC implies SOC variation of -50%, the EPR is 1 and the market period is one hour, the efficiency will be the one corresponding to power output of 0.5 per unit.

The output of this block will be a single number and will be used as explained in equation 4.26.

3. Market time-period

Power band is offered on market each market session. In the period between two market sessions there will be no updates: there is necessity of a block able to keep the value constant for a time-period, having the value updated just once each market session. Therefore, even if band computed in Band Management block varies continuously, the model must be able to take just one value each market session. This is the aim of this block of the model, that does not introduce any other change in the value.

4. Allowing block and Allowing switch

Allowing block is usually an on-off controller: it must give as output a boolean 0 (off) or 1 (on). If the output is 1, the switch downstream the block will return as output regulating band. Otherwise the switch will return 0. There can be cases in which even a number among 0 and 1 is a possible output: these cases are the ones in which the band can be selected partially. The number among 0 and 1 will be the coefficient to multiply by the band upstream to obtain accepted band that will survive downstream. In these cases, there will not be a switch, but a multiplier downstream allowing block. In the allowing block there is the simulation of the market, in case service is sold on market. Otherwise, the block can represent a particular condition in which service is enabled or suspended. E.g. if during the day owner wants only to provide end-consumer services, this block will return 0 for all Ancillary services in those hours. Inputs of the block can be several: prices of electricity, market prices, a signal by remote control defining priorities, etc. The output is instead always a number among 0 and 1, usually zero or 1, associated to a multiplier (if service allows partial regulating band to be selected, therefore a share among null and 1 of maximum regulating band computed upstream) or to a switch (if service only allows total or null band to be selected). After both the block and the switch (or the multiplier), the number obtained is the surviving band, grid side, in per unit. It could be equal to the band entering the allowing block, a fraction of it or null.

5. Input Management block

This block will take the input or input-related parameter by TSO or owner of the battery setting the regulating value required each instant for provision of service. This value will be multiplied by regulating band to obtain the power setpoint (positive or negative) required to cell. In case of grid service, the output of this block will represent the value to be multiplied by the regulating band to obtain the power setpoint requested by grid (in per unit). The signal, in the framework of a simulation, will be given as input at its beginning. It could require or not some modifications. Therefore, the Input management block can simply be the reception of an array from workspace or a more complex tool for modifying that signal in a share of regulating band.

The value coming from this block is multiplied by the output downstream Allowing switch and directly fed to cell model.

6. Output

The output is exactly the value to be fed each instant to cell model. The output is the power setpoint requested grid-side, since it is the value required from grid or from loads, and it is in per unit, representing the share of nominal power requested. In case the model requires c-rate, it is enough to divide it by EPR of battery. If it is required battery side, it must be divided by system efficiency.

7. Asymmetric bands

For asymmetric services is better to treat the two Reserves as two different services with two different subsystems. In some cases, sharing of the system could make easier the construction of the model, but

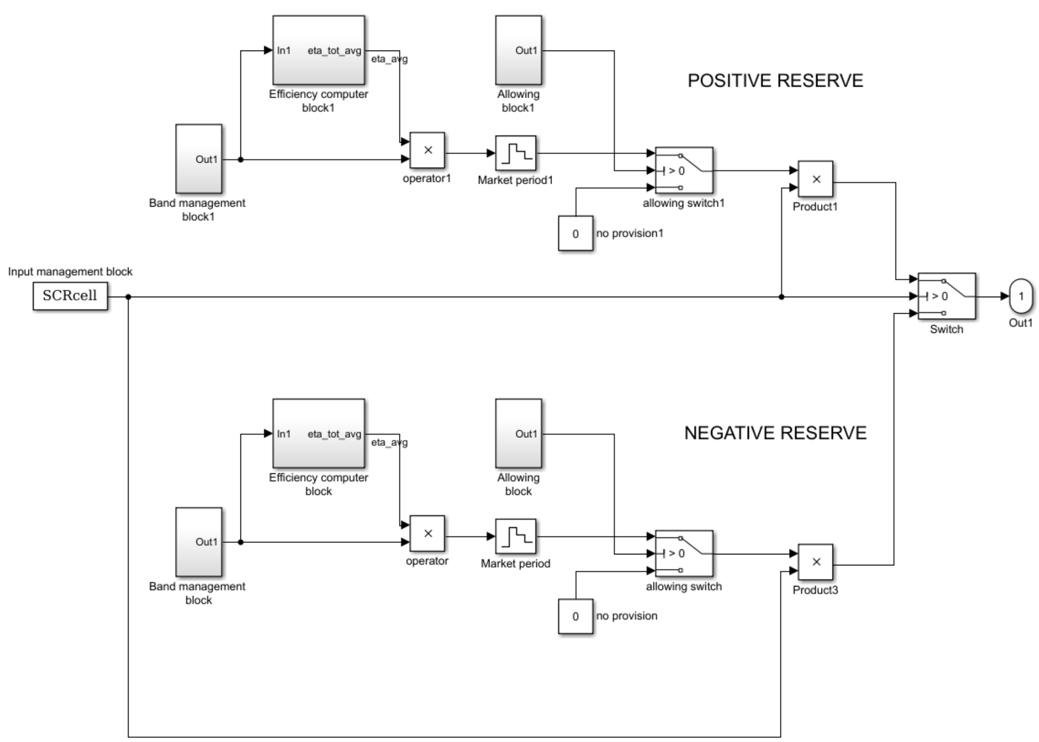


Figure 4-9 Multi-service tool for asymmetric services. Case of asymmetric SCR

usually positive and negative Reserves are computed in similar but completely detached way. The system would look like in Figure 4-9.

This procedure is thought to better introduce how the study continues in implementing services and manage the combination of them. The first goal is allowing multiple services to be provided simultaneously. Studies quoted up to now and considered as reference in multiple services provision (see 3.5), only studied multiple services provision with a secondary application only performing while primary application is idle. In this work simultaneous services provision is the rule, to be feasible with ASM regulation. Furthermore, the tool can be utilized as a basis by who is desiring to continue the study on services modeling at every level of complexity: the blocks are in fact the fundamental units not to forget. They can be as complex as desired to take in account of logics and strategies of the provision.

Here below the modeling of PCR in Italy is also presented in the framework of the four blocks, to show that both complex and trivial services can be modeled using the procedure. PCR in Italy is a service mandatory, permanent, symmetric, not subject to any market.

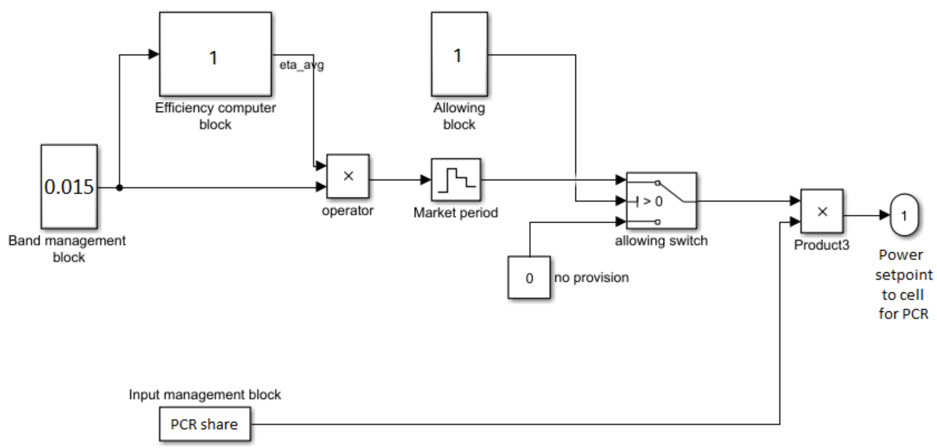


Figure 4-10 Multi-service tool for PCR

1. Band Management block is a constant value within 0 and 1. In fact, primary is in Italy a fixed band service (service is a percentage of nominal power output of plant). In the field of this study, various bands have been used for PCR. The standard 1 is 1.5% of nominal power. It will be used for this brief example. Constant value is therefore 0.015.
2. Efficiency block returns constant output equal to 1. Since band required grid side is a percentage of nominal power, band management block has already given the right constant value. Therefore, Efficiency Computer block returns 1.
3. Market period is "infinite". Since the service is permanent, the value can be updated once per simulation. So, this block can be set to a parameter higher than simulation time: the value of band will pass through it just at the beginning of simulation and then it is constant until the end.
4. Allowing block will be always 1. There is no market, no priority level changing during simulation since PCR must be provided mandatorily. Output of the block is the constant value 1. The switch will always allow the band to be the option selected.
5. Input management block will receive frequency trend of the simulation time-period as an array at the beginning of simulation and will implement the droop strategy (see equation 3.2, P_{reg} should be set to 1 in order to use well number coming from band management block). Since droop is fixed,

this conversion from Δf to $\dot{\Delta P}$ can be performed also before the beginning of the simulation. The output of the block will be every instant a number within [-1,1] representing the share of regulating band required to cell.

6. Output is the share of regulating band required times the regulating band: power in per unit required to battery.

Scheme for PCR as in Italian rules for conventional units is shown in Figure 4-10.

4.3.1 Secondary Control Regulation in the model

Secondary Regulation is the next service implemented. In Italian ASM, SCR is a symmetric service traded in 6 sessions per day. Each session selects units providing positive and negative Reserve for next 4 hours.

This periodic market requires a different effort in band management with respect to PCR mandatory provision. Primary Regulation inputs were given to model in an array: there were no more computations to do, PCR setpoints were already given by data. SCR provision will require instead a strategy development from controller: it will decide the bands during simulation, at each market session, based on the operating condition of the battery. In particular, since the first aim is avoiding saturation of SOC due to SCR provision, SOC level at the beginning of each traded period (every 4 hours) will be used to build SCR regulating bands. SCR setpoints are built in runtime during the simulation, multiplying each loop the regulating band accepted by the regulation signal indicating share of band to provide.

In 4.3.1.2 the implementation in model or symmetric SCR will be described. Then, in 4.3.1.3 asymmetric SCR will be proposed. The importance that asymmetric Reserves could have for BESS has already been highlighted. To test it, the Authors' decision was to relax Italian requirements and allow asymmetric SCR provision. This can increase economic return of investment in BESS and perform SOC restoration strategy. The band management strategy presented in Paragraph 4.3.1.3 implement the SOC restoration mechanisms.

SOC evolution control is the most important thing while working with BESS. Link among SOC and power band construction is tight. Therefore, it is fundamental to understand precisely the link among power band offered for one service and maximum SOC variation caused by its provision. The right estimation of the contribution of each service to SOC variation can lead to exploit conveniently the energy band of the battery without hitting the saturation limits. This means cycles with high DOD without saturation. Next Paragraph is aimed to present the way selected for computing these variations. It will introduce some parameters then used in regulating band construction.

4.3.1.1 Services contribution in SOC variation over a period

A statistical analysis has been performed by checking values of frequency variation (for PCR) and regulation signal (Segnale di livello for SCR). This analysis aims to define which are the likely contribution to SOC variation in the period among a market session and the following one. In particular, among two consecutive market sessions for SCR. Each service in Italian market implies both positive and negative power contributions. In a single time-period there could be majority of positive power setpoints requested which leads to decrease in SOC. This would happen if for a long period of time frequency stays below 50 Hz. Vice versa, if there is a period of overfrequency, there could be a majority of negative power setpoints decreasing SOC. There will be a maximum level of variation possible for every service. This is given by the product among regulating power and time-period:

$$\Delta SOC_{max,i} = \frac{\int_t^{t+1} \Delta \dot{P_{reg,\iota}} \ dt}{EPR} \simeq \frac{P_{reg,i} * \Delta t}{EPR} \quad 4.27$$

Where $P_{reg,i}$ is the power band in per unit dedicated to service *i* and Δt is time period considered.

This condition is only reached when the contribution for a service remains stable to maximum request for the whole period. This means that frequency should remain either above (50+Δf_{max}) Hz or below (50-Δf_{max}) Hz for 4 hours (with $\pm\Delta f_{max}$ ±57.5 mHz or ±35 mHz, depending on droop chosen). Segnale di Livello should remain 0 or 100 for 4 hours.

The analysis aims to understand how often $\Delta SOC_{max,i}$ is reached and how far is statistically reasonable SOC variation due to contribution of each service. The approach chosen to find it out is explained here below (process is summarized by flow chart in Figure 4-12).

1. Take a log of the parameter of interest of a previous period with respect to the one simulated, maybe a period that could have correlation with the one simulated. E.g.: log of Segnale di Livello of February-March 2016. Same months, one year before the simulated period.
2. Divide the log in *k* intervals elapsing exactly time *t* among two consecutive events of interest (e.g.: 4 hours, interval among two market sessions for SCR in Italy) and create a new array of parameter's log for each interval.
3. Translate the information on parameter in power setpoints requested in per unit, using the relation among parameter and power. E.g. Segnale di livello (among 0 and 100) can be translated in power requested in pu (among -1 and 1) using the following:

$$\Delta \dot{P}_{scr}(t) = \frac{Segnale\ di\ Livello(t) - 50}{100} * 2. \quad 4.28$$

4. Pass from power to energy using equation 4.3.
5. Pass from energy to ΔSOC:

$$\Delta SOC_{i,k} = \frac{E_{i,k}}{EPR} * 100 \quad 4.29$$

6. Create a new array for the whole analyzed period with each $\Delta SOC_{i,k}$. It will have *k* ΔSOC values: one for each time-period.
7. Verify by eye if the array of SOC variations can be approximated with a normal distribution. If yes, compute μ and σ of that approximated distribution. (e.g.: in Figure 4-11 there is the distribution of ΔSOC in each interval due to Segnale di Livello in Feb-Mar 2016)

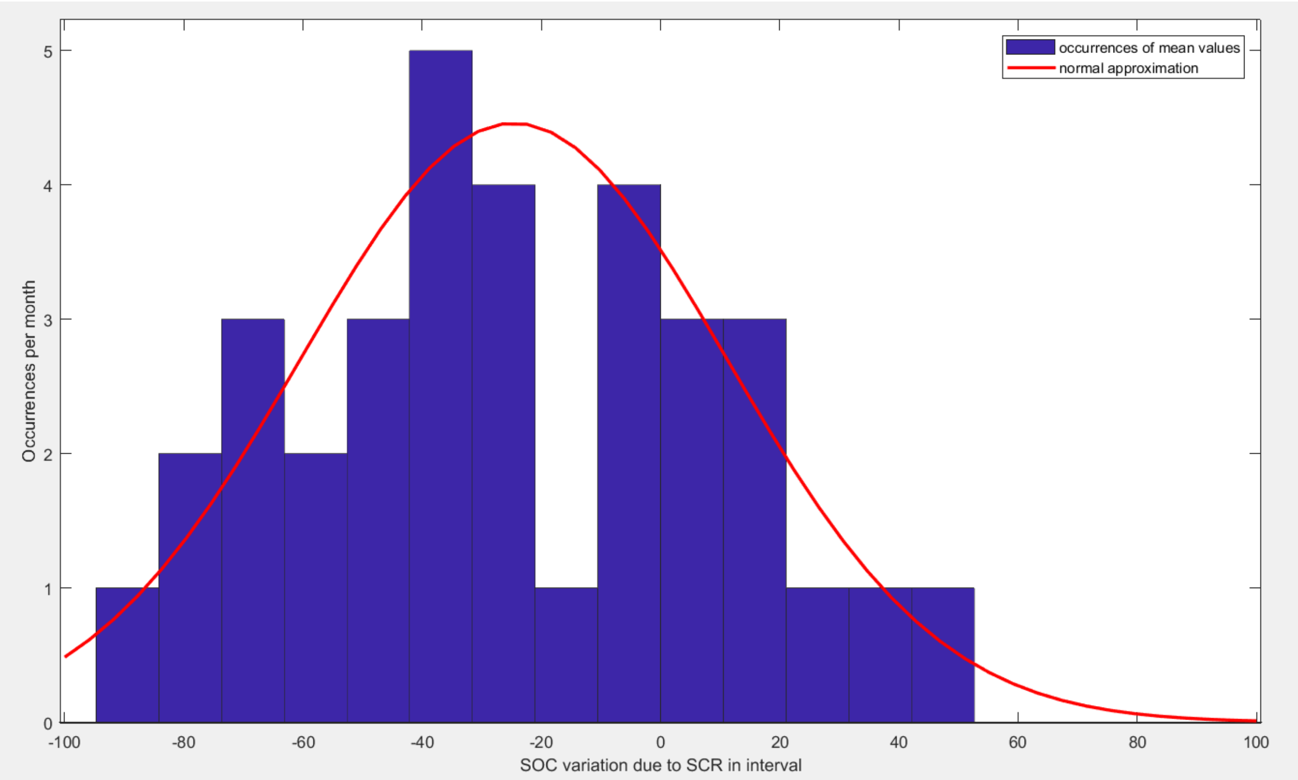


Figure 4-11 Occurrences in Feb-Mar 2016 for SOC variation by SCR in 4 hours, $P_{reg,scr}$ = 1 pu, EPR = 2

8. Decide the confidence level to apply. The strategy used is to have confidence level (CL) on the joint probability of every ΔSOC estimated as close as possible to 95%, taking eventually a safety margin (CL>95% is accepted, <95% no). This can be done roughly by increasing CL of the services which imply ΔSOC above average (SCR), allowing to decrease CL of the ones causing ΔSOC below average (PCR). Empirical algorithm followed is below explained.

    a. Joint CL must be 95%, so by default single CL (CL_{single}) are found by inverting this equation, where n is total number of services:

    $$CL_{joint,std} = 1 - \left(1 - CL_{single,std}\right)^{n} \qquad 4.30$$

    b. ΔSOC_i for each service at CL 95% is found, by using previously computed distributions. ΔSOC_{mean} is the mean among ΔSOC_i. $CL_{single,I}$ for each service is:

    $$CL_{single,i} = \min\left(0.95, CL_{single,std} * \frac{\Delta SOC_i}{\Delta SOC_{mean}}\right) \qquad 4.31$$

    c. The joint CL updated, that should be equal or greater than 95%, is:

    $$CL_{joint} = 1 - \prod\left(1 - CL_{single,i}\right) \qquad 4.32$$

d. If condition expressed in c is respected, from table of normal distribution can be found z-value for each service.

9. For each service SOC variations at correct CL are:

$$\Delta SOC_{IC,i\,(+,-)} = \pm\mu_i \pm z_i * \sigma_i \qquad 4.33$$

10. And desired ratio for each service (SOC variation not overpassed at desired CL/maximum SOC variation) is:

$$ratio_{\Delta\mathrm{SOC,i}(+,-)} = \min\left(1, \frac{\Delta SOC_{IC,i\,(+,-)}}{\pm\Delta SOC_{max,i}}\right) \qquad 4.34$$

e.g. in case of SCR

$$avg_{segnale\ di\ livello(+,-)} = \min\left(1, \frac{\pm\mu_{SCR} \pm z_{SCR} * \sigma_{SCR}}{\pm\Delta SOC_{max,scr}}\right) \qquad 4.35$$

With:

$$\pm\Delta SOC_{max,scr} = \pm P_{reg,scr} * \frac{4h}{EPR} * 100 \qquad 4.36$$

The use of minimum value is to take in account that approximation by normal distribution can lead to some distortion and result in a CL that overtake theoretical maximum of SOC variation.

