Politecnico di Milano

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Master of Science – Energy Engineering

Effective Management of Aggregated Energy Storage Systems at Domestic Level for Self-Consumption and Frequency Regulation

Supervisor
Prof. Davide Falabretti
Co-Supervisor
Eng. Giuliano Rancilio
Eng. Filippo Bovera

Candidate
Helen Córdoba – 908053

Academic Year 2019 – 2020

Acknowledgments

I want to acknowledge everyone who played a role in this step of my life. Thank my parents and my beloved sister, who supported me with love and understanding even if we were at a distance. To my friends and family in Panama for trusting and believing in me. To all my dear friends here in Italy that made my university stage a journey of experiences that I will never forget. I also want to express my sincere gratitude to Giuliano for its excellent supervision and continuous encouragement throughout this time.

Sommario

Il presente studio affronta il tema delle risorse di flessibilità del sistema elettrico italiano attraverso la partecipazione della domanda al mercato, concentrando l'analisi a livello nazionale. In particolare, la tesi si focalizza sulle diverse strategie che un prosumer potrebbe adottare per ottenere l'aumento dell'autoconsumo, in aggiunta alla partecipazione al mercato dei servizi di dispacciamento.

Sono presi in considerazione tre diversi casi studio: la fornitura di solo autoconsumo (caso Behind-the Meter), la fornitura di autoconsumo e di riserva terziaria in un mercato senza vincolo di offerta minima (caso Unconstrained) e uno scenario che considera entrambi i servizi con il vincolo della dimensione minima dell'offerta (caso Aggregated), che rappresenta un probabile schema di regolamentazione futuro.

I primi tre capitoli del lavoro forniscono una rassegna della letteratura in materia di (1) ruolo del Prosumer residenziale, fornendo una panoramica delle sinergie tra sistema fotovoltaico e storage; (2) Mercati dell'energia elettrica in Italia, con particolare attenzione alla struttura del Mercato del Giorno Prima (MGP) e del Mercato per il Servizio di Dispacciamento (MSD) e all'evoluzione del mercato; (3) Aggregazione, con il dettaglio delle tipologie di aggregatori e degli usi a livello mondiale. Nel capitolo 4 viene spiegata la metodologia e vengono presentati i modelli di sistema di accumulo a batteria per i diversi casi. Il capitolo 5 illustra la descrizione dei dati utilizzati nella tesi. Il capitolo 6 mostra i risultati delle simulazioni e dell'analisi di sensibilità in tutti gli scenari.

Gli esiti dello studio mostrano che la partecipazione al MSD permette ai Prosumer di aumentare l'autoconsumo e anche migliorare la redditività dell'investimento. Se ci concentriamo sull'aggregazione, emerge che avendo più utenti residenziali aggregati, è possibile ottenere risultati migliori. Tuttavia, è meglio diminuire la dimensione minima dell'offerta per incrementare la quota di energia scambiata su MSD; eliminando addirittura il vincolo di offerta minima, si incorre in un caso ancora migliore, perché si conseguono l'autoconsumo più elevato e i maggiori ricavi.

Parole Chiave: Prosumer, aggregazione, autoconsumo, riserva terziaria, sistema di accumulo elettrochimico, mercato dei servizi ancillari.

Abstract

This study addresses the issue of increasing the flexibility resources of the Italian electric power system through the participation of the demand in the market, focusing on the analysis at a domestic level. It focuses on different strategies that the prosumer could integrate to guarantee the increase of self-consumption, but also the participation in the Ancillary Services Market (ASM)

Three different case studies are considered: the provision of only self-consumption (Behind-the Meter case), provision of self-consumption and tertiary reserve in a market with no minimum bid (Unconstrained case), and another case considering both services with the constraint of the minimum bid size (Aggregated case), representing a likely future regulatory scheme.

The first three chapters provide a literature review of (1) The Domestic Prosumer role, providing an overview of the synergies between Photovoltaic System and Battery Energy Storage Systems (BESS); (2) Electricity Markets in Italy, with particular attention to Day-Ahead Market(DAM), ASM, and the evolution of the market; (3) Aggregation, detailing the types of aggregators, and the uses worldwide. In Chapter 4, the methodology is explained, and the models of the BESS for the different cases are presented. Chapter 5 shows the description of the data used in the thesis, while Chapter 6 shows the results of the simulations and sensitivity analysis in all the cases.

The outcome of this study highlights that participation in the ASM allows prosumers to increase self-consumption, increase revenues, and, thus, the BESS investment interest. If we focus on aggregation, it is noticed that by having more houses aggregated, better results can be achieved, but we do better if the minimum bid size is decreased to have more energy exchanged on ASM; whereas by do not have a minimum bid size, we do even better since it shows the highest self-consumption and the highest revenues of all the cases.

Keywords: Prosumer, aggregation, self-consumption, tertiary reserve, battery energy storage system, ancillary services market.