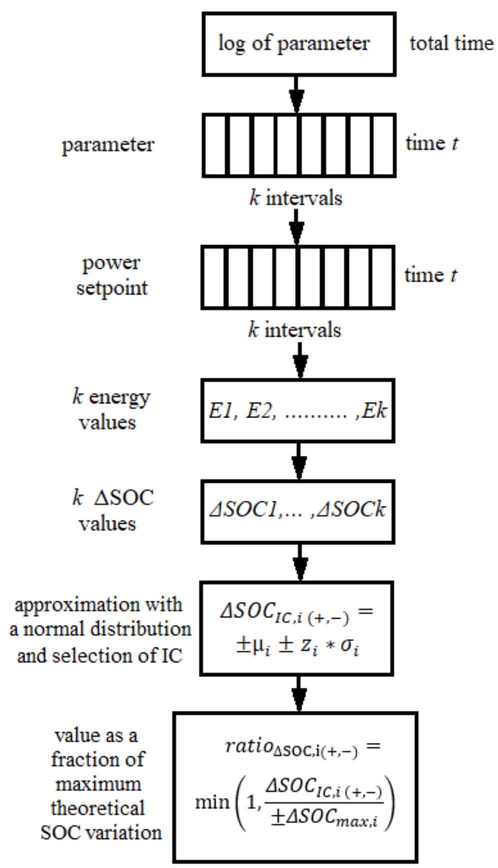


Figure 4-12 Flow chart for statistical SOC variation computation

Briefly repeating the analysis done: regulating band of service *i* (included $SB_{+,-}$ for SCR) can be increased by dividing it for the $ratio_{\Delta SOC,i(+,-)} \in [0,1]$, which defines the likely highest SOC variation of that service with respect to theoretical maximum one. It is enough to choose correctly the parameter and the relationship among that parameter and SOC variation. For PCR, parameter is frequency and relation is droop control law. For SCR, parameter is Segnale di livello converted in a value in the interval from -1 to 1 to have the share of power band. Decreasing $CL_{joint,std}$ will imply larger regulating bands offered and more risks of LOR due to SOC saturation limits hitting. An economic optimal value can be found.

This statistical analysis allowed the computation of four indexes that will be used for computation of band offered for PCR and SCR provision, for each Reserve.

1. $ratio_{\Delta \mathrm{SOC,PCR}(+,-)} = \frac{variation_+}{\Delta SOC_{max,pcr}}, \frac{variation_-}{-\Delta SOC_{max,pcr}}$ for PCR contribution to ΔSOC. $Variation_+$ and $variation_-$ will be used.
2. $ratio_{\Delta \mathrm{SOC,SCR}(+,-)} = avg_{segnale\ di\ livello+}, avg_{segnale\ di\ livello-}$ for SCR contribution to ΔSOC.

4.3.1.2 Italian ASM model: Symmetric SCR provision

As already explained in 3.3, Italian SCR market accepts offers every 4 hours, on symmetrical regulating bands called semi-bands (SB) for positive and negative power. This is a limit for batteries, since it would require offering on market, for both positive and negative reserve, the minimum power compatible with the energy contribution to reach the upper or lower limit in next 4 hours (see 3.4.2). The strategy implemented in Band Management block of the Multi-service Tool is in the following.

1. At the beginning of the 4 hours regulating period, battery has its SOC (SOC_{init}).
2. In next 4 hours there could be a positive or negative variation in SOC given by complying with other services provided by battery, e.g. PCR ($variation_-$, $variation_+$).
3. The minimum of the two ΔSOC residual to get to saturation levels is the maximum in energy that can be provided for SCR in next 4 hours (see Figure 4-13).
4. To get to regulating band, energy must be multiplied by EPR and divided by time (4 hours). There will be two bands values, one for reaching upper SOC saturation limit, the other one for reaching lower.
5. A further update of regulating band is done by considering the statistically reasonable extreme values of Segnale di Livello in the 4 hours period, obtained with the statistical analysis explained in Paragraph 4.3.1.1. This means: Segnale di Livello is unlikely sticking to its extreme values for a long period and two maximum statistical values (in positive and negative direction) of its average in 4-hours intervals can be found. The values representing the ratio among statistical and theoretical extreme values of Segnale di Livello (rescaled on interval from -1 to 1) in 4 hours are found as follows:

$$ratio_{\Delta \mathrm{SOC,SCR,pos}} = avg_{segnale\ di\ livello+} = \frac{max\ mean\ value\ over\ 4\ hours - 50}{100 - 50} \quad 4.37$$

$$ratio_{\Delta \mathrm{SOC,SCR,neg}} = avg_{segnale\ di\ livello-} = \frac{50 - min\ mean\ value\ over\ 4\ hours}{50 - 0} \quad 4.38$$

Regulating band is divided by the 4.37 and 4.38, plus eventually a safety margin, to get output value of Band Management block.

The safe margin will be introduced during simulations only if justified by high level of LOR. If LOR remains low, the statistical analysis performed allowed to increase the bands and therefore the economic return with no costs in performance.

PCR band is fixed and defined at beginning of simulation, since PCR is mandatory and not subject to market. Therefore, all the other services must manage their band by taking in account the SOC variation statistically caused by PCR, represented by $variation_-$, $variation_+$. The methods used for getting to $variation_-$, $variation_+$, $avg_{segnale\ di\ livello\ -}$, $avg_{segnale\ di\ livello\ +}$ has been explained in Paragraph 4.3.1.1. Regulating band for SCR is the power band giving the complementary SOC variation to get to saturation limit (theoretically or by using a confidence level). Since there are two saturation limits (SOC_{min} and SOC_{max}) there will be two power bands: in case of symmetric service, the minimum among the two power bands is adopted for both, as suggested by [72] and already described in 3.4.2.

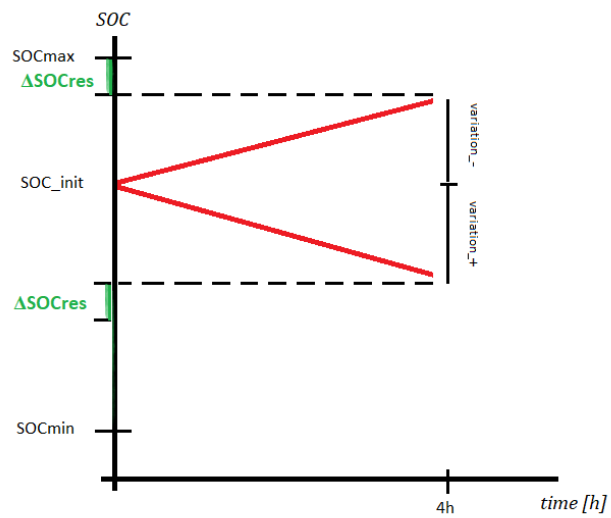


Figure 4-13 Diagram for computation of ΔSOC_{res} that can be offered in case of symmetric SCR

As can be noticed from Figure 4-13, where SOC_{max} and SOC_{min} are 100% and 0, there is a non-negligible part of SOC included neither in SB* nor in $variation_-$, $variation_+$. This means the sum of the regulating bands is implying maximum ΔSOC lower than 100%. Moreover, SCR service is not working as SOC restoration, since the ΔSOC due to SCR provision can be equally probably either in positive or negative direction, just depending on Segnale di Livello in subsequent 4 hours.

By calling SOC_{init} the SOC at the beginning of the 4 hours period, the equation to get to output of Band Management block (that will be called SB*) is the minimum among SB^*_+ and SB^*_-:

$$SB^* = \min\left(\frac{(SOC_{max} - SOC_{init} - variation_-)}{100 * avg_{segnale\ di\ livello-}} * \frac{EPR}{4}, \quad \frac{(SOC_{init} + variation_+ - SOC_{min})}{100 * avg_{segnale\ di\ livello+}} * \frac{EPR}{4}\right) \qquad 4.39$$

Then, SB* will pass in Efficiency Computer block. It is needed to convert regulating band from battery to grid side: since regulating band is symmetric, the lowest value among

$$SB_+ = SB^*_+ * \eta_{sys+} \qquad 4.40$$

$$SB_- = \frac{SB_-^*}{\eta_{sys-}} \quad 4.41$$

will be offered on market.

$\eta_{sys\,+,-}$ are estimated in two separated Efficiency computer block as the efficiency of inverter and cell for the constant setpoints of power needed respectively to get to SOC = 0 and SOC = 100%.

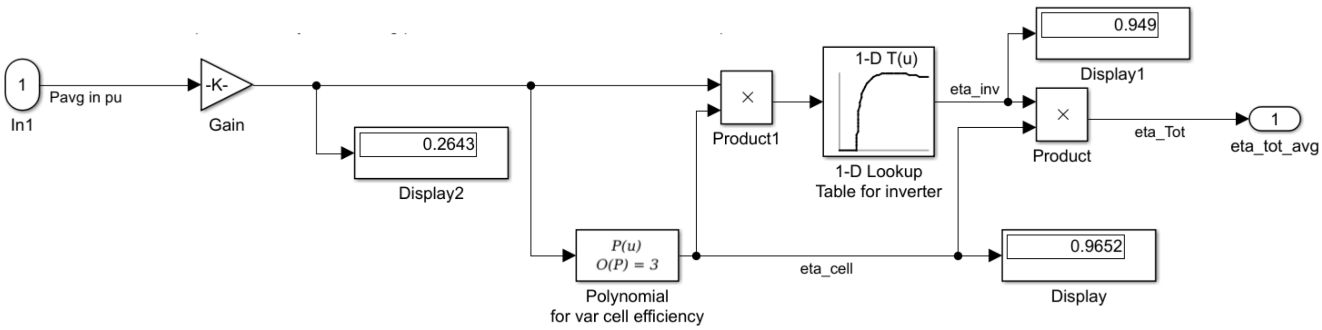


Figure 4-14 Block for efficiency computation in positive reserve

This is the strategy already suggested in 4.3: the efficiency is the one the system undergoes if it is subject to constant power output for the whole period of market, and exactly the power output allowing to reach SOC saturation limit at the end of the period.

Two similar subsystems (for both positive and negative reserves) in the model emulate a market happening every 4 hours of the simulation: it is the content of the Allowing blocks. The model is Mercato di Bilanciamento (MB = Balancing Market), as of in Italian regulation, even if with differences and simplifications.

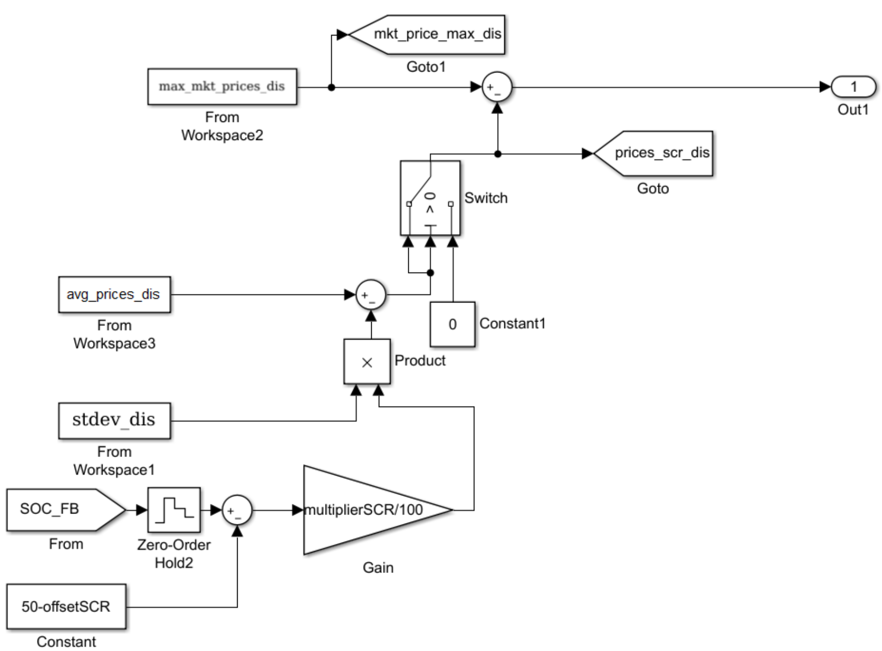


Figure 4-15 Simulink Model Block with market, for positive reserve

A price signal is implemented to help in SOC restoration by making easier being selected for positive Reserve if SOC is high, negative if SOC is low. The block represented in Figure 4-15 takes as input SOC by model, updated every 4 hours. SOC (in %) at beginning of the 4 hours is subtracted by 50, divided by 100 and multiplied by standard deviation of market price for the reserve of interest. This term is subtracted to mean price of the market in that hour for the relative Reserve, obtained after statistical analysis. The maximum among 0 and the price computed is the bid on market (no negative prices allowed on Italian market). BESS enter the market in an hour if price offered is lower than maximum accepted price for that hour (negative prices in case of negative Reserve). Price is hourly, and market is every 4 hours. This means SOC is updated every 4 hours but result of markets change each hour. OffsetSCR and MultiplierSCR are two parameters to have steeper or less steep change in bid with respect to SOC.

The equations of hourly offered prices are:

$$price_{scr+}(t) = mean\,price_{+}(t) - \left(SOC_{init} - (50 - offsetSCR)\right) * \frac{multiplierSCR}{100} * stdDev_{+}(t) \qquad 4.42$$

$$price_{scr-}(t) = mean\,price_{-}(t) - \left(SOC_{init} - (50 + offsetSCR)\right) * \frac{multiplierSCR}{100} * stdDev_{-}(t) \qquad 4.43$$

Where *t* is in hours and SOC_{init} is SOC at the beginning of the 4 hours period. A study on recent ASM prices on Italian framework was performed for obtaining mean prices, their standard deviations, maximum and minimum prices for each hour. Data source was GME website (archive: MB – Secondary Reserve) [101].

1. Market prices used are exactly the ones practiced in the simulation period.
2. All the data necessary to build the offered price were taken by statistical study on same period of previous year (Feb-Mar 2016). A mean price for each hour for a standard working day and a non-working day were computed. This statistical study aimed to give market truthfulness: it is based on data of a previous period with respect to the one simulated.

Offer is accepted every time price offered is lower than maximum accepted price. It must be highlighted once more that on Italian ASM prices for positive Reserve must be positive and for negative Reserve must be negative (provider is purchasing energy from market and paying for it).

The output of this block is a Boolean: 1 if offer is accepted on market, 0 if not. No selection of partial regulating band is allowed. With 1, the following Allowing switch will let SCR band pass and be multiplied by Input, coming from Input management block. Otherwise 0 will be multiplied by Input. Since the market prices are hourly, the result of Allowing block can change every 1 hour and therefore the provision of SCR can stop or restart every 1 hour.

Input from Input management block is the regulation signal (Segnale di livello) coming from TSO, just moved from original interval (with minimum at 0, maximum at 100, the zero at 50) to interval from -1 to 1, with zero for power output null. This conversion is functional for multiplying each instant this value by output of Allowing switch and get SCR provision requested grid-side in per unit.

As previously described, there are still issues in this Multi-service: the SCR provision added is a symmetrical service. Symmetrical services imply limits for BESS operation.

A simulation shows how often SOC is getting to saturation limits and how often there is LOR in case the model provides both PCR and SCR as described above (as requested in Italian Grid Code, Chapter 4 [57]).

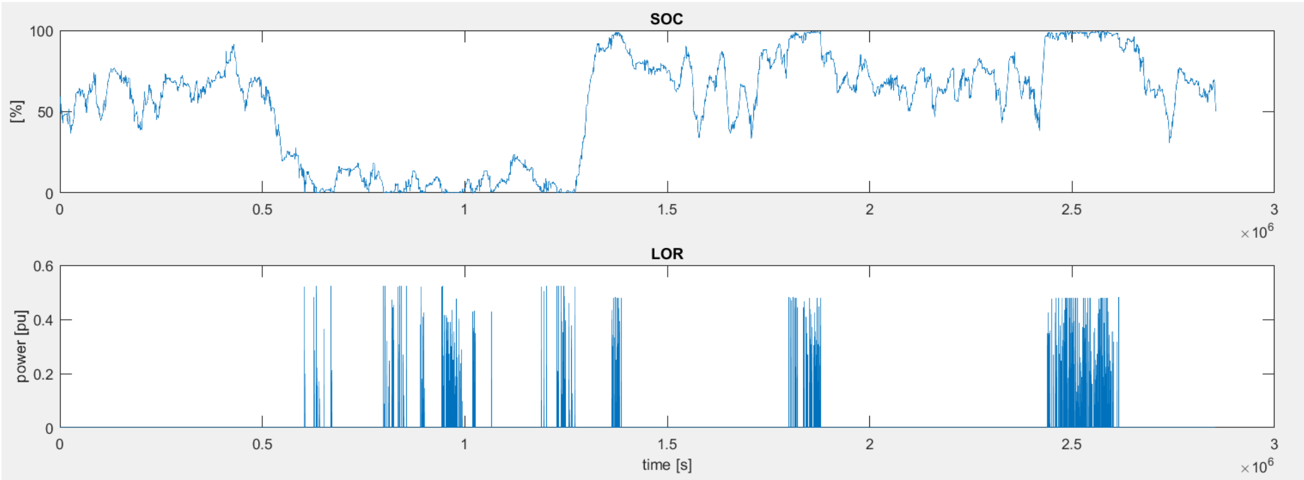


Figure 4-16 Results of simulation for BESS providing both PCR and SCR with symmetric bands

This happens because when SOC gets close to saturation, regulating band for SCR gets to 0 and battery only offers PCR. This is the limit of symmetric services for batteries: when one of the two bands gets to zero, the other one must follow and there is no more provision of that service. The situation is not different from the case described by study [93] – where BESS offers only PCR with no SOC restoration strategies – and implies same (high) levels of LOR.

4.3.1.3 A more suitable service for evolution of Italian ASM: Asymmetric SCR provision

This Paragraph will show how the constraint of symmetry on Italian Secondary Reserves has been relaxed in the implementation in the model of asymmetric SCR. This new product, a modification of Italian ASM, allows regulating bands for positive Reserve (*a salire* in Italian market) and for negative Reserve (*a scendere* in Italian market) to be different. This means that positive and negative reserves for automatic Frequency Restoration are separated, as already happens in German, Dutch, Belgian market [102]. The symmetry of some services (every provider must offer on market same regulating bands for positive and negative reserves) has been already highlighted as a barrier for opening ASM to new actors, e.g. aggregators or BESS [72] [102]. The topic has already been discussed in 3.4.2, highlighting a trend towards asymmetry.

In this case, as highlighted in Figure 4-17, there would be two different Band Management block, offering two different outputs for positive and negative reserve (it is the case of two parallel Multi-service tools, as described in 4.3) able to exploit better each residual SOC margin, computed as follows:

$$P_{regSCR}{}^{*}_{+} = SB_{+} = \frac{SOC_{init} + variation_{+} - SOC_{min}}{100} * \frac{\frac{EPR}{4}}{avg_{segnale\ di\ livello+}} \qquad 4.31$$

$$P_{regSCR}{}^{*}_{-} = SB_{-} = \frac{SOC_{max} - SOC_{init} - variation_{-}}{100} * \frac{\frac{EPR}{4}}{avg_{segnale\ di\ livello-}} \qquad 4.32$$

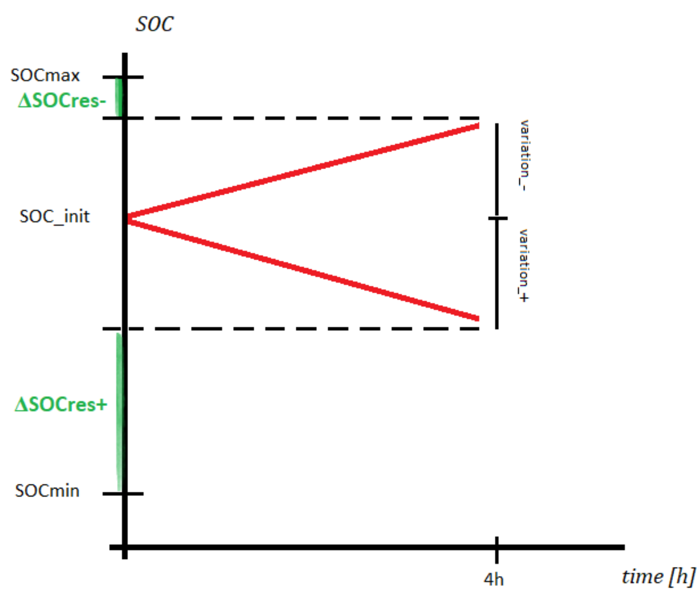


Figure 4-17 Diagram for computation of ΔSOC$_{res}$ in case of non-symmetric market

In this way SCR uses better remaining power band and works as SOC restoration. This is a most interesting way of working for a BESS playing in ASM.

The two Efficiency Computer blocks work in same way described for symmetric SCR in 4.3.1.2. One block works with regulating band for positive Reserve and multiplies system efficiency related to constant power output to get in 4 hours to lower saturation output. The other one takes as input regulating band for negative

Reserve and divides by system efficiency associated to power setpoint able to get to 4-hours to upper saturation limit.

Even for what concerns Allowing block and Input management block, everything is the same as already described in case of symmetric SCR. The only difference is in the number of systems: the two systems in parallel will give as output two different regulating bands for positive and negative Reserves. Positive regulating band will be multiplied to positive value of regulating signal and vice versa, as depicted in Figure 4-9.

The Paragraph above was meant to explain all the process for getting to SCR power setpoints. The scheme is exactly the one presented in Figure 4-9. This way of reasoning can be extended to most of ASM products to extend the Multi-service model.

4.3.2 Regulating bands share choice

A BESS providing multiple grid services can be designed as a sum of smaller size BESSs each one providing just one of the services. This happens if a regulating band (P_{reg}) is set for each service and the sum of those does not exceed 1 (per unit) or another threshold: $P(t) < P_n \; \forall t$ in batteries is not a mandatory limit.

1. For PCR, P_{regPCR} is imposed and corresponds to power related to $-\Delta f_{max}$ in droop control curve, as of in Figure 4-6. It is symmetric.
2. For SCR, P_{regSCR} is defined by:

$$P_{regSCR} = \max(P_{regSCR_+}, P_{regSCR_-}) \tag{4.44}$$

   But in model $P_{regSCR+}$ and $P_{regSCR-}$ are limited by P_{regPCR}:

$$\begin{cases} P_{regSCR+} = \min(P_{regSCR+}, \max(0.8, 1.3 - P_{regPCR})) & if \;\; P_{regPCR} > 0 \\ P_{regSCR+} = \min(P_{regSCR+}, 1) & if \;\; P_{regPCR} = 0 \end{cases} \tag{4.45}$$

   And the same can be repeated for $P_{regSCR-}$. The choice of 1.3 per unit is due to the fact inverter has a maximum rated power set as 130% of nominal power. The choice of 0.8 is arbitrary. Anyway, the instants in which power is more than 1 per unit are in the order of few hours per month and are monitored during simulation. In case of provision of only SCR, the limit for maximum power exploited each instant has been set to 1 per unit. The reasons for this have already been highlighted in Paragraph 4.2.2.2.

Defined what are regulating band and which are relation among them in the model, the second step is decide which share is the best and which criteria must be selected:

1. Following criterion of limiting LOR, there must be a minimum threshold of SCR band, since this service works as SOC restorer. Given the relation among regulating bands of PCR and SCR explained in 4.45 and 4.44, a minimum threshold on P_{regSCR} implies a maximum threshold on P_{regPCR}. Value chosen:

$$\begin{cases} P_{regSCR} \geq 0.3 \\ P_{regPCR} \leq 1 \end{cases} \tag{4.46}$$

2. For maximizing revenues, market remunerations are fundamental. If the framework is Italian market, remuneration for PCR is usually less than half the remuneration for SCR. So, the choice is minimizing P_{regPCR}. As explained some rows above, there is interest in keeping at least a low provision of PCR, therefore a minimum threshold also for it ($P_{regPCR} > 0.3$ per unit), since limits on maximum power can rise to 1.3 per unit in case of two simultaneous services.

4.3.3 EPR choice

As described in 4.2.2.3, EPR is chosen based on the relation among SOC variation statistically expected and regulating power for the specific services provision selected. The issue is that for certain services regulating band is constant, for others it changes runtime. There will be more than one optimal EPR, based on different logic used to compute it. The equation at the basis is always 4.25, but the regulating band appearing in it can vary. The time-period among two market sessions is 4 hours.

In the case analyzed:

1. For PCR, regulating band is constant and chosen at the beginning of simulation. The positive and negative SOC variations associated to the unit of regulating band are (in case of maximum droop = 0.075%, based on $variation_{(+,-)}$):

$$\frac{\Delta SOC_{stat,PCR,\pm}(EPR)}{P_{reg,PCR}} = \left(\frac{-23.6\%}{EPR}, \quad \frac{26.2\%}{EPR}\right) \qquad 4.47$$

2. For SCR, regulating band is varying with time. It stays within the interval stated in equation 4.45. The positive and negative SOC variations associated to the unit of regulating band are (based on $avg_{segnale\ di\ livello(+,-)}$):

$$\frac{\Delta SOC_{stat,SCR,\pm}(EPR)}{P_{reg,SCR}} = \left(\frac{-113.5\%}{EPR}, \frac{80.0\%}{EPR}\right) \qquad 4.48$$

To stay as robust as possible, the case considered among negative and positive variation is the one whose sum of the contributions to SOC variation by PCR and SCR is larger, therefore the issue is on positive Reserve. In fact the worst case, by summing 4.47 and 4.48, is for negative SOC variation, that is larger in absolute value:

$$\frac{|-23.6 - 113.5|}{EPR} > \frac{|26.2 + 80.0|}{EPR} \qquad 4.49$$

Value of regulating band for PCR considered is 0.5 per unit. Value for SCR regulating band is 0.8 per unit. By sizing EPR on the positive Reserve and using equation 4.25, two optimal value are found, with the interval of values among them considerable acceptable solutions:

1. In case $P_{reg,SCR} = P_{reg,SCRmax} = 0.8$, then $EPR_{opt} = 1.93$
2. In case $P_{reg,SCR} = \frac{P_{reg,SCRmax}}{2} = 0.4$, then $EPR_{opt} = 1.03$

Acceptable values for EPR in case of provision of PCR ($P_{regPCR} = 0.5$) and asymmetric SCR ($P_{regSCRmax} = 0.8$) are:

$$EPR_{acc} = [1.03, 1.93] \qquad 4.50$$

Since the aim of the study is being as robust as possible by system point of view, even higher values are acceptable. EPR = 2 will be considered as a highly conservative choice, to assure LOR as low as possible even at the expense of larger investment cost. Furthermore, a higher EPR value will preserve more the system from the stress caused by setting 1.3 per unit as maximum power flow.

4.3.4 LOR allocation choice

According with what stated in 4.2.2.1, the services must be listed following their Priority. In this study, PCR is considered the service with Priority, SCR is without Priority. In the case of addition of end-consumer services, they will be listed after grid services. This mechanism will allow to allocate as before described LOR. The outputs of the study will be an absolute value of LOR for each service.

5 Simulations and results

In this Chapter are reported the results of simulations for the BESS operating to provide several grid services and with different regulating bands. All simulations have been performed with the model described in detail in Section 4.1. Simulations will provide indexes to evaluate quantitatively the performance of BESS. The results will be analyzed following two main routes.

The first is the interest of the System Operator, whose focus is the security of grid. Provision of an Ancillary service is satisfactory if the power requested to unit is always provided. It can be evaluated by measuring the amount of energy non-provided on the total energy requested. Therefore, the index selected to define the performance is Loss of Regulation (LOR). The smaller LOR is, the better is provision. All possibilities of LOR to happen must be avoided. It has already been described in Section 4.3 how a consistent selection of services, a correct management of bands, a correct sizing of the battery could lead to achievement of this objective.

On the other side, the interest of the owner of the battery must be preserved. Since it must decide if investing in the BESS and if providing Ancillary Services, he will be concerned in the return of his investment. Consequently, indexes as Net Present Value (NPV) and Payback Time (PBT) must be computed. To understand the remuneration of investment in grid services, individuation of the revenue streams is necessary. It is moreover important to understand how to take in account of each one. And in which framework an Ancillary service is more remunerated. Finally, sizing of battery is important also for economic analysis since the investment cost is the predominant negative cash flow during BESS lifetime. To perform economic analysis, it is necessary to set the parameters to be used and define the indexes. Also detecting revenue streams is fundamental. This is not straightforward when dealing with ASMs. ASMs, as highlighted many times in the course of this study, are a system undergoing rapid changes. To find average prices and to make a prediction of them in next future is not easy. This is why so large importance is done in next Section to economic analysis on the Italian and German markets. The outcomes of the analysis, aimed to be as reliable as possible, will be used in the computations of economic results of simulations.

Layout of the Chapter includes the presentation of the economic analysis done to identify the revenues stream in both Italian and German context and the definition of economic indexes used in the study, in Section 5.1. In Section 5.2, dissertation goes towards the simulations presenting the validation done on empirical model, to accept its use in the study. The details and all the parameters utilized in simulations are presented in Section 5.3. From 5.4 to 5.10 all cases studied are shown and described in detail, offering quantitative, qualitative analysis and linking every scenario simulated with the following one to understand the line of reasoning that led to this course. The analysis of Terna's energy-intensive projects described generally in Paragraph 3.5.4 is presented in Appendix A. The reason to put it at the end of dissertation is giving a comparison among what has been studied and simulated during this thesis and what is the state of art of provision of services by BESS in Italian framework.

5.1 Economic parameters and indexes used

Economic analysis is the study of the viability of the investment. It measures economic return and it can be based on different indexes. The aim of this study is providing comparison among different situations: different services provided, different sizing of battery and different ASM are evaluated by point of view of return on investment. There is not deep study in how to optimize cash flows, but analysis of macro differences among different approaches to services provision. Since the aim is staying in the context of Italian electricity market, revenues come directly by remunerations scheme from Italian grid code. There is also a comparison for an investment on BESS providing Ancillary services in German context. A statistical analysis has been carried out to give an overview of the remuneration schemes in these two countries and to set the parameters for economic simulation.

5.1.1 Statistical study of revenue streams for PCR and SCR on Italian and German ASM

An analysis using studies and data from market managers allowed to define scheme for remuneration of PCR and SCR in Italy and Germany reported in Table 5-1.

Table 5-1 PCR and SCR scheme for Italian and German ASM

	Italy [9] [11] [103]	Germany [89]
PCR	1.5% of P_n reserve, symmetric, permanent (mandatory service)	2% of P_n reserve, symmetric, weekly auctions
Remuneration type	Energy, fixed remuneration by Grid Code	Capacity, pay-as-bid
Average prices	-35€/MWh negative; 85 €/MWh positive (as of 2017)	2700 – 4700 €/MW/week
SCR	Positive and negative reserve, symmetric, 4-hours auctions	Positive peak/off-peak; negative peak/off-peak, non-symmetric, weekly auctions
Remuneration type	Energy, pay-as-bid	Capacity + energy, pay-as-bid
Average prices	-25€/MWh negative; 110 €/MWh positive	Incremental: 800 – 1800 €/MW/week + 85 – 65 €/MWh Decremental: 200 – 2000 €/MW/week + (-50) – 0 €/MWh

These numbers lead to possibility of finding an overall average remuneration of the MWh for PCR and SCR (by finding average MWh exchanged per MW offered, capacity payment can be translated in energy payment):

Table 5-2 Average prices €/MWh estimated for Italian and German ASM

	ITA	GER
€/MWh PCR	25.00	217.65
€/MWh SCR	42.50	98.00

To allocate remuneration on the single MWh and compare among Italian and German situation, some hypotheses have been done:

1. Efficiency of BESS is 100%.
2. Over a period, net energy exchange due to services provision is null. This means that positive and negative Reserves are used in same amount during time. Therefore, same MWh were purchased and sold for positive and negative service provision. To verify this hypothesis for PCR, it is sufficient to state that average value of frequency in long periods is within the dead band: since droop control law is symmetric and linear, positive and negative Reserves have been used in long period in same amount. This hold in Central Europe (CE) Synchronous Area [104]. For SCR in Italy, following same reasoning, the average Segnale di Livello value should be 50. In a 4 months analysis, from February to May 2017, average value was 41.8 [100]. It has been judged close enough to 50 to approve this hypothesis. So, payment for each unit of energy is defined as follows.

$$energy\ remuneration_1 \left[\frac{€}{MWh}\right] = \frac{\left(energy\ remuneration_{pos}\left[\frac{€}{MWh_{pos}}\right] + energy\ remuneration_{neg}\left[\frac{€}{MWh_{neg}}\right]\right)}{2 * mean\ gross\ energy\ exchange\ \left[\frac{\frac{MWh}{MW}}{period}\right]} \quad 5.1$$

The remuneration on energy is based on the differential among positive and negative price (with a plus since the latter is negative). The value 2 at denominator is due to the fact the differential is gained every 1 MWh positive and 1 MWh negative exchanged = 2 MWh.

3. Remuneration in capacity over the period, for positive and negative Reserves, can be allocated equally on each unit energy utilized by each reserve, by simply dividing:

$$energy\ remuneration_2 \left[\frac{€}{MWh}\right] = \frac{average\ capacity\ remuneration\ \left[\frac{\frac{€}{MW}}{period}\right]}{mean\ gross\ energy\ exchanged\ \left[\frac{\frac{MWh}{MW}}{period}\right]} \quad 5.2$$

4. Ratio MWh/MW per period used in 5.2 is known. They are computed using the inputs utilized for the whole study: frequency logs for PCR and Segnale di Livello for SCR (therefore, SCR requirements are related to Italy). By having inputs and the relation among inputs and power requested (droop control law with 0.075%/P_{regPCR} fixed droop for PCR and regulating band for SCR), power requirements for each instant can be computed. From power requirements, it is straightforward to obtain energy requested for a period. The numbers shown in Table 5-3 are the average values for the weeks among February and May 2017 for SCR and February and March 2017 for PCR (input data on frequency were limited to that period). Those numbers are related to 1 MW of regulating band offered for PCR and for SCR. Who offers a certain SCR band is generally exchanging more energy than the one offering same band as PCR. The figures obtained are in Table 5-3.

Table 5-3 Gross energy requirements per service

PCR	**17.0 MWh/MW/week**
SCR	25.0 MWh/MW/week

Following the assumptions up to now proposed, the numbers in the table are gross numbers that can be divided by two to obtain positive and negative energy flows (i.e.: 8.5 MWh/MW/week for positive Primary Reserve, etc.)

This analysis shows large differences among the first and second system of services remuneration. By simply multiplying the numbers in Table 5-2 and Table 5-3, the different remunerations per week can be compared, for a unit offering 1 MW of regulating band for both PCR and SCR.

Table 5-4 Revenues per week

	Italian	German
PCR revenues [€/week]	425	3700
SCR revenues [€/week]	1063	2450
TOT revenues [€/week]	**1488**	**6150**

Indicative weekly revenues for PCR and SCR provision in Table 5-4 show how German market is more remunerative than Italian one, with the first featuring more than 4 times the revenues of the latter. Main differences come from PCR remuneration. These are the revenues that can be earned by a hypothetical device providing perfectly the services mentioned in a standard week by offering and always complying with 1 MW band offered for PCR and 1 MW band offered for SCR. No market and technology constraints have been considered. This revenue can be considered a theoretical maximum revenue for standard period. The aim is just showing the relative magnitude of remuneration in two different frameworks, Italian and German. The simulations in this Chapter will instead clarify revenue streams for a BESS providing PCR and SCR with specific regulating bands. BESS have to deal with finite energy content, therefore with variable regulating bands available and with LOR.

This statistical analysis was considered of interest since it provides strong qualitative outcomes on the two ASM frameworks analyzed. Germany is remunerating more than Italy the Ancillary Services provision. Furthermore, Germany is remunerating better PCR than SCR. This is perfectly agreeing with the trend in countries highly RES-penetrated of rising importance of Frequency Containment services. Germany saw a large increase in wind and PV generations in last years (see Paragraph 3.4.3) and it acted consequently giving importance for PCR. In Italy, PCR is a mandatory service for large-scale units, remunerated only if requested. The same rise in non-programmable RES-E has been seen also in Italy, but no adaptation of remuneration scheme has followed.

After this statistical analysis, in next Paragraphs the study approaches simulations: all cash flows considered in the study of output of simulations are presented.

5.1.2 Italian framework

In this economic study, *C* will be used for costs (they appear with a minus in NPV); *P* will be used for profit (the revenues, appearing with plus in NPV); *p* will be used for single unit prices (a negative price indicates a cost for the user). The reference period is one month (30 days). Number of years for investment (*N*) has been taken as 20 (long-term investment). Revenue streams in Mercato Servizi di Dispacciamento (MSD), the Italian ASM, have been already presented and here below are detailed and discussed.

For PCR, remuneration in Italy comes by grid code, is energy-based and it is not subject to a market. PCR is a mandatory service involving 1.5% of nominal power of each relevant unit (> 10 MVA, programmable unit). Grid code defines remuneration as a function of zonal price. In the model, average remunerations for positive (p_{PCRpos}, [€/MWh]) and negative (p_{PCRneg}, [€/MWh]) PCR in 2016 [9] have been computed as follows:

$$P_{PCR} = 12 * (E_{PCRpos} * p_{PCRpos} + E_{PCRneg} * p_{PCRneg}) \quad 5.3$$

$$p_{PCRpos} = 85 \frac{€}{MWh} \quad 5.4$$

$$p_{PCRneg} = -35 \frac{€}{MWh} \quad 5.5$$

Where E_{PCRpos} and E_{PCRneg} are in MWh and as absolute value. Since volatility of zonal price is not so high, the use of average remunerations instead of hourly PCR remunerations has been selected as feasible by Authors.

SCR in Italy is traded in ASM. Units participating make a bid with a hourly power offered for both positive and negative Reserve and two hourly prices, one positive for positive Reserve and one negative for negative Reserve. Every 4 hours, hourly offers for next 4-hours period are selected. The market simulated used hourly maximum positive and negative accepted price for each hour of the simulated period. The market:

1. Accepted an hourly positive offer if and only if the price of bid was lower than maximum price accepted that hour.
2. Accepted an hourly negative offer if and only if the price in bid was lower than the maximum price offered that hour. Since prices are negative, offered price was accepted if its absolute value was higher than the one clearing the market. I.e. if in hour *h* offered price for negative SCR is -35 and -20 is the maximum accepted, the unit is selected for negative provision.

Therefore, revenues by SCR are:

$$P_{SCR} = 12 * \sum_{h}^{24*30} P_{SCR}(h) \quad (5.6)$$

$$P_{SCR}(h) = E_{SCRpos}(h) * p_{SCRpos}(h) + E_{SCRneg}(h) * p_{SCRneg}(h) \quad (5.7)$$

Given that $E_{SCR(+,-)}(h)$ is different from 0 only in case offered price has been accepted for that hour and for that Reserve.