Extended Abstract

Effective Management of Aggregated Energy Storage Systems at Domestic Level for Self-Consumption and Frequency Regulation

Helen Córdoba

I. Introduction

One of the most critical changes to electrical systems is the increasing penetration of Renewable Energy Sources (RES) into the distribution network [1]. Higher diffusion of RES into distribution networks increases the needs of power reserves [2] for ensuring system stability since the intermittent and unpredictable production dramatically affects the security and reliability of the system. This need for flexibility implies substantial changes in the way energy systems and markets are handled [3].

Recently, the electricity market has been opened to generation sources that previously were not enabled to provide balancing services, such as Distributed Energy Resources (DERs). Regulators are moving in the direction of more inclusive markets, where participants provide more resources at a lower cost.

The implementation of RES aggregation through entities known as Virtual Power Plants (VPPs) is one of the most recent and effective ways to achieve this, and thanks to the concept of aggregation, regulators are opening up Ancillary Services Market (ASM) to RES and DERs participation. For instance, this is gradually happening in Italy [4].

This study addresses the issue of increasing the flexibility resources of the Italian electricity system through the participation of the demand in the market, focusing on the analysis at a domestic level. It will be focused on different strategies that the prosumer could integrate to guarantee the increase of self-consumption, but also the participation in the market for frequency regulation. These domestic users equipped with ESS will participate in Day-Ahead Market (DAM) and in the ASM, where Tertiary Reserve (TR) is offered.

Considerable attention will be dedicated to representing the regulatory framework correctly. Some assumptions will be introduced to represent a likely future regulatory scheme and to obtain results that can be generalized.

II. Proposed Methodology

A BESS numerical model was implemented in a Matlab Simulink tool.

The model requires as inputs:

- Energy to Power Ratio (EPR) for battery, defined as the ratio among nominal energy E_n $[kWh]$ and nominal power $P_n[kW]$.
- The Power requested to the BESS.
- Saturation levels for SoC: SoC_{min}=0 and SoC_{max}=100.
- Sampling-rate of 1/3600 Hz for all the cases since each step of the simulation is equivalent to an hour.

This model [5] can simulate the runtime provision of grid services by the BESS, considering the energy flows exchanged with the network in DAM and ASM.

The prosumer is subject to the dedicated withdrawal of PV generation. In DAM, the Balance Responsible Party (BRP) is the one in charge of providing the injection/withdrawal program; on the other side, the Balancing Service Provider (BSP) functions as an aggregator and provides services to the ASM. The model considers that the BRP behaves ideally by incurring no errors in the program. The imbalances paid by the prosumer will be only when BESS reaches the saturations limits due to inadequate management, whereas the energy non provided to the ASM will be charged to the BSP that eventually shares the cost and benefits with the prosumer.

It has been proposed different case studies that show which is the optimum point where a prosumer could work.

- **Behind-The-Meter**

By having the power produced by the PV plant (P_{PV}) and the load consumption (P_{Load}), it is computed the difference in power (P_{diff}).

$$P_{diff} = P_{Load} - P_{PV} \qquad (1)$$

For a matter of simplicity, all the values in the model are in per unit. This difference in power is transformed into c-rate and becomes the required by the controller in AC, $c - rate_{reqAC}$. By having $c - rate_{reqAC}$ and then $c - rate_{aux}$ coming from an auxiliary contribution, the prosumer has the total in AC required to the battery($c - rate_{req\ tot\ AC}$).

If $c - rate_{req,totAC}$ is positive; it means that the battery gets discharged (Eq. 3). Instead, if $c - rate_{req,totAC}$ is negative, this means that the battery could get charged (Eq.2)

$$c - rate_{totDC} = c - rate_{req,totAC} * \eta_{ch} \qquad (2)$$

$$c - rate_{totDC} = \frac{(c - rate_{req,totAC})}{\eta_{dis}} \qquad (3)$$

Both η_{ch} and η_{dis} depends on $c - rate_{req,totAC}$ and SoC.

After computing $c - rate_{totDC}$, it is only considered real power ($c - rate_{real,totDC}$)

flowing in the battery in the case the battery is within the limits of SoC. If the battery is outside these limits, this means that the battery is not capable of providing the requested and the prosumer has imbalances. After having $c-rate_{real,totDC}$, it is converted from DC to AC to compare the real in AC ($c-rate_{real,totAC}$) with the total required in AC. By having the real power and comparing it with P_{diff} (Eq.1), it is possible to know the exchanges of the prosumer with the grid which could be due to the saturation of SoC or when $P_{diff} > P_n$.

$$P_{gap} = P_{diff} - P_{real,AC} \qquad (4)$$

If $P_{gap} > 0$, the prosumer withdraws from the grid, instead, with $P_{gap} < 0$, injects energy into the grid.