After revenues, a description of costs considered is presented. Operation & Maintenance costs have not been considered since cost of investment (C_{inv}) is taken as an all-inclusive offer by producer of BESS. Replacement cost (C_{rep}) has been defined as 50% of investment cost. Replacement is taking place at EoL of the battery. 50% is justified by the fact that inverter and auxiliaries can last more than battery and that battery price is exponentially decaying. Furthermore, battery can be sold at EoL: 80% capacity is still a performance of interest for stationary use [105]. Figures used are:

$$C_{inv} = 400 \frac{k€}{MWh_{installed}} \quad (5.8)$$

$$C_{rep} = k_{rep} * C_{inv} \quad (5.9)$$

$$k_{rep} = 0.5 \quad (5.10)$$

Actualization rate used was 6% (medium-risk investment):

$$r = 0.06 \quad (5.11)$$

Residual Value (RV(N)) of BESS is accounted by dividing value of BESS (replacement cost) by the years of life of BESS (lifecycle due to cycle ageing) and by subtracting this number times (N – year of replacement):

$$RV(N) = C_{rep} * \left(1 - \frac{N - year\ of\ last\ replacement}{BESS\ lifetime}\right) \quad (5.12)$$

Main indexes used for the analysis are:

1. Net Present Value (NPV): it evaluates the profitability of an investment at a certain year N by analyzing net cash flows (incomes – costs) of each year of investment up to that year. A discount rate or actualization rate r is used to take in account cost related to loan. The equation of NPV is:

$$NPV[€] = -C_{inv} + \sum_{y=0}^{N} \frac{NCF(y)}{(1+r)^{y}} + RV(N) \quad (5.13)$$

The elements of the formula are explained below.

a. NCF(y) is the Net Cash Flows relative to year y. It includes the sum of the revenues by services provision and the cost of investment or replacement of BESS. BESS is bought at year 0 at an investment cost (C_{inv}) and replaced at End of Life. Replacement costs are equal to a coefficient k_{rep} within 0 and 1 times the investment cost.

$$NCF(y) = P_{PCR} + P_{SCR} - C_{rep}(y) \tag{5.14}$$

With Crep(y):

$$C_{rep}(y) = \begin{cases} C_{rep} & if \quad y = (k * BESS\ lifetime) \ \ (k = 1, 2, 3, \dots) \\ 0 & elsewhere \end{cases} \tag{5.15}$$

b. RV(N) is the residual value at year N, computed as defined before.

2. Payback Time (PBT): it is the index indicating the year in which NPV gets over 0.

3. Profitability Index (PI): it will be just used when comparing investments of different size, i.e. when the study will deal with most convenient EPR for the Multi-service application. This index puts in relation NPV and C_{inv} by computing the ratio among these two quantities. PI measures the amount of value created per unit of investment. The larger is PI, the more € can be obtained by putting the same initial amount of €. PI is defined as:

$$PI = \frac{NPV}{C_{inv}}$$

Also Cost of Cycle (computed as in equation 3.12) have been used in this study. It defines the opportunity of performing or not a cycle. For the battery modeled, in case of EPR = 1, it is:

$$CostOfCycle = 35 \frac{€}{cycle} = 17.5 \frac{€}{MWh} \tag{5.16}$$

Each cycle allowing to equal or overtake this revenue is attractive by economic point of view. The value of the MWh is more useful for the computation done in this study: every service provided by this BESS should have differential among positive and negative Reserve's remuneration greater than 17.5 €/MWh, otherwise the provider is actually losing money by providing the service.

5.1.3 German framework

In the final part of the study, a brief parenthesis is dedicated to the possibility of proposing the same investment in the German market. Revenue streams are much different and more attractive in that market. The study just modified the Revenues values by keeping constant market structure: the permanent PCR provision and the 4-hours SCR market are kept constant (with asymmetric SCR), but prices are substitute with average German remunerations. German remunerations are both based on capacity and energy. There is so a need of update of P_{PCR} and P_{SCR}. Source is the analysis previously done.

For what concerns PCR, just capacity-based payment is in place. Revenues are computed as follows.

$$P_{PCR,GER} = 12\, months * \frac{30 \frac{days}{month}}{7 \frac{days}{week}} * P_{regPCR} * p_{PCRweekly} \tag{5.17}$$

$$p_{PCRweekly} = 3700 \frac{€}{\frac{MW}{week}} \tag{5.18}$$

For SCR, both energy and capacity payments, considered here by taking average prices following analysis done:

$$P_{SCR,GER} = 12 * \left(E_{SCRpos} * p_{SCRpos,GER} + E_{SCRneg} * p_{SCRneg,GER} + 4 * P_{regSCR} * p_{SCRweekly}\right) \quad 5.19$$

$$p_{SCRpos,GER} = 75 \frac{€}{MWh} \quad 5.20$$

$$p_{SCRneg,GER} = -25 \frac{€}{MWh} \quad 5.21$$

$$p_{SCRweekly} = 1200 \frac{€}{\frac{MW}{week}} \quad 5.22$$

The way of computing NPV and PBT remains the same.

5.2 Empirical model validation

Before entering the analysis of simulations done, it is necessary to offer the validation of empirical model performed in order to use it in the framework of this study. Empirical model validation took place during the study, although it is anticipated here to avoid stopping the flow of case studies when starting analysis of simulations. Electric model implemented in Simulink by BESS4PCR tool [2] shows limited computational speed. A simulation over 1 month is performed in 12-14 hours. During the study, interest towards increasing the number of simulation to analyzed different sizing and different provision of grid services foster the interest towards validation of the empirical model described in 4.1.3. Empirical models guarantee lower computational effort but imply some loss in accuracy while approximating some particular behaviors of battery operation. Specifically, it has been already described how empirical model can offer inadequate precision when SOC level is above 90% and below 10%, when c-rates required are very high and when ambient conditions are far from experimented ones. The study performed in this work should not involve high c-rates and extreme ambient conditions. Sometimes it can involve SOC values close to saturation limits. To verify adequacy of empirical model in approximating electric one, some tests on real-operating cycles and test cycles have been carried out. In detail, some simulations involving provision of PCR and Asymmetric SCR (conditions of CASE D and CASE E analyzed in Paragraph 5.7 and 5.9) with different bands and EPR of battery have been performed by using both models. And the two models performed a test featuring square wave power inputs for 2 hours. To qualitatively and quantitatively understand the degree of accuracy, both superposition of logs and computation of gross energy flows over the simulation have been performed.

For what concerns the real-operation tests, energy flows cycled in simulating period of one month, for provision of both PCR and SCR, shown differences always below 4%. This means that the difference among both positive and negative energy flows during the whole month by the two models always stayed in the interval 2-4%.

A comparison by eye is given in Figure 5-1 for SOC and LOR logs of the two models (days 1-10):

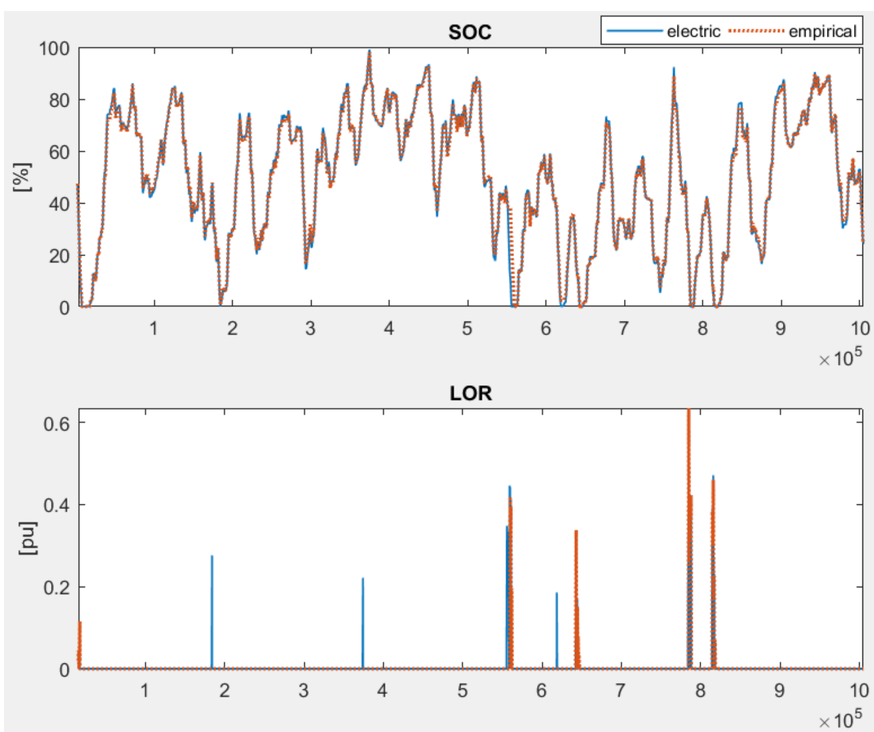


Figure 5-1 SOC and LOR comparison for electric and empirical model on real-operation test

Empirical SOC is almost overlapping electrical. Some more LOR computed for electric model. Anyway, since average c-rates of real operation for this study are always around 0.1 and maximum c-rate is almost always limited to 0.65, accuracy is high. Divergences of the models are larger when close to SOC saturation. In Figure 5-2 there is a detail of a sector of simulation in which SOC is stuck to lower saturation limit. Comparison shows the difference among the models, with empirical model getting prompt to limit, while electric one decreases output while reaching it. Empirical model stays steady and stuck to SOC_{min}, while electric model cannot get to minimum due to voltage limits, therefore it undergoes unsteady behavior, getting closer and farther from limit without reaching it. The result is that electric log is detached from empirical one while departing from limit. Anyway, next session of market (and different regulating bands offered), will take the models back to overlap. Since LOR is very low from CASE D on, where this model is utilized, these instants are few tens of minutes during a month.

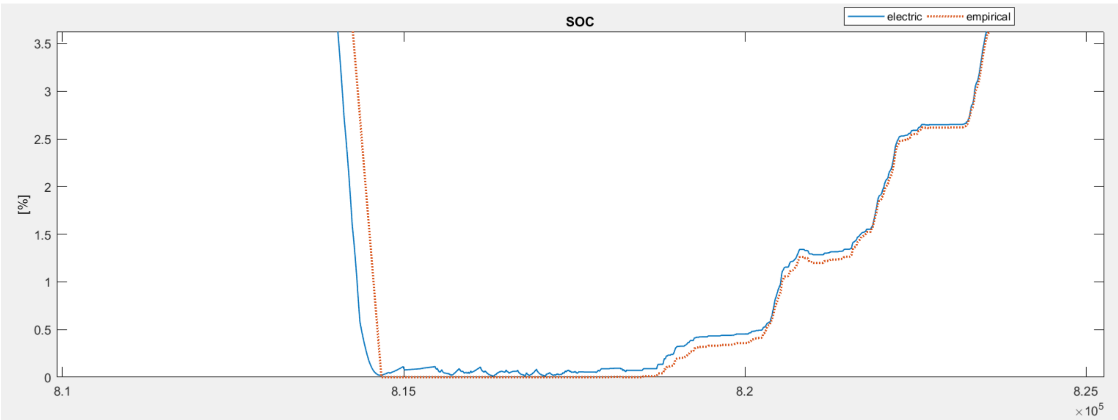


Figure 5-2 SOC behavior for electric and empirical models at saturation

The model is tested to be used in simulations from CASE D on. Time of simulation is decreasing from 12 hours to 15 minutes, reducing by a factor of 50. This improvement in possibilities of performing more simulations and analyze more cases led to accept a marginal decrease in accuracy of less than 5%. Another test has been carried out on a square wave with 0.5 c-rate. Still divergence is slight: 1% SOC less for electric model after 2-hours test, with difference in energy flows among the two models of 6%. Model was selected to be used in final part of the study, allowing to increase number of cases simulated.

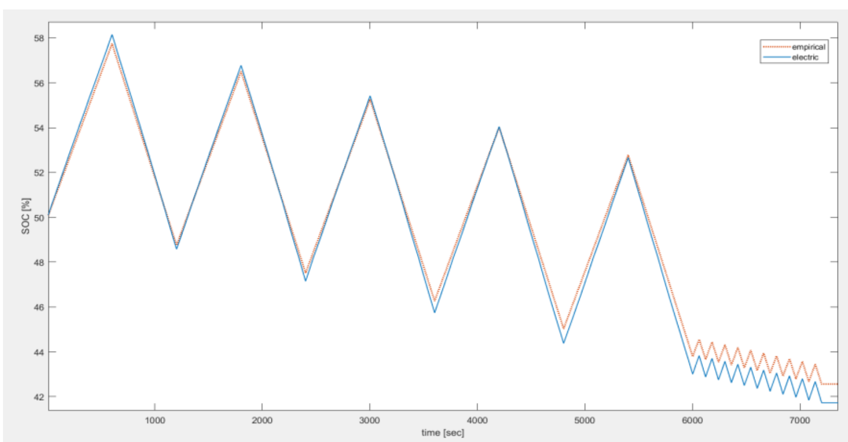


Figure 5-3 SOC comparison on a square wave power profile among electric and empirical model

5.3 Technical parameters and simulations set-up

After defining the parameters for economic evaluations and validating the model used, study finally passes to simulations. Definition of the BESS parameters used throughout all the simulations is here below detailed and explained. A battery is characterized by its nominal power, its nominal energy, by its technology. Each simulation is instead characterized by the period of evaluation, the inputs data, the initial SOC, the sampling rate of its inputs and outputs. Simulation of a BESS providing grid services is characterized by the regulating bands offered for each service and the way to implement them.

The battery characterization starts with the choice of nominal power. Projects analyzed all over the world utility-scale, set power from some hundreds of KW to tens of MW. With arbitrary choice, power was set to 1 MW. It can be expected by a private investor some hesitations in an investment of more than 1 million in a technology and application still not solid. Furthermore, 1 MW is a number easy to be scaled up, providing more prompt understanding of quantitative results. Once defined power, the relation with energy is fundamental in BESS. This is because in batteries, both energy and power content are related to the device. EPR provides this relation. Paragraph 4.3.3 analyzed a study on EPR consistent with provision of PCR (0.5 per unit regulating band) and SCR (0.8 per unit regulating band). A range of EPR values consistent with this services spans from 1.03 to 1.93 h. EPR was set to 2, taken as upper limit of this interval. It is a prudent choice to give priority to security of grid and lower LOR. It implies larger investment cost, therefore it could be penalizing in terms of economic return. EPR = 2 has been set as a constant basis for most of the study, to allow same investment cost and direct comparison of NPV. In the end of the study the optimal sizing of battery is also analyzed, relaxing the constraint on constant EPR. Technology of battery chosen is related to model used. Model approximates the behavior of a Li-ion battery, the Swing® 5300 by Boston-Power. Lithium ions batteries are the predominant technology for future of BESS. This study aims to stay general and propose mainstream solutions, since the aim is working on the strategy and control of battery operation more than evaluating a specific technology. In this view of the problem, Li-ion was the natural choice. For what concerns ageing, evaluation of lifetime will follow what described in Paragraph 4.1.6. Lifetime of batteries will be the minimum among 12 years (calendar ageing) and cycle lifetime coming from SOH estimation via the diagram linking capacity-fade per cycle and average c-rate presented in Figure 4-5. In the year of the EoL, replacement cost will take place, computed as 0.5 times cost of investment. As before described, this number has been selected since the prices of BESS are exponentially falling and since power electronics and auxiliaries are expected to last more than battery, therefore are not replaced so frequently.

All simulations are spanning the same 33 days period, from February 15 to March 19, 2017. Then, results are rescaled on monthly basis. This decision was made to have the as large as possible period of analysis, limited by the 33 days-long logs of frequency. Longer period allows less bias linked to peculiarity of the single day. 3 days means an increase of 10% in time of simulation. Results on monthly basis are instead of easier consultation. Logs of frequency are first-hand data coming from IoT-Storage Lab in Department of Energy of Politecnico di Milano. Data on regulating signal for SCR (Segnale di livello) come instead from Italian TSO website [100]. Market data for Italian framework (prices for units selected for each one of SCR Reserves) come from market manager website [101]. In case of German prices, they are taken as average prices from a statistical study [89], as already introduced. Sampling rate of inputs is 1 Hz. It has been considered sufficient for the study. The precision offered by 1 Hz setpoint-following is larger than precision offered by conventional units providing same service (PCR, since SCR in Italy sends a setpoint per minute). The initial SOC is set to 50% as arbitrary choice. Regulating band for PCR is symmetric, constant and given as input by user. Initial regulating bands for SCR provision are consistent with initial SOC of 50%. For computing regulating bands of SCR, statistical index of SOC variation caused by each service are needed. This statistical data are numbers defining the maximum reasonable SOC variation caused in 4 hours for provision of each service. They are computed as described in Paragraph 4.3.1.1. The joint Confidence Level adopted throughout all the simulations is 95%. This means that PCR and SCR will cause a variation in SOC in 4 hours larger than the one foreseen by $variation_{(+,-)}$ and $avg_{segnaledilivello(+,-)}$ only in 5% of cases. LOR penalties were always set to 100€/MWh for both PCR and SCR, selected arbitrarily.

In Table 5-5 main parameters of simulations are reported. It is always specified if a simulation differs from this set up. For each simulation, taking as a reference a monthly period of 30 days, the elements listed below will be reported.

1. A table summarizing data on BESS and on simulation highlighting differences with respect to parameters introduced in Table 5-5.
2. The scope of logs from Simulink simulation (where applicable), featuring: SOC, c-rate, gross LOR, c-rate required for each service.
3. A table summarizing results of simulation in terms of: Energy flows for each service, LOR for each service, equivalent cycles, average c-rate, cycle ageing-related lifetime, revenue and penalty streams, net cash flows, PBT and NPV (20 years).

Table 5-5 Standard parameters for simulations

Description	**Value**
Type of model	Empirical
Simulation span	15 Feb – 19 Mar (33 days)
Sampling rate for inputs and outputs	1 Hz
Nominal power	1 MW
Maximum allowed power	1.3 per unit
EPR	2 h
Initial SOC	50 %
SOC max	100 %
SOC min	0 %
Maximum lifetime (calendar ageing)	12 years
PCR data	
Dead-band for PCR	±20 mHz
Fixed droop value	0.075% [equivalent to 5%]
SCR data	
SB	Asymmetric
Confidence level for estimation of SOC variations for each service	≥95%
Economic parameters	
Investment costs	400 k€/MWh installed
Replacement costs	50% of investment costs
Actualization rate	6%
LOR penalty	100€/MWh for both PCR and SCR

The final aim of these simulations, as before described in detail, is to manage a BESS providing grid services with minimization of LOR and maximization of economic return, expressed by NPV at 20 years. Besides, the provision of services must happen without SOC restoration strategy presenting energy flows on purpose for getting SOC back to 50%. This further requirement is thought, as already described, both to increase revenues for owner (no energy flows for SOC management to be purchased and paid) and to avoid regulatory issues. These latter can arise due to the fact of being a consumer and a producer of energy instead that just a provider of services. Instead of using dedicated energy flows for SOC restoration, the strategy aims to provide SOC management using convenient services in best mix. LOR below 5% can be indicatively defined an interesting result.

The reference case to start from is the one already described in [93] by Dr. Iurilli in Politecnico di Milano: PCR provision without SOC restoration mechanisms. Its analysis highlighted very high LOR level (above 20%), only decreasing when applying SOC restoration strategies. That result was achieved with EPR of 1.1 h, considered as best by economic point of view. Different results, in the direction of higher security of grid, could be reached by using EPR = 2 h. Therefore, the starting case is PCR provision. Then the procedure is adding SCR, with symmetric and then asymmetric Reserves, to define its quality in providing SOC restoration.

Only after having found a mix of Ancillary services allowing low LOR level, economic return will be optimized. For the economic optimization, two main strategies have been selected, by facing the problem by both the points of view of the TSO and of the battery owner. TSOs, as described in 3.4, are intensifying interest towards PCR and enhanced forms of Frequency Containment in last years. BESS can be the best provider of these new forms of Primary Regulation, given its precision and the almost unlimited ramp rate allowing fast response. TSO can act by defining a consistent price of PCR for increasing attractiveness towards multiple service provision. TSO can even design a different setup of PCR, allowing increased security and guaranteeing more remunerations. On the opposite side, owner of battery can design the best device to put on field. This means, primarily, to size correctly the battery: optimal EPR of the battery for economic return can be analyzed.

In Table 5-6, the cases analyzed are briefly summarized.

Table 5-6 Simulations summary

		PCR band [per unit]	Max SCR band [per unit]
CASE A	Reference case	1.0	-
CASE B	PCR + SCR	0.5	0.8 (Symmetric)
CASE C	Asymmetric SCR	-	1.0 (Asymmetric)
CASE D	PCR + Asymmetric SCR	0.5	0.8 (Asymmetric)
CASE D2	PCR + Asymmetric SCR with minimum droop (0.03%/P_{regPCR})	0.5	0.8 (Asymmetric)
CASE E	Study on EPR optimal	0.5	0.8 (Asymmetric)
CASE GER	German remuneration	0.5	0.8 (Asymmetric)

Layout of the Chapter is the following.

1. In 5.4 the analysis of provision of PCR only is presented (CASE A).
2. In 5.5 is simulated PCR and SCR services as from Italian rules (CASE B).
3. In 5.6 there is the introduction of Asymmetric SCR (CASE C).
4. In 5.7 is provided the first example of multiple services provision with asymmetric service. The simulated case is with PCR symmetric and SCR asymmetric (CASE D).
5. In 5.8 is presented a study on PCR remuneration. The aim is providing attractiveness in simultaneous provision of PCR and SCR by analyzing PCR with different droops and by hypothesizing a PCR remuneration scheme (comparison CASE C – CASE D – CASE D2).
6. In 5.9 an analysis on optimal EPR for provision of PCR and SCR is presented (CASE E).
7. In 5.10 a comparison among Italian and German revenues is detailed (comparison CASE E – CASE GER).

5.4 Reference case: PCR provision only

As introduced, this study moves from an initial case already studied in Politecnico di Milano: provision of PCR only. PCR is a service mandatory in Italian framework. Therefore, it is not traded on the market and only marginally remunerated. Primary Reserve is anyway a service with rising importance in the scheme of ASM of countries with high RES penetration. PCR is evolving: inertia of the grid is decreasing due to rise of inverter-based systems. Consequently, an unbalance causes larger deviation of frequency with respect to the past. The choice made by Authors is using provision of Primary Regulation as reference case to define the relative improvements detected. In this moment of the study empirical model has not been validated yet. The interest at the beginning was in doing few simulations as accurate as possible, even by considering that there was not information on the amount of time passed at SOC close to saturation, where empirical model can differ by electric one. Therefore, electric model is used in this CASE A. Nominal power of battery considered is 1 MW and EPR is 2 h. For the implementation procedure for PCR, refer to Paragraph 4.2.1.

CASE A: PCR	
PCR power band	1.0
SCR power band	0
Notes	
Model type	Electric

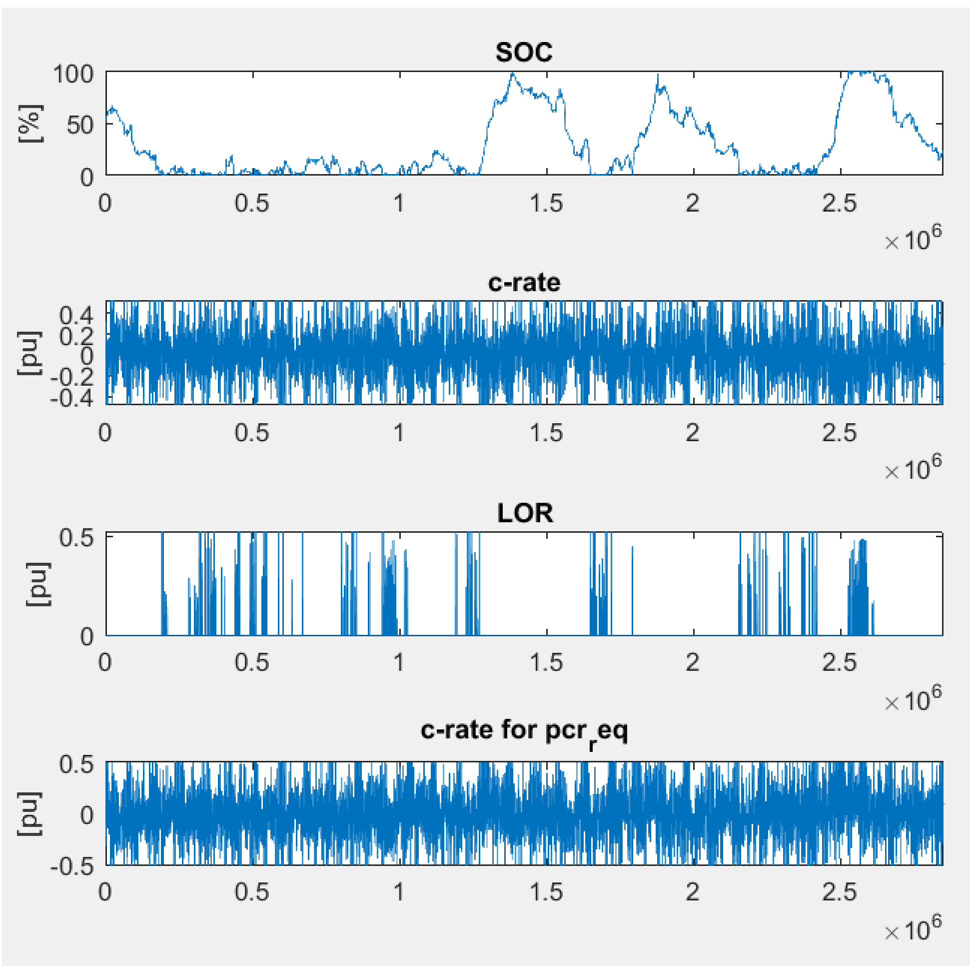


Figure 5-4 Results of simulation for PCR provision

RESULTS PCR		
Energy		
PCR positive	38.89	MWh
PCR negative	41.27	MWh
PCR gross	80.16	MWh
Gross total	80.16	MWh
PCR LOR ratio	13.16	%
Equivalent cycles	20.06	1/month
Average c-rate	0.05	
Life (cycle ageing only)	27.68	Years
Monthly Cash flows		
PCR net revenues	1268.79	€/month
LOR penalties	653.80	€/month
Net Cash Flow	614.99	€/month
PBT	-	Years
NPV (20 years)	-813.0	k€

From the point of view of performance results of simulation show large LOR. As can be seen by logs of SOC it is used to get to saturation limits. When battery gets to saturation limits, there is not a strategy to bring it towards safer values. The outcome is that the provision of service only depends on the conditions of grid: if SOC is close to upper limit and negative power is asked, battery cannot provide it. If it is at lower limit and it is asked to inject power in grid, there is LOR, too. Battery energy band is not well exploited. Cycles of battery have low Depth of Discharge (DOD) since the SOC variation they provide is very low. Even power band is exploited less than possible. Maximum c-rate is 0.5 since maximum power is 1.0 per unit and EPR is 2 hours. Equivalent cycles per month are around 20. This implies low c-rates and calendar ageing overcoming cycle ageing: battery gets older even if it has not been exploited. Lifetime is set to 12 years, led by calendar ageing, based on study described before. Given the low level of energy cycled, even economic return is extremely far. Therefore, battery is both not controlled and not sized consistently with its application. There are several ways to improve PCR provision.

The first one is sizing correctly the battery. EPR so high is not feasible for this application, that is not energy intensive. Statistically maximum SOC variation in 4 hours have been computed as (26/EPR) %. This means that it would require at least 8 hours of contribution in same direction to span SOC from 100% to 0 and vice versa. In fact, SOC performs cycles with 100% DOD only 3-4 times per month. EPR lower would be feasible and would imply lower investment cost.

Second way is to act on regulating power band. It could be increased to have higher maximum c-rates and higher number of equivalent cycles per month. A consistent sizing and power band for PCR provision only have been found by Dr. Iurilli in his study. EPR of 1 h and power band of 1.1 per unit are set as economic optimal for PCR provision. Even in that case, without SOC restoration mechanisms active, there is a large share of LOR (around 20%).

Therefore, third way to provide PCR more conveniently can be to add SOC restoration strategy. This leads to low LOR. Mixed with good sizing and good choice of power bands it can lead to interesting results. This work does not want to implement active SOC restoration mechanisms for reasons already discussed. SOC restoration mechanisms imply energy flows to be purchased and increase ageing due to higher c-rates.

Therefore, the choice made is to implement other Ancillary services. Within staying in the rules and priorities of Italian ASM, SCR has been selected.

5.5 Italian ASM situation: PCR and SCR

The provision of PCR only showed negative results by both point of view of performance and economic return. Therefore, this study passes to implementation of simultaneous PCR and SCR provision in framework of actual Italian ASM. SCR provision is subject to a market happening every 4 hours and contracting 4-hours periods (6 market sessions per day of MSD ex-ante and MB [101]). The provision of SCR is made on symmetric Reserves. Still a 1 MW battery with EPR of 2 hours is modeled by using electric model. Implementation of SCR is performed as described in Paragraph 4.3.1.2.

CASE B: PCR + SCR - Italian ASM	
PCR power band	1.0
SCR power band	0.8
Notes	
SCR method	Italian ASM rules
Model type	Electric

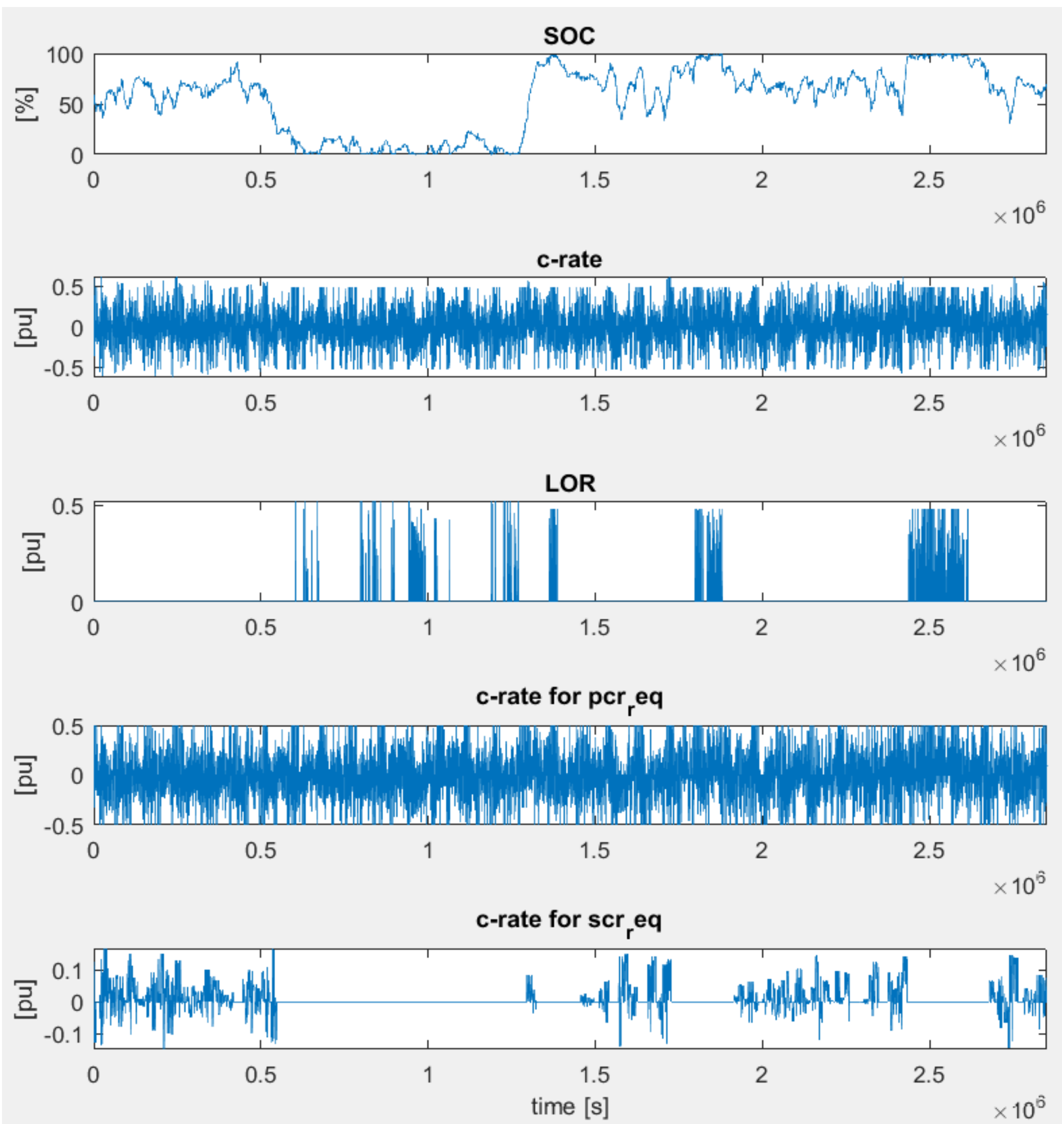


Figure 5-5 Results of simulation PCR + SCR in Italian ASM

RESULTS PCR + SCR ITALIAN ASM		
Energy		
PCR positive	38.89	MWh
PCR negative	41.27	MWh
PCR gross	80.16	MWh
SCR positive	20.25	MWh
SCR negative	6.81	MWh
SCR gross	27.06	MWh
Gross total	107.22	MWh
PCR LOR ratio	11.50	%
SCR LOR ratio	0.00	%
Equivalent cycles	24.28	1/month
Average c-rate	0.06	
Life (cycle ageing only)	22.35	Years
Monthly Cash flows		
PCR net revenues	1691.82	€/month
SCR net revenues	2441.64	€/month
LOR penalties	838.39	€/month
Net Cash Flow	2589.54	€/month
PBT	-	Years
NPV (20 years)	-465.5	k€

With respect to CASE A with only PCR provision, the addition of SCR does not change sensibly the outcomes. These is still no PBT within 20 years. NPV is largely negative. LOR is still above 10%. Still the same issues on exploitation of energy band are shown: battery sees a first 10-days period of saturation to lower level, then a period of equal length of hitting of upper SOC saturation limit. Equivalent cycles are still around 20 per month. Calendar ageing is predominant over cycle ageing, therefore lifetime is set to 12 years.

Battery behaves very similarly to what happened in case of PCR provision only, and this is no surprise. It depends on behavior of SCR variable regulating band, computed as in equation 4.39. It is large when initial SOC entering in market session is around 50%. Since the values of $avg_{segnale\ di\ livello+}$ and $avg_{segnale\ di\ livello-}$ are both around 0.4 and the maximum variation of SOC in 4 hours due to PCR provision is reported in 4.47, regulating band with respect to initial SOC can be computed. If SOC is 50% at beginning of 4-hours period, SCR band in both directions (symmetric Reserves) is 0.52 per unit. And this is the maximum value of band can be asked for SCR. Maximum c-rate requested over the simulation period, given EPR of 2 h, is therefore 0.26. Since Segnale di Livello is not always requesting the whole band, only some minutes over the whole month ask more than c-rate 0.1 for SCR provision. This is shown in Figure 5-5 in c-rate for SCR diagram. Therefore, main contribution to power setpoints requested to cell still comes from PCR provision (energy flows for PCR are more than 3 times the ones for SCR). Furthermore, when getting to SOC saturation limits, band for SCR decreases. Band dedicated to SCR becomes 0 for SOC higher than 93% and lower than 6%. Any help can come from SCR for SOC restoration close to saturation limits because there is no SCR provision at all. There are no studies, in fact, indicating symmetric services as useful for SOC management in batteries.

There is necessity for a service able to increase regulating band in the direction bringing SOC back to 50%. Next steps of simulation will implement SCR asymmetric provision.

5.6 SOC restoration through services provision: SCR asymmetric

The superposition of two symmetric services as PCR and SCR in the context of Italian rules did not bring any better result in terms neither of LOR nor of economic return of investment with respect to PCR provision. Asymmetric services can be an interesting way to provide both SOC restoration and increase of economic return. In this simulation, PCR provision will be avoided to dedicate as much as possible regulating band to SCR. And asymmetric SCR will be implemented as described in detail in Paragraph 4.3.1.3. SCR only provision is used here to define an economic target in the forecast of reintroduction of multiple services provision in the continuation of this study: since SCR in Italy is much more remunerated than PCR, economic return of SCR provision only should be higher. A comparison among this simulation and a next simulation providing simultaneously PCR and asymmetric SCR will be used to define a convenient remuneration for PCR. Asymmetric SCR is provided here with maximum band set at 1.0 per unit, 1 MW of nominal power and EPR of 2 hours. Still the model in use is electric.

CASE C: SCR asymmetric	
PCR power band	0.0
SCR power band	1.0
Notes	
Model type	Electric

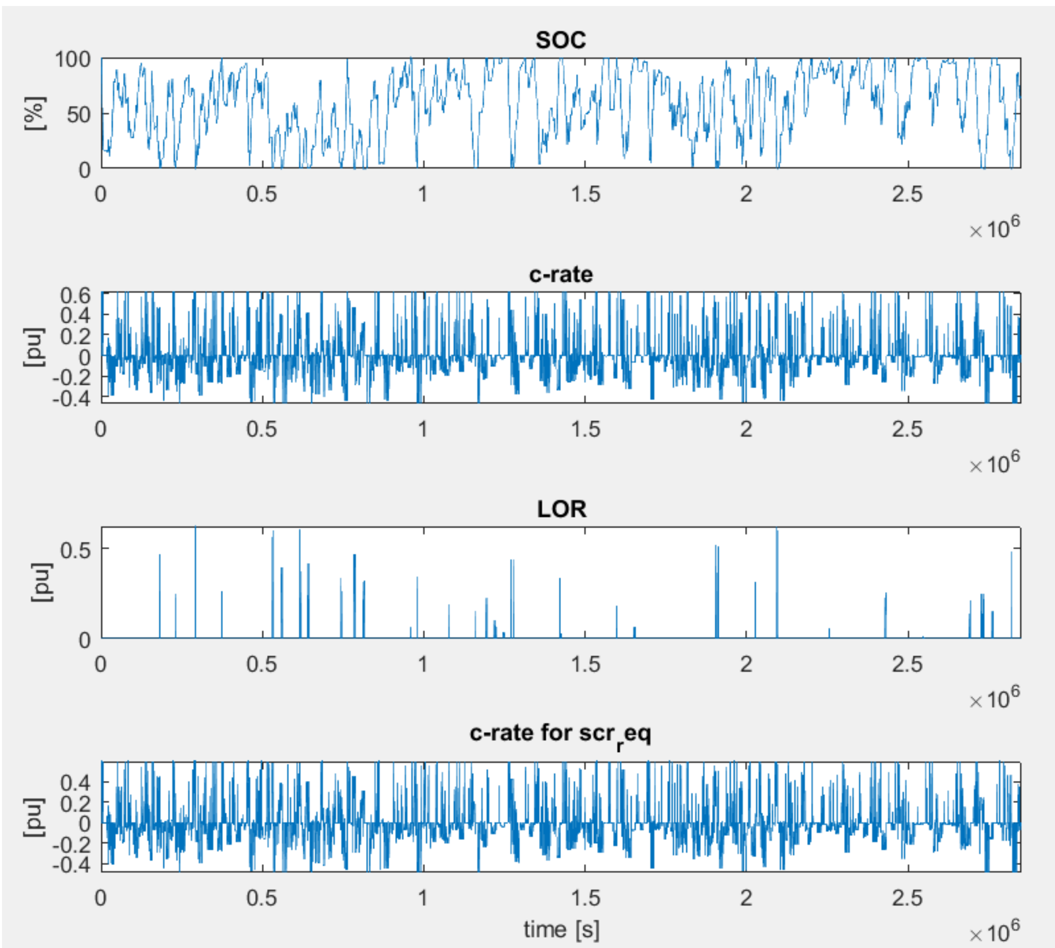


Figure 5-6 Results of simulation SCR asymmetric

RESULTS SCR ASYMMETRIC		
Energy		
PCR positive	0.00	MWh
PCR negative	0.00	MWh
PCR gross	0.00	MWh
SCR positive	97.66	MWh
SCR negative	105.90	MWh
SCR gross	203.56	MWh
Gross total	203.56	MWh
PCR LOR ratio	-	%
SCR LOR ratio	4.52	%
Equivalent cycles	50.60	1/month
Average c-rate	0.13	
Life (cycle ageing only)	9.35	Years
Monthly Cash flows		
PCR net revenues	0.00	€/month
SCR net revenues	10064.17	€/month
LOR penalties	836.33	€/month
Net Cash Flow	9227.85	€/month
PBT	12	Years
NPV (20 years)	298.6	k€

Outcomes of simulation of CASE C are completely different from previous ones. LOR is 4.5%, acceptable since below the selected acceptability threshold of 5%. NPV at 20 years is positive and PBT is 12 years. C-rate allows cycle ageing to overcome cycling ageing. Therefore, lifetime of the BESS is 9.5 years and no more 12. Revenues per month are around 4 times the revenues of CASE A and CASE B.