❖ Unconstrained Case

In this case, the prosumer still takes care of the self-consumption (SC) logic but also it is introduced the participation to ASM with the provision of the tertiary reserve. This implies:

- the forecast of the power band available in the following market session for tertiary reserve, considering the expected SoC variation due to self-consumption;
- the market model for defining the quantity awarded in the market.

In this market, since the prosumer does not have a constraint on the minimum bid size, all the available power is bid. The market model defines if the offer is either awarded or not, by comparing the prices bid and the prices of the market taken from historical data.

Tertiary Prediction

To evaluate the amount of energy available for tertiary reserve, the prosumer must estimate the energy variation for the whole market session due to all the services provided by the BESS. Since the market gate closure happens one hour before the delivery time (t-1) and the market session lasts 4 hours (from hour t to t+3), the prediction must involve five hourly energy variations.

The model first calculates SC logic and provision of tertiary from the previous market (Eq. 5)

$$\mathrm{E}_{t-1}\,[kWh] = \mathrm{Load}_{pred(t-1)} - \mathrm{PV}_{pred(t-1)} \pm \mathrm{E}_{real,TR(t-1)} \qquad (5)$$

Where:

- E_{t-1} [kWh], is total energy predicted one hour before the delivery.
- $\mathrm{Load}_{pred(t-1)}$ and $\mathrm{PV}_{pred(t-1)}$, are the Load and PV energy predicted one hour before the delivery.
- $E_{real,TR(t-1)}$ is the real energy exchanged based on the awarded quantity for hour t-1 in the previous market session.

For the market session,

$$\mathrm{E}_i\,[kWh] = \sum_{i=t}^{t+3} \mathrm{Load}_{pred(i)} - \mathrm{PV}_{pred(i)} \qquad (6)$$

Where i is the hour of delivery, E_i [kWh] is the total energy predicted for each hour, and $\text{Load}_{pred(t)}$, $\text{PV}_{pred(t)}$ are Load and PV energy predicted for each hour.

The total variation depends on the hourly predictions in Eq. 5 and Eq. 6

$$Tot\_E_{var,estimated}[kWh] = E_{t-1} + E_{\mathrm{i}} \quad (7)$$

With Eq. 7 then it is possible to compute how much potential energy the prosumer has for upward and downward services.

For upward, it is as followed:

$$A\_E_{TR,up}[\text{kWh}] = (SoC_{in} - SoC_{min}) * E_n - Tot\_E_{var,estimated} \quad (8)$$

where: $A\_E_{TR,up}$[kWh] is the total available energy for upward, SoC_{in} is the actual SoC, SoC_{min} is equal to 0% and E_n, is the nominal energy of the battery.

The available power for the next hours is then evaluated considering an average efficiency (η_{avg}) of the system and a safety factor (K_s) aimed to increase or decrease the risk on the market.

$$A\_P_{TR,up}[\text{kW}] = \frac{A\_E_{TR,up}[\text{kWh}]}{4[h]} * K_s * \eta_{avg} \quad (9)$$

For the downward service, the prosumer follows the next equation:

$$A\_E_{TR,dn}\ [\text{kWh}] = (SoC_{max} - SoC_{in}) * E_n + Tot\_E_{var,estimated} \quad (10)$$

Where: $A\_E_{TR,dn}$[kWh] is total available energy for downward, SoC_{in} is the actual SoC, SoC_{max} is 100%.

The available downward power ($A\_P_{TR,dn}$) for the next hours is:

$$A\_P_{TR,dn}[\text{kW}] = \frac{A\_E_{TR,dn}\ [\text{kWh}]}{4[h]} * \frac{K_s}{\eta_{avg}} \quad (11)$$

After the model has the available power for both services ($A\_P_{TR,dn}, A\_P_{TR,\mathrm{up}}$), the model checks the power that is allowed to bid by comparing the prices that the prosumer bids and the one that is in the market. For upward reserve, the prices that are accepted, should not be greater than the one set by the market (Eq.12), differently for downward reserve, where bids are accepted in case the price bid is greater than the one on the market (Eq.13)

$$p_{\ TR,up,bid} < p_{\ TR,up,mkt} \quad (12)$$

$$p_{\ TR,dn,bid} > p_{\ TR,dn,mkt} \quad (13)$$

In this model, the strategy to choose between upward and downward reserve to request to the battery is oriented to avoid SoC saturation. If the battery is closer to SoC=54%, the prosumer bids upward. Instead, if the battery is below 54%, bids downward. These bids are requested to the battery and after knowing $P_{real,AC}$ of the battery, the model decides how much is given to tertiary reserve and SC by giving priority to this latter since the program proposed by the BRP must be respected by the prosumer.

❖ **Aggregated Case**

Most of the ASMs only accept bids larger than a minimum threshold (in MW). This minimum threshold limits the participation to ASM of DERs unless they aggregate together. The aggregated unit is managed by the BSP that participates in the market on behalf of DERs. In the framework of this study, it is adopted a minimum reference size of 0.2 MW for both upward and downward reserve