The reason is found in energy-band exploiting allowed by asymmetric SCR. Regulating power bands are completely resizing based on initial SOC of each interval (see Figure 5-7). If initial SOC is around 50%, as before, both regulating power bands are around 0.6 per unit. A bit higher than in CASE B since there is no provision of PCR leading to contribution to SOC variation. The divergence increases by moving toward one of SOC saturation limits. If initial SOC is 75%, for next 4 hours BESS is offering on market regulating band for positive Reserve equal to 0.94 per unit, and band for negative Reserve of 0.31 per unit. If initial

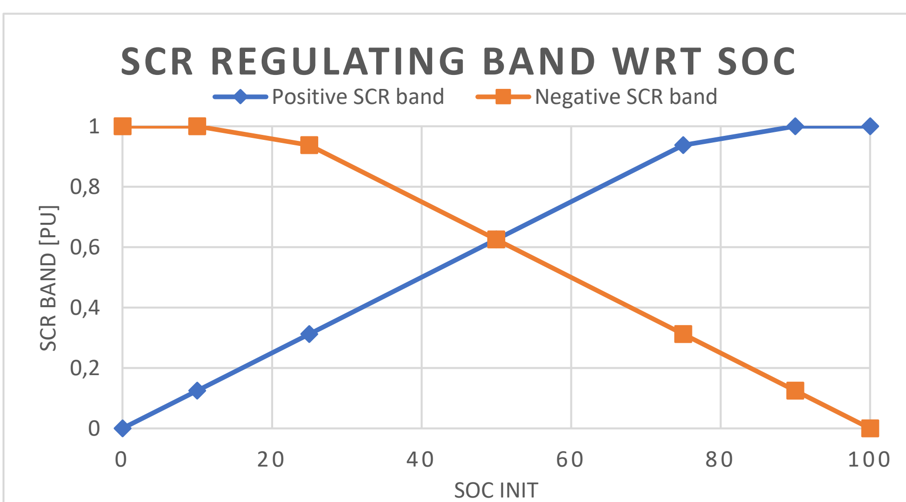


Figure 5-7 Band for SCR in CASE C with respect to SOC at the beginning of market session

SOC is 95%, band for positive Reserve computed by Band Management block (see Section 4.3) will be 1.13 and for negative will be 0.07. Since the maximum regulating band allowed for SCR is set to 1.0 per unit in this simulation, positive band will be set to 1.0. SOC evolution is therefore no more linked only to grid conditions. Battery Controller is deciding how much power is feasible to offer separately in each direction to avoid hitting SOC saturation limits. This is largely limiting LOR. Moreover, battery Controller can set regulating bands larger than before. As shown, maximum band in this case could be even larger than 1.0 per unit, while before it was limited around 0.52. This allows energy cycled to increase: SCR gross energy cycled is over 200 MWh per month. In CASE B, it was 27 MWh per month, due to both limitations in band and saturation of SOC.

This band management leads to the repeated cycles at large DOD (around 80%) shown by SOC diagram in Figure 5-6. Battery is exploiting the whole energy band. EPR, by eye inspection of logs that show "hilly" SOC profile, is convenient with its application. By c-rate logs is shown how power requested to battery is for some hour prevalently negative, then for next hours prevalently positive. This is how complete cycles are performed. CASE C proves the consistency of the regulating bands management strategy up to now only theorized. Provision of services, that is largely involved in unpredictability, can be managed to cause forecastable behaviors in SOC evolution.

Market is performing in a reasonable manner, too. Battery is selected for provision around 50% of sessions. The average prices of the market are reasonable: positive MWh is sold at average price of 133.4 €/MWh, negative MWh is bought at 18.5 €/MWh. Price signals are introduced in the bidding strategy: when SOC is high, price offered for provision of positive Reserve decreases. When SOC is low instead, price for negative Reserve provision increases its absolute value. This means that BESS pays more for purchasing energy when SOC is low, therefore is more likely selected by market. The mechanism implemented has already been explained in Paragraph 4.3.1.2.

In CASE C, provision of PCR has been left. This was to provide an optimal economic return given by provision of SCR as large as possible. This strategy is convenient if BESS is trading in Italian ASM. In most of the other countries, PCR is paid as much or more than SCR. And this trend of rising importance of PCR is increasing in many ASM. Even more services are under introduction as enhanced PCR or virtual inertia. This evolution should involve all the countries showing RES-E rising penetration, Italy included. Consequently, possibilities that PCR provision in Italy could modify in next years are not negligible. Change could involve both the requirements of the service, in direction of faster response, and an increasing remuneration of the service.

CASE D will analyze the reintroduction of PCR in provision, beside asymmetric SCR.

5.7 Multi-service: PCR and asymmetric SCR

Simulations get back to Multi-service. The interest is to verify if PCR and SCR can coexist and give positive return hypothesizing asymmetric Reserves for SCR. Two services provided simultaneously imply a management of bands more complex. SOC variation due to PCR will enter SCR regulating bands formation as described in equation 4.31 and 4.32, limiting SCR dedicated power. Even maximum SCR band allowed, given as user's input, has been decreased from 1.0 to 0.8 per unit to stay within limits imposed in Paragraph 4.3.2. It was in this time frame during the study, that empirical model validation was performed. Interest towards this procedure were fostered by forecast of several simulations to perform to try different droop values for PCR. These droops value will be experimented in CASE D2, presented after CASE D. The level of similarity among the different logs (SOC, LOR) and the limited difference among energy flows computed convinced in use of empirical model for the rest of simulations. Outcomes in energy flows and LOR terms from both modelling are shown in summarizing table to have a comparison.

CASE D: PCR + asymmetric SCR	
PCR power band	0.5
SCR power band	0.8
Notes	
Model type	Electric and Empirical

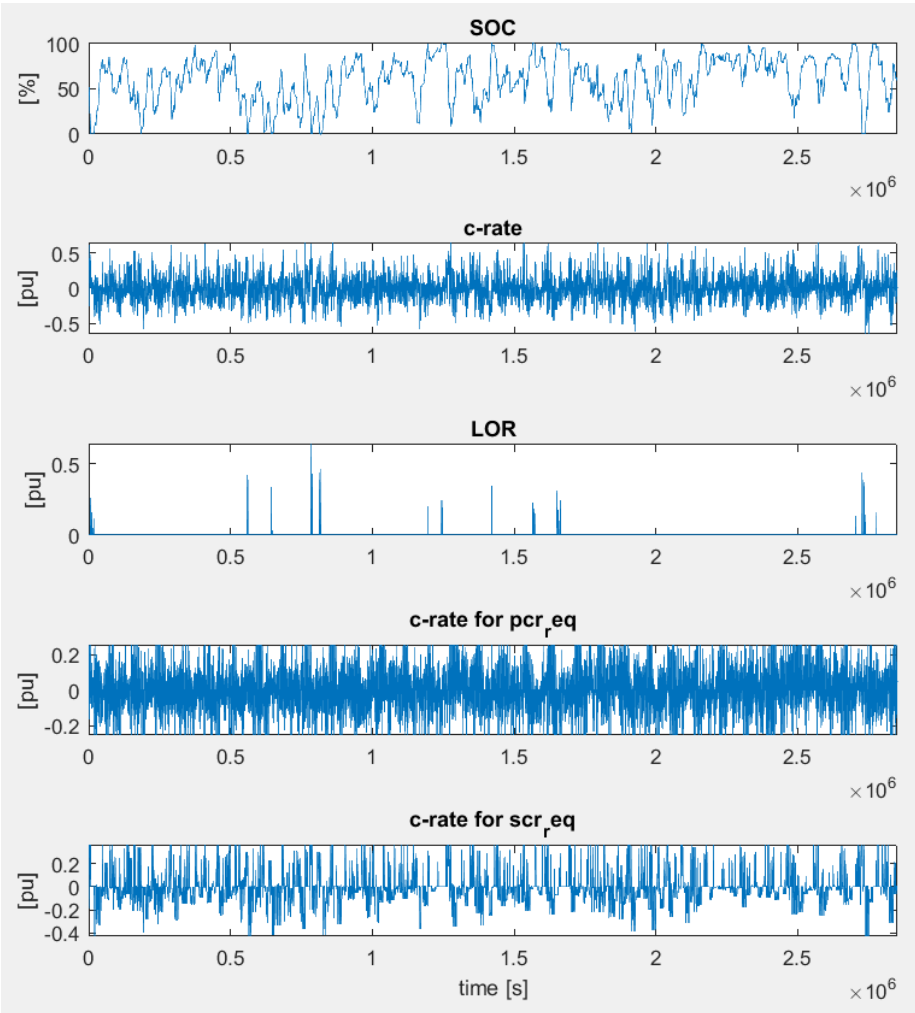


Figure 5-8 Results of simulation PCR + SCR asymmetric

RESULTS PCR + SCR ASYMMETRIC

Energy	Electric	Empirical	
PCR positive	19.44	19.44	MWh
PCR negative	20.64	20.64	MWh
PCR gross	40.08	40.08	MWh
SCR positive	61.76	64.74	MWh
SCR negative	72.45	73.03	MWh
SCR gross	134.22	137.77	MWh
Gross total	174.30	177.85	MWh
PCR LOR ratio	2.31	1.19	%
SCR LOR ratio	2.55	1.70	%
Equivalent cycles	39.89	39.83	1/month
Average c-rate	0.10	0.10	
Life (cycle ageing only)	12.52	12.54	Years
Computation time	12 hours	15 minutes	
Monthly Cash flows			
PCR net revenues		845.91	€/month
SCR net revenues		6629.42	€/month
LOR penalties		256.16	€/month
Net Cash Flow		7215.28	€/month
PBT		18	Years
NPV (20 years)		122.5	k€

CASE D represents the first setup of Multi-service with PCR and asymmetric SCR. Results in terms of performance are outstanding, reducing gross LOR for both services to 1.6% (2.4% if taking electric model as reference). The strategy of "passive" SOC restoration via asymmetric grid services provision works. The lower regulating band allocated for SCR allowed a further LOR decrease with respect to CASE C.

Inspecting SOC diagram in Figure 5-8, still the repeated cycles of large DOD through the whole month can be recognized. This is a marker of convenient exploiting of energy band. When SOC is high, a period in which positive power is required begins and vice versa. This happens thanks to the Band Management strategy implemented in the model Controller, that increases the band offered on market requesting power in direction of 50% SOC.

From the point of view of economic return, this case worsens the outcome of CASE C. PBT gets from 12 to 18 years. This is mainly due to the reduction of available bands of SCR. By repeating the computation shown for CASE C, if initial SOC of the 4-hours period is 50%, power band offered for SCR is around 0.55 per unit in both directions. If initial SOC is 75%, positive Reserve regulating band is 0.82 per unit, negative is 0.24. At 95%, positive regulating band is 1.06 and negative gets to 0. Given the limit on maximum band accepted, from 75% to 100% positive band is steadily 0.8 per unit. Vice versa, if initial SOC spans from 0 to 25%, negative band will be limited to 0.8 per unit. These limits come from analysis on maximum power feasible with BESS. A power lower of equal to 130% the nominal power has been defined feasible for both the battery and the inverter. Therefore, if BESS is providing 0.5 per unit power band for PCR, it cannot offer more than 0.8 for SCR provision. This means that nominal energy and nominal power of BESS are not perfectly mixed: more energy band could be exploited close to SOC saturation, but thresholds on maximum power are limiting provision. This issue will be analyzed in CASE E, where optimal EPR will be studied.

The interference among bands took to large decrease in energy cycled for SCR provision with respect to CASE C, only devoted to asymmetric SCR. Energy for SCR passed from a gross monthly total of 203 MWh, to 138 MWh. On the other side, energy for PCR passed from 0 in CASE C to 40 MWh. Sum of the two contributions leads to 178 MWh per month, lower than 203 MWh of CASE C. This could mean a possible improvement, as already said, in sizing of battery. And it can be a signal of possible improvement even in management of bands for the two services. As of now, the implementation of services as in CASE D allowed to reach an interesting result in terms of LOR. The point of view of the TSO can be satisfied by this certainty in the provision of service and therefore in the security of grid. Meanwhile, owner is still not attracted by investment in BESS for Multi-service.

As before stated, maintaining the PCR provision is an arbitrary choice of this study. It is motivated by the rising effort by power systems of countries with high RES-E share in the production mix towards fast-response frequency control. Therefore, it is likely in the future improved mechanisms of frequency containment provision will be in place in Italy and in most of countries. A fast-response service can imply a rise in energy cycled per month for PCR, increasing equivalent cycles and therefore c-rates. This trend is feasible and even suggested for the BESS studied applicated as in CASE D. Its average c-rate is in fact low. It causes predominance of calendar ageing over cycle ageing in this simulation. Higher economic return can be obtained by exploiting more BESS during operation.

CASE D allows anyway a fundamental statement: it demonstrates the possibility of providing Ancillary services with BESS by guaranteeing high security of the grid and even a positive return on investment. The provision of the two most important services for AC power systems can coexist on a battery with outstanding performances. With respect to reference case, LOR passed from 13% to 1.6% by gradually implementing grid services and improving their management. NPV passed from largely negative value to positive value. Anyway, the largest economic return as of now is obtained by excluding PCR provision. And this is not good for security of network, since Primary Regulation is fundamental and its importance is increasing in a network more and more dependent from non-programmable RES-E. The second statement that can be made regarding Italian framework is consequently that the economic optimum for the investor does not coincide with the optimum for TSO. These two counterparties should work together, but they are actually pointing to different directions. The larger degree of grid security (by assessing rising interest towards PCR shown in most of countries) guaranteed by CASE D takes to economic return halved with respect to CASE C.

Economic return of CASE D can be still optimized. Two different routes will be analyzed to get to better NPV: a different remuneration of PCR service and the optimal sizing of the battery.

5.8 Multi-service: proposals for PCR enhancement and remuneration in Italian framework

By data obtained in previous analyzed cases, it can be said that PCR remuneration scheme in Italian framework is insufficient to define attractive the investment in BESS providing PCR and SCR. Provision of SCR as in CASE C offers a PBT of 6 years less and almost doubles the NPV. From CASE C to CASE D, the implementation of PCR led to a decrease in the total monthly energy flows of 13%, meaning that there are margins of improvement in regulating bands management. These statements are referred to a hypothesized framework for the future in which SCR provides asymmetric Reserves. Introduction of asymmetric Reserves is among the trends of ASMs (see Paragraph 3.4.2).

The analysis proposed in this Paragraph aims to define a remuneration that would lead to interest towards Multi-service. Furthermore, some modifications in droop value allowed to experiment different kinds of PCR. Since BESS guarantees a very high ramp rate (see 3.4.2) and ASM trends across Europe are directing towards enhanced-frequency control (or even virtual inertia), it could be attractive to figure out how service of PCR as in place in Italy could be modified in this sense.

The fixed droop control curve experimented as of now used is the one represented in Figure 4-6. The value of droop up to now in use is 0.075%/P_{regPCR}. Value of droop will be now taken to the opposite limit of the interval highlighted in Paragraph 4.2.1: 0.030%/P_{regPCR}. Since regulation band for PCR is 0.5 per unit, droop value will change from 0.150% to 0.060%. In this way, droop control curve is proportional to a 2% droop on the conventional 1.5% power band: it is the minimum value admitted in Italian Grid Code. It indicates a fest response to solicitations. PCR provision in this study on BESS is provided using regulating bands much larger than mandatory one in Italy. The perspective is that in the future there could be a limited share of selected units providing PCR with enhanced requirements and subject to a market, as happens for SCR in Italy. In that case, BESS would be among best candidates to provide PCR due to their precision in following setpoints and high ramp rate. Private investors would only have interested in providing PCR if it is remunerated conveniently. Therefore, the TSO could decide to adequate its remuneration scheme to the new needs.

In this Paragraph, a new remuneration scheme is presented. To do this, CASE C and CASE D are compared, and another CASE D2 is simulated. In CASE D2, PCR is provided simultaneously with asymmetric SCR, as was happening in CASE D. PCR droop value is instead lower in this simulation: 0.030%/P_{regPCR}. All the simulations use same battery (the standard configuration) with 1 MW of nominal power and EPR of 2 h.

CASE D2: PCR + asymmetric SCR droop minimum	
PCR power band	0.5
SCR power band	0.8
Notes	
Droop	0.060 %

In the following table, CASE C, CASE D and CASE D2 are analyzed and the difference among energy flows and NPV is visible.

COMPARISON: CASE C – CASE D – CASE D2				
Energy	CASE C	CASE D	CASE D2	
PCR positive	0.00	19.44	36.14	MWh
PCR negative	0.00	20.64	38.64	MWh
PCR gross	0.00	40.08	74.78	MWh
SCR positive	97.66	64.74	55.27	MWh
SCR negative	105.90	73.03	63.93	MWh
SCR gross	203.56	137.77	119.21	MWh
Gross total	203.56	177.85	193.99	MWh
PCR LOR ratio	-	1.19	1.15	%
SCR LOR ratio	4.52	1.70	0.66	%
Life (cycle ageing only)	9.35	12.54	11.62	Years
Monthly Cash flows				
PCR net revenues	0.00	845.91	1562.69	€/month
SCR net revenues	10064.17	6629.42	5590.72	€/month
LOR penalties	836.33	256.16	149.52	€/month
Net Cash Flow	9227.85	7219.18	7003.70	€/month
PBT	12	18	19	Years
NPV (20 years)	**298.6**	**122.5**	**60.0**	**k€**

What happens is that increasing the amount of PCR requested, automatically SCR provided decreases. And Net Cash Flow decreases too, since each MWh of PCR provided is less remunerated in Italy than the same amount of SCR. Energy provided for SCR decreases both in case of increase of regulating band serving PCR and in case of decrease of droop. This is because lower droop implies larger $variation_{(+,-)}$, that act limiting SCR band. Therefore, CASE D2 has lower SCR provision than CASE D, that has lower SCR provision than CASE C. This negative variation in SCR provision is balanced by increase of energy for PCR. The following study aims to set a PCR remuneration able to compensate the revenues lost with SCR.

The scope is to obtain same NPV at 20 years by changing PCR remuneration. This will allow to understand which is the minimum remuneration for providing economic attractiveness towards Multi-service in Italian framework. The choice operated by the Authors is to fix negative remuneration for PCR at 0 and let positive PCR remuneration vary to get the result (in €/MWh) providing same NPV at 20 years as in CASE C. Remunerations equal or greater than the ones shown in Table 5-7 will lead to attractiveness towards Multi-service as of now defined.

Table 5-7 Remuneration schemes for PCR proposed

REMUNERATION SCHEME				
Energy	CASE C	CASE D	CASE D2	
PCR positive	0.00	19.44	36.14	MWh
PCR negative	0.00	20.64	38.64	MWh
Monthly Cash flows				
PCR positive remuneration	-	114.44	96.11	€/MWh
PCR negative remuneration	-	0.00	0.00	€/MWh
PCR net revenues	0.00	2225.21	3473.00	€/month
Net Cash Flow	9227.85	8392.29	8598.28	€/month
PBT	12	12	12	Years
NPV (20 years)	**298.6**	**298.6**	**298.6**	**k€**

These results were found by setting price for negative Primary Reserve to 0. This means for BESS that it is withdrawing power from grid at 0 costs. CASE C presents larger cycle ageing (therefore lower lifetime) and higher LOR. Therefore, monthly cash flow of CASE D and CASE D2 are lower than the one of CASE C, even obtaining same NPV at 20 years.

These outcomes show that providing a fast-response primary could cost less for BESS since energy provided per month would almost double. Therefore, remuneration proposed from TSO could be lower (96 €/MWh instead of 114 €/MWh). In UK, EFR is up and running since 2016. If the trends in RES-penetration increase will continue in next years in Italy, palliative for inertia lost will become necessary. In both CASE D and CASE D2, LOR percentage guaranteed by BESS is below 2%. It is an outstanding performance highlighting battery fitness for the provision of Ancillary services.

Smaller droops providing faster response have been tested, too. They do not add any significant improvement in economic return (remuneration for parity does not decrease more). They could be interesting, instead, on technical side, for creating new improved services already in place in other countries (such as EFR by UK or various forms of Virtual Inertia).

Next and last step for defining BESS viability in Multi-service provision in Italian framework will modify last parameter still not optimized: EPR. Sizing of battery is a crucial point for economic return, since investment cost in battery is the largest negative cash flow in BESS investment.

5.9 Multi-service: optimal EPR

To obtain the most favorable economic return from an investment there are two main ways: increasing revenues and decreasing costs. Costs in a BESS investment is related to energy (or capacity) of battery (a general way to allocate cost of battery is in €/MWh). Sizing conveniently the battery is good for avoiding motiveless expenses. In Paragraph 4.3.3, a way of sizing the BESS on a specific application has been proposed. It leads to range of acceptable EPR depicted in 4.50, depending on the way to take in account for variable regulating band of SCR: EPR should be in the interval 1.03 – 1.93 if the aim is providing PCR with 0.5 per unit regulating band and asymmetric SCR with 0.8 per unit maximum regulating band. Simulations have been repeated by offering these same services. The services provided are same as in CASE D. The BESS considered is always featuring the standard nominal power of 1 MW. What is changing is nominal energy, set accordingly to EPR investigated at each simulation. Profitability Index (PI) has been added in this case for economic analysis. Since the comparison is among different initial investments (related to different EPR), PI could provide better vision of the possibilities. Outcomes here below are therefore in terms of LOR, NPV and PI. Model used is empirical model.

CASE E: PCR + asymmetric SCR	
PCR power band	0.5
SCR power band	0.8
Notes	
EPR [h]	1.03 – 1.25 – 1.50 – 1.75 – 1.93

COMPARISON: OPTIMAL EPR FOR LOW LOR AND HIGH ECONOMIC RETURN						
EPR[h]	1.03	1.25	1.50	1.75	1.93	CASE D 2.00
LOR total [%]	**3.75**	**2.54**	**1.57**	**1.30**	**1.39**	**1.60**
NPV (20 years) [k€]	-15.7	37.3	182.1	76.8	71.1	122.5
PI	**-0.04**	**0.07**	**0.30**	**0.11**	**0.09**	**0.15**

By analyzing LOR and NPV, there is an area of optimal solutions among EPR 1.50 (max NPV) and 1.75 (min LOR). If TSO interests must be preserved, EPR of 1.75 h will be adopted. By the point of view of the owner, best investment is EPR of 1.5 h.

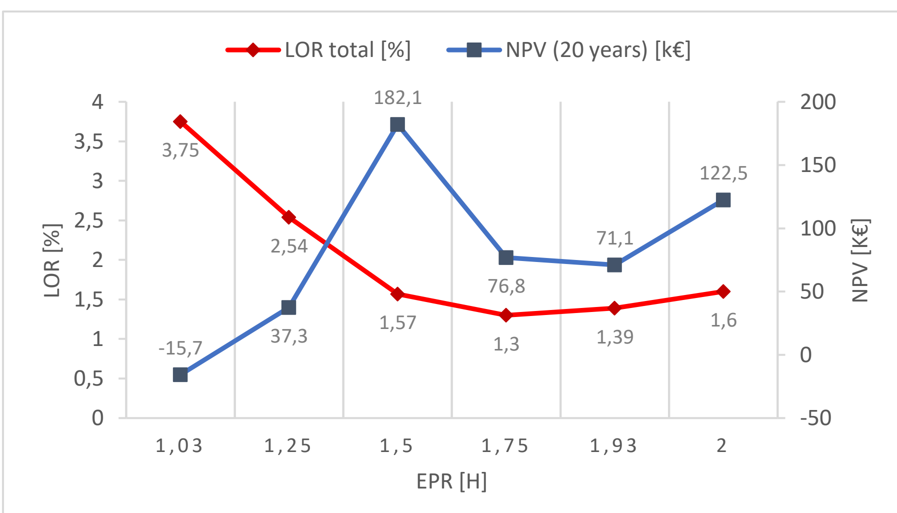


Figure 5-9 NPV and LOR comparison for optimal EPR

When introducing also PI, the interest towards EPR of 1.50 h increases. PI of this sizing is in fact doubling the next one (EPR = 2).

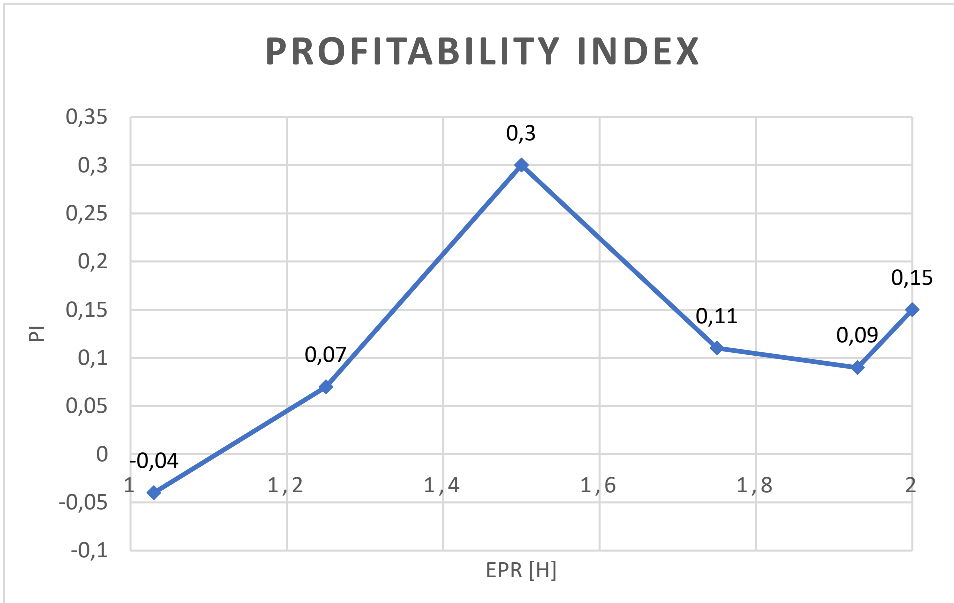


Figure 5-10 PI with respect to EPR

Value of interest (higher NPV and lower LOR) are in the middle of the interval of EPR selected in Paragraph 4.3.3: apparently, the relation among energy and power requirements have been computed conveniently. There is a trend of increasing LOR towards lower EPR. EPR too low (up to 1) is not an attractive choice by the point of view of TSO. Anyway, every combination allows LOR lower than acceptability threshold of 5%. Economic return higher than the one found in CASE D is achieved for EPR of 1.5 h with almost same LOR value and double PI value: there is high interest in decreasing EPR for better economic return, since it is not compromising the performance. Analyzing once more by investor point of view, there are better ways to manage the mix of services provided. When decreasing EPR, in fact, PCR increases its relative weight in the provision with respect to SCR. In fact, nominal power of battery and regulating power for PCR are kept constant. Therefore, PCR requests the same amount of MWh per month and the decrease in energy-band available reduces SCR provision only. This setting has been arbitrarily chosen by Authors to give priority to PCR, but it is not the best set up for economic return given low remuneration in Italy for PCR. This shows once more how this study is mainly devoted to security of network with respect to economic return of investment, and how margins are still available to improve attractiveness of an investment in BESS for provision of Multi-service in Italian Framework.

If the interest is towards economic return, anyway, Italian framework is not the most remunerative neither for PCR nor for SCR. A rough modification of the pricing system will allow to test qualitatively what happens in case of trading in the context of German ASM.

5.10 Comparison among Italian and German economic return

Size of BESS consistent with the simultaneous provision of PCR and asymmetric SCR has been discovered in the analysis of CASE E. EPR of 1.5 h guarantees the highest NPV and PI for an investment in Italy. Here below is proposed the detailed analysis of that setting and a rudimental comparison of same setting remunerated with German scheme. This is not a comparison among the two markets, since the hybrid ASM structure used (asymmetric SCR, market every 4 hours) is halfway between Italian and German market. But a qualitative analysis of the divergence (in order of magnitude) of the two remuneration schemes is useful. German revenues have been implemented as defined in 5.1, by considering both energy and capacity payments with average prices coming from the analysis introduced in that Section. LOR penalties have been kept at 100€/MWh for both services and for both frameworks.

CASE GER: PCR + asymmetric SCR with EPR = 1.5 and German remuneration scheme	
PCR power band	0.5
SCR power band	0.8
Notes	
EPR	1.5
Remuneration	German scheme: capacity-based for PCR, energy and capacity-based for SCR

COMPARISON: PCR + SCR ASYMMETRIC WITH EPR = 1.5 – ITALIAN VS GERMAN REMUNERATIONS			
Energy			
PCR positive		19.44	MWh
PCR negative		20.64	MWh
PCR gross		40.08	MWh
SCR positive		58.52	MWh
SCR negative		67.84	MWh
SCR gross		126.36	MWh
Gross total		166.44	MWh
PCR LOR ratio		2.17	%
SCR LOR ratio		1.40	%
Equivalent cycles		49.80	1/month
Average c-rate		0.13	
Life (cycle ageing only)		9.53	Years
Monthly Cash flows	Italian	German	
PCR net revenues	845.74	7071.43	€/month
SCR net revenues	5912.81	8350.35	€/month
LOR penalties	240.28	240.28	€/month
Net Cash Flow	6518.27	13781.25	€/month
PBT	14	3	Years
NPV (20 years)	182.1	1268.6	k€

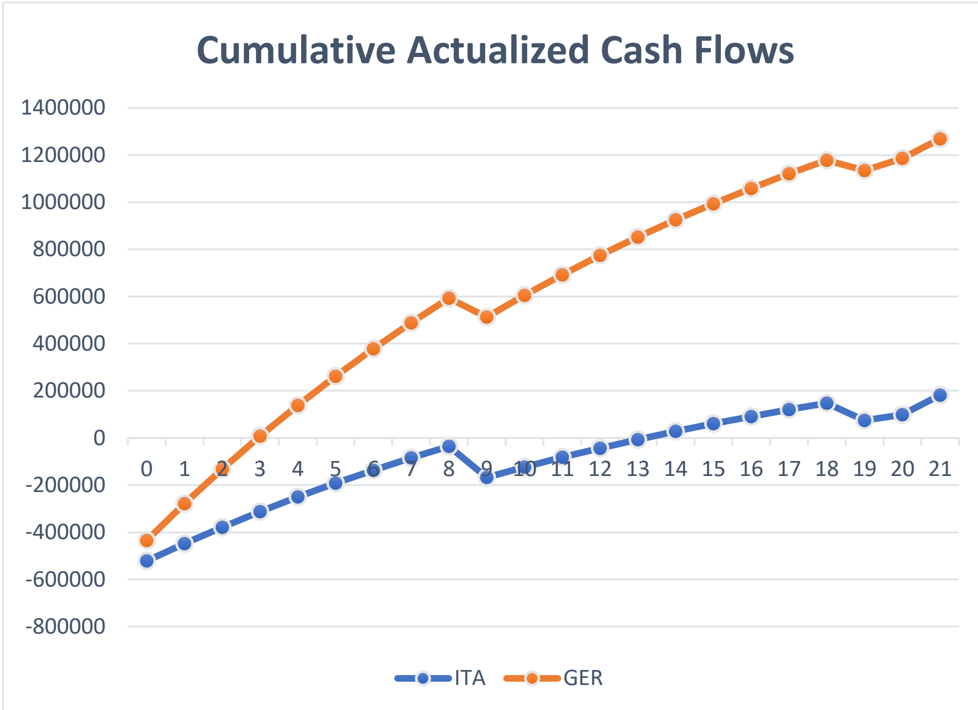


Figure 5-11 Cumulative Actualized Cash Flows diagram for comparison among Italian and German framework

By applying German remuneration scheme to energy flows and regulating power band of CASE E, with the EPR selected of 1.5 h, the qualitative difference among the revenue streams of the two investments are clear. Every month, the net cash flow for a BESS playing on German market is more than double. German framework allows PBT in 3 years and NPV of more than 1 M€. Italian ASM guarantees PBT of 14 years, NPV of 182 k€. In Figure 5-11, the comparison among the NCF can be inspected. In the diagram, the two negative NCF in the years of battery replacement can be noticed. The RV of battery at year 20 is added in year 21 and it gives the last point of the diagram.

This battery setting favors more German situation since PCR have more than 30% share in energy. Great difference among remunerations in PCR defines this large delta among the two solutions. German revenues for PCR per month are 9 times Italian ones. Italian remuneration scheme is highly penalizing PCR, and this is against the common trends of increased importance of Primary Regulation in countries with large share of RES-E.

This simulation cannot be considered a comparison among nowadays structure of Italian and German ASM, but just a tool for showing the difference among remunerations using the same hybrid ASM structure. Some negative and positive characteristics can be found in each of the two markets if deciding to invest in BESS. German market presents larger remunerations and asymmetric Secondary Reserves. Italian structure is preferred for the 4 hour-based Reserve provision scheme. This allows to perform better management of regulating bands with respect to initial SOC. In Germany instead, the provision of service is traded in weekly capacity auctions. It would not be feasible for batteries to provide the same band for one week, given their finite energy content. A change in both systems is needed for allowing BESS to play on Italian or German ASM. The solution could be halfway these two systems.

5.11 Simulations Recap

The diagram shown in Figure 5-12 report a brief recap of the whole study, in terms of both economic return and performance.

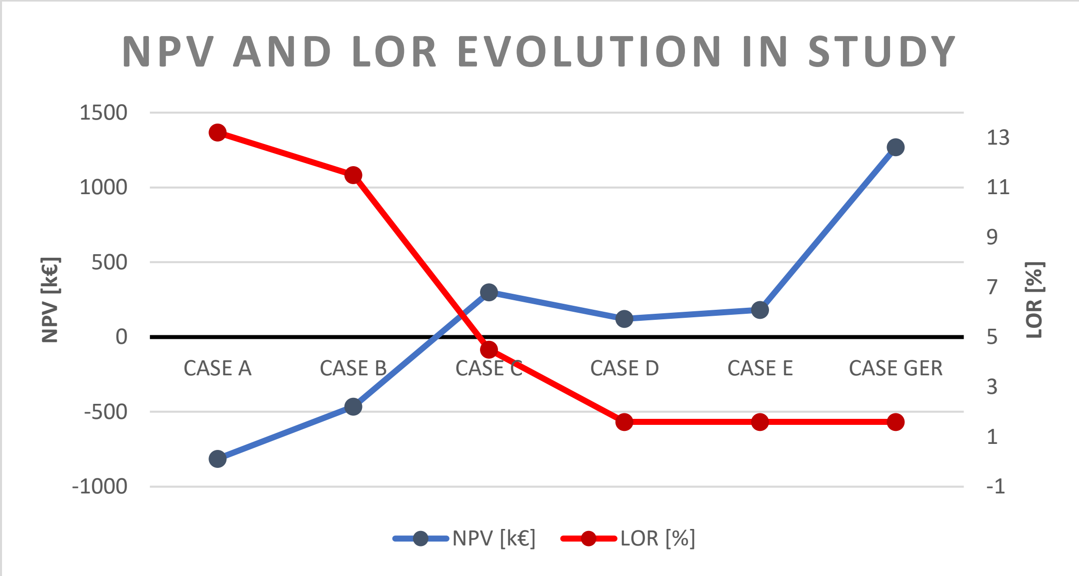


Figure 5-12 NPV and LOR for each CASE studied

It can be noticed how, from start to finish, improving in management and in services selected led to enhance economic return and performance. Best results were obtained when introducing asymmetric services in the provision. The variation among CASE B and CASE C is in fact the clearest: NPV passed from negative to positive and LOR reached acceptable values, below 5%. A consistent regulating power band management was fundamental to exploit the advantages of asymmetric Reserves. This relation among power offered and SOC is the key point when controlling BESS for Ancillary services provision. And it must be the key even in the TSO choices in reforming ASM for integration of these new market players. CASE C gave the best outcome in terms of NPV for Italian framework. The trends towards lower LOR, instead, continued to find an optimal in simultaneous provision of PCR and asymmetric SCR. This combination allowed LOR lower than 2%, both in CASE D and in CASE E (optimal EPR). As already stated, the fact that the optimum for NPV and security of grid is found in two different CASES is something negative. It could mean that the price signals given by market are not correctly calibrated. In general, it means that in Italian simulation TSO and investors are not simultaneously satisfied. CASE GER, at far right, shows NPV higher by an order of magnitude with respect to next ones. Furthermore, Germany gives price signals agreeing with the trends of ASM described in this study, since PCR is better paid than SCR.

6 Conclusions

The scope of this study was modeling and simulating the operation of a Lithium ions Battery Energy Storage System (BESS) in performing provision of multiple grid services in the framework of an Ancillary Service Market (ASM).

Given the target of the work, analysis of the state of art on both battery modelling and on ASM structures and evolutions was necessary. The study of battery models helped in selecting the suitable tools to be used for this application. An electric and an empirical model were selected. Validation of empirical model was necessary in the study for use in this application. Study of ASM allowed instead to correctly implement in the model the grid services and to recognize global trends in Ancillary services provision. Among these, the rising interest towards fast-responding frequency containment regulation was taken as a guideline for developing choices to address the study. In fact, BESS are the energy conversion system fitting the most for the sudden ramps required in enhanced frequency control.

The study was performed by simulating 30 days of Ancillary services provision. A Simulink tool featuring the electric and the empirical model of Li-ion battery was utilized for simulations. The design of the controller of the BESS was the core of this work. The controller now holds a comprehensive procedure for implementing grid services. During the study, Primary Control Regulation (PCR) and Secondary Control Regulation (SCR) provision were implemented. The main framework was Italian ASM.

Main outcome of the study is the effectiveness of asymmetric Ancillary services as “passive” State of Charge (SOC) restorers, i.e. these services can bring SOC far from saturation values of 0 and 100% and avoid hitting those limits by managing the provision of service itself. Main issue related to BESS providing grid services is the management of SOC. When SOC is close to 0, BESS cannot provide positive power to grid. Vice versa, if it is close to 100%, it cannot withdraw energy from grid. If SOC hits too frequently saturation limits and cannot provide power requested, BESS cannot provide the requested reliability for playing on ASM. Usually SOC restoration mechanisms require large energy flows on purpose. Instead, asymmetric services allowed a clever management of regulating bands offered on market. When asymmetric Reserves and consistent regulating band management were in place, SOC was brought easily back towards 50% and barely reached saturation.

Authors were interested in optimizing two aspects of the performance: the quality of the provision and the economic return of investment. The quality of the provision can be measured via Loss of Regulation (LOR). LOR is defined as the share of energy non-provided on the overall energy requested for grid services. The lower LOR is, the higher is security of grid guaranteed by service provision. Therefore, minimizing the LOR is the main goal of the Transmission System Operator (TSO). Outstanding performance was offered by the simultaneous provision of PCR and SCR. SCR was provided as asymmetric service, namely by offering on market different regulating power bands for positive and negative Reserves. The optimal value found was 1.6% of LOR. On the other side, economic return is the main target for the investor. And best economic return, analyzing Italian context, was guaranteed by the provision of asymmetric SCR only. This means that optimum for TSO and private investors do not coincide in Italy. This is mainly due to low remuneration of PCR in Italian framework

More generally, Italian framework is not remunerating Ancillary service in a convenient way to allow viability and attractiveness of investment in BESS for grid service provision. Lowest Payback Time (PBT) of investment is 12 years. Situation change drastically providing same services in Germany. A simulation by using prices of German ASM highlighted PBT of 3 years and Profitability Index (PI) of 1.54. Germany has remunerations averagely doubling Italian ones. With respect to Italy, Germany is remunerating more

PCR than SCR provision. Rising care towards fast frequency containment mechanisms is a general tendency in countries with large electric Renewable Energy Sources (RES-E) share in power production mix, due to increasing unpredictability of generation and loss in network inertia. In Italy, poor remuneration of PCR is the main cause of low attractiveness for BESS investment in ASM.

Results of all cases inspected are briefly summarized in Table 6-1, in terms of LOR and economic indexes. The clear trend is the minimization of LOR if and only if asymmetric SCR is provided. Best economic outcomes are instead reached when there is no PCR provision.

Table 6-1 Simulations results summary

	CASE A	CASE B	CASE C	CASE D	CASE E	CASE GER
PCR band (per unit)	1.0	0.5	0.0	0.5	0.5	0.5
max SCR band (per unit)	0.0	symm 0.8	asym 1.0	asym 0.8	asym 0.8	asym 0.8
LOR [%]	13.2	11.5	4.5	1.6	1.6	1.6
NPV [k€]	-813.0	-465.5	298.6	122.5	182.1	1268.6
PBT	-	-	12	18	14	3
PI	-1.02	-0.58	0.37	0.15	0.3	1.59

PCR with enhanced-response has been tested and showed good performance and improvement in economic return for BESS investment. Economic return improves when battery trades more MWh per each MW offered on market. The direction of fast-responding grid services could be among future interests for studies correlated to this.

Further future steps for this study could be the addition of other services, specifically end-consumer services, to increase economic return. Interesting application, mentioned in this study, is the possibility of increasing end-user arbitrage by using BESS. During the night, when price of electricity is lower, the BESS charges up cheaply. During the day, when electricity is more expensive, BESS discharge to increase self-consumption of the owner and avoid purchase at high price from grid. This kind of application could be compatible with asymmetric Ancillary services provision: during the night, battery provides positive Reserve and just buys more energy at low price to charge up. During the day, battery provides negative Reserve and has more energy available for end-consumer loads. If the cost of investment is payed back by more revenue streams, the owner can be encouraged to acquire BESS and provide more grid security in an increasingly challenging power system.

7 Appendix A

Case Study: Terna's energy-intensive projects

Final focus of this thesis is the analysis of a case study, one of the few references already in place, allowing us to define the state of art of multiple services provision by BESS. It is a pilot project by Italian TSO, involving 3 large-scale BESS providing grid services for frequency regulation and RES-E integration.

The description of the project, of the aims and methodologies have been already presented in 3.5.4. Now the interest is giving a brief report of an analysis carried out by the Author of this work, both from technical and economic point of view. The results of this analysis are gathered in this Section. The aim of this study is giving a comparison of the simulation carried out during this work with respect to what has been really put in place as of now, by breaking the regulatory barriers listed during all this work. Furthermore, the analysis could be used to define what can be modified or improved for future projects and which qualities and trends this project was already able to show.

Next paragraph will analyze how the provision of services has performed. The main service requested to BESS was the mitigation of the wind power curtailment. In that area of the network, considered by TSO a critical area, curtailment was frequent up to 2015, when the project was put on field. For that specific service, a quantitative analysis of the performance has been done by the Author. In Paragraph 7.2, an economic analysis of the project will be presented. The scope is providing indexes of economic return comparable with the ones obtained after simulations during this study. Since the Frequency Control services (PCR and SCR) have been performed in a slightly different manner with respect to the ones of this study (different droop control law, different band management) and since not all the data are available in Report from those projects, a brief introduction on methodology followed will be necessary.

7.1 Technical analysis

As described in Paragraph 3.5.4 the three energy-intensive BESS installed by Italian TSO in three different nodes of the Medium Voltage (MV) network, aimed to provide three grid services: mitigation of wind power curtailment, PCR and SCR.

For what concerns mitigation of power curtailment, a database by Terna allows to analyze the performance of the provision. The mechanism of the service is explained in 3.5.4 and it is based on three signals: S1, S2 and S3. When S1 is given to battery, battery should start discharging and get to target SOC value of 0. S2 active indicates the beginning of the "emergency" period, in which battery must withdraw power from grid at nominal power in order to ease a local congestion. Withdrawn from network must continue either up to the end of emergency or up to reaching of saturation SOC value of 100%. S3 means the end of local congestion and of "emergency" period.

By definition provided by Terna's Report [71], S2 activates in the moment in which a congestion on the main MV line feeding the BESS takes place. The congestion happens when power flow on that MV line overpasses a specific threshold. By analyzing logs on power flow, S2 evolution can be found and stored in a MATLAB array for the duration of all the 2nd semester of 2016. The result is a Boolean array: it is 1 when S2 is active, 0 when not. In other words: the element of the array is 1 when threshold on the MV line is overpassed by instant power flow, 0 elsewhere. The sampling-rate of power flow log, therefore of the Boolean array, is 15 minutes.

A study by the Author in MATLAB environment has defined an ideal battery responding to S2 signal. The log of this battery can be compared to the log of the real BESS providing the service. Ideal battery activates when S2 array returns 1 and gets back to 0 power output when the array returns 0. The real battery should behave the same.

The ideal battery was created based on data of the MV line feeding Scampitella BESS, one of the three sites of Terna's project. That BESS is composed by 9 different batteries. A log of power for each battery was provided. By comparison between power log of the battery and the ideal battery created, it was possible to state that real batteries followed ideal battery averagely 65% of the times. The average delay among the ideal battery and the real batteries was -4.2 ±15 min. As already said, power log has 15 minutes sampling rate. Therefore, this number with this uncertainty can be considered as an index of average delay 0. It was not possible, with data available, understand what was happening when real battery did not follow ideal battery. In some cases, SOC was already at upper saturation limit when S2 activated, but in most of cases it was not. Averagely, it can be said that mitigation of wind power curtailment was provided positively by Scampitella BESS, even if there are case of unanswered call. Energy prevented from curtailment by this BESS in 2nd semester 2016 has been 2850 MWh.

For what concerns PCR and SCR, not enough data were available for a complete analysis of performance. What can be said is that the regulating band used for PCR was small with respect to simulations carried out during this study. It was around 0.1 per unit. The power band was not exploited by this service.

The EPR adopted was 6.3 h. In this study, EPR much lower showed to be consistent with provision of PCR and SCR. EPR lower is generally convenient for economic return.

7.2 Economic analysis

The economic analysis on this project aimed to be as close as possible as the economic analysis previously presented with simulations in Chapter 5. As already said, this comparison is only indicative, since Terna's projects differ by many elements with respect to previous simulations. First, the BESS is Sodium-Sulfur, not Li-ion: performances, SOH evolution, efficiencies, operating condition (e.g.: temperature) and costs are different. Second, Terna's project is a pilot project, a study aiming to be basis for next improvements. The provider is the TSO itself, not a private owner, consequently this project is not involved in ASM framework and does not deal with necessity of economic return. The project was put on field to answer a precise need: the high level of wind power curtailment (MPE) in a critical zone of the network. Third, services provided are modelled in slightly different way with respect to the ones of simulations.

Anyway, a qualitative study can be performed. This study has been performed on data published by Terna in the project Report about 2nd semester of 2016 [106]. Scampitella SANC was selected as framework of this economic analysis. Since from report it can be stated that the performances by the three BESSs are similar, the arbitrary choice of analyzing this BESS only was considered acceptable. This will provide results easier to understand and anyway consistent.

NPV and PBT has been computed as described in 5.1. Same c_{inv} and c_{rep} has been selected, in order to give significance to the comparison. Anyway, large value of nominal energy (72 MWh), leads to huge total investment cost of 21 M€. Lifetime has instead been set to 20 years. It is a high level, justified only in part due to extremely low usage rate and average c-rate. The average number of equivalent cycles per month is 16.3 cycles. It is very low if compared to simulations of this study.

Revenue streams changed and must be recomputed and defined. As described in 3.5.4, these energy-intensive project aim to perform three main services.

1. PCR

It is performed during the whole of the project duration. The specifications are:

a. ±20 mHz dead band.
b. 2% fixed droop
c. Regulating power equal to 200% of nominal power (200% of 10 MW, if each of the 3 BESSs Ginestra, Flumeri and Scampitella was taken as a whole).
d. This droop control curve, slightly different from the one used in model:

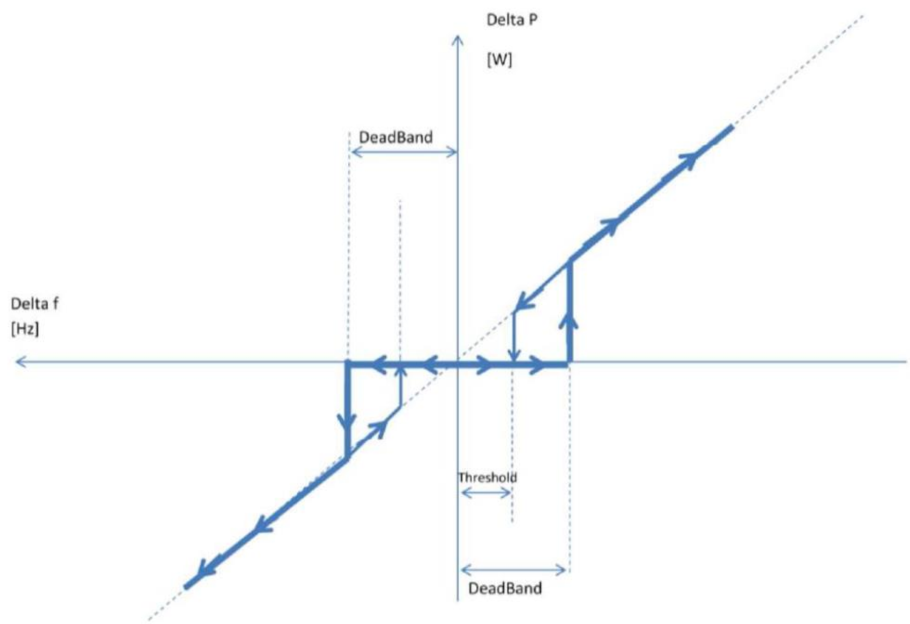


Figure 7-0-1 Droop control curve for Terna's project

Main differences with model are the values of droop and the fact that the regulating power is not reflecting the effort of the provision. In the simulations made in this study, the regulating power was the main setting and the droop was changing consequently as in equation 4.19. This allowed to define the effort of PCR provision as proportional to regulating band dedicated. Here it is necessary to define an equivalent regulating band, by defining the "maximum frequency variation expected" during the 6 months:

$$\Delta f_{max} = \pm 150\ mHz \tag{7.1}$$

It is not the real maximum, but a statistical maximum arbitrary chosen after analysis of frequency trends in the month sampled in Politecnico di Milano's laboratory (maximum frequency variation in that month was 134 mHz) and functional to the definition of regulating band as follows (by inverting droop law):

$$P_{regPCR,Terna} = \frac{\Delta f_{max}}{50\ Hz} * \frac{P_n}{droop} = \mp 1.62\ MW \tag{7.2}$$

Where P_n is nominal power of Scampitella BESS: 10.8 MW. Maximum frequency variation considered is proportional to regulating power. It has been chosen far higher than the one, for instance, considered in the model (±57 mHz) in order to avoid doubts on the rudimental way the PCR revenue stream will be computed: it is certainly estimated for excess.

The reason why the value of regulating band is needed to compute revenue stream by PCR is the fact the data on total energy exchanged over the period for this service are not published. Only the percentage in time in which the service is on is among the data (75% for Scampitella). Therefore, to compute energy positive and negative exchanged for PCR, the statistical data already presented in Table 5-3 will be used:

$$E_{posPCR,weekly} = E_{negPCR,weekly} = \frac{17}{2}\frac{MWh}{\frac{MW_{offered}}{week}} \quad 7.3$$

Since P_{regPCR} is 1.62 MW, there are 26 weeks in one semester and usage rate is 75%:

$$E_{posPCR} = E_{negPCR} = \frac{537.0}{6}\frac{MWh}{month} \quad 7.4$$

P_{PCR} is computed as in 5.3:

$$P_{PCR} = 2237.63\frac{€}{month} \quad 7.5$$

2. SCR

SCR is provided as in the model, by defining a regulating band (20-100% of nominal power) and offering capacity in market. For SCR, there are cumulative positive and negative value of energy exchanged for the semester:

$$E_{posSCR} = \frac{2520}{6}\frac{MWh}{month} \quad 7.6$$

$$E_{negSCR} = \frac{4260}{6}\frac{MWh}{month} \quad 7.7$$

There are not the relative market prices. Prices found as average for 2017, already presented in Table 5-2 will be used, and P_{SCR} is computed as follows:

$$P_{SCR} = E_{posSCR} * p_{posSCR} + E_{negSCR} * p_{negSCR} = 43950\frac{€}{month} \quad 7.8$$

$$p_{posSCR} = 130\frac{€}{MWh} \quad 7.9$$

$$p_{negSCR} = -15\frac{€}{MWh} \quad 7.10$$

As can be seen, P_{PCR} is negligible with respect to P_{SCR}. This is because SCR uses sometimes 20%, sometimes 100% of nominal power as regulating band, with respect to very narrow band used by PCR.

3. MPE mitigation: mitigation of wind power curtailment

This service is not present on Italian ASM. It is given as priority service every time it is requested by Terna remote-controller. It uses 100% of nominal power as regulating band. Data give the cumulative MPE avoided in energy:

$$E_{MPEavoided} = \frac{2850.0}{6} \frac{MWh}{month} \tag{7.11}$$

A remuneration was proposed for this service:

$$p_{MPEavoided} = 100 \frac{€}{MWh} \tag{7.12}$$

It is a high value, given the fact it would add to generation costs and increase Levelized Cost of Energy (LCOE) by almost doubling it. The revenue stream for a month would be:

$$P_{MPEavoided} = E_{MPEavoided} * p_{MPEavoided} = 47500 \frac{€}{month} \tag{7.13}$$

Total of monthly revenue streams would be:

$$P_{tot} = P_{PCR} + P_{SCR} + P_{MPEavoided} = 93687.63 \frac{€}{month} \tag{7.14}$$

7.3 Simulation results

An economic analysis of the project put in place in Italy by Italian TSO is useful to have a comparison among simulated situations analyzed up to now and what is already in place. This energy-intensive projects were set up in 2015 and data up to second semester 2016 are now available [71]. These projects feature extremely large-scale BESS. In particular, these results come from data published about Scampitella BESS about 2nd semester 2016.

Terna's energy-intensive projects: Scampitella BESS	
Nominal power	10.8 MW
Nominal energy	72 MWh
EPR	6.7 h
PCR power band	0.15
SCR power band	variable: 0.2 – 1.0
Notes	
NO LOR considered	

RESULTS TERNA'S PROJECTS		
Energy		
PCR positive	44.75	MWh
PCR negative	44.75	MWh
PCR gross	89.50	MWh
SCR positive	420.0	MWh
SCR negative	710.0	MWh
SCR gross	1130.0	MWh
MPE avoided	475.00	MWh
Gross total	1694.51	MWh
Equivalent cycles	16.33	1/month
Life (arbitrary choice)	20.00	Years
Monthly Cash flows		
PCR net revenues	2237.63	€/month
SCR net revenues	43950.00	€/month
MPE avoided net revenues	47500.00	€/month
Net Cash Flow	93687.63	€/month
PBT	-	Years
NPV (20 years)	- 7580.7	k€

The economic analysis of this project shows largely negative results. The huge investment cost (29 million €) leads to large gap from positive economic return. NPV is -7 million €. EPR chosen is much larger than the ones used for similar application in this study. More than this, the small regulating band used for instance for PCR led to a very low number of equivalent cycles per month. Anyway, this projects by TSO shows crystal-clear interest in BESS participation to ASM and Reserves provision. The work done in this study can offer, in case of continuing the experimentation and the pilot projects, some suggestions and directions to follow to increase viability of an investment in BESS.

Acknowledgments

I would like to thank so much Dr. Pietro Iurilli for the detailed explanation of his study he provided me and for the time he spent discussing with me during my work. It would have been harder to finish this thesis without his help. I wish him the best luck in whatever he will decide to do in the future.

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List of Abbreviations

AC	Alternate Current
ASM	Ancillary Services Market
BESS	Battery Energy Storage System
BM	Balancing Market
BMS	Battery Management System
BoL	Beginning of Life
BSP	Balance Service Provider
CAES	Compressed Air Energy Storage
CC	Combined Cycle
CHP	Combined Heat and Power
$\mathbf{C_n}$	Nominal Capacity
DAM	Day-Ahead Market
DC	Direct Current
DER	Distributed Energy Source
DG	Diffuse Generation
DOD	Depth of Discharge
EFR	Enhanced Frequency Response
$\mathbf{E_n}$	Nominal Energy
EoL	End of Life
EPR	Energy to Power Ratio
ESS	Energy Storage System
EV	Electric Vehicle
GHG	Greenhouse Gases
GT	Gas Turbine
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communications Technology
LOR	Loss of Regulation
LV	Low Voltage
MPE	Mancata Produzione Eolica
MSD	Mercato dei Servizi di Dispacciamento
MV	Medium Voltage
MVA	Megavoltampere
NAS	Sodium Sulfur
NPV	Net Present Value
OCV	Open Circuit Voltage
OECD	Organisation for Economic Co-operation and Development
PA	Primary Application
PBT	Payback Time
PCR	Primary Control Regulation
PHES	Pumped Hydro Energy Storage
PI	Profitability Index
$\mathbf{P_n}$	Nominal Power
$\mathbf{P_{reg}}$	Regulating Power
pu	Per unit
PV	Photovoltaic
RES	Renewable Energy Sources
RES-E	Electric Renewable Energy Sources

S1, S2, S3	Signal 1, Signal 2, Signal 3
SA	Secondary Application
SANC	Sistema di Accumulo Non Convenzionale
SB	Semi Banda
SCR	Secondary Control Regulation
SEI	Solid Electrolyte Interphase
SOC	State of Charge
SOH	State of Health
TCR	Tertiary Control Regulation
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
V2G	Veichle to Grid
wrt	With respect to

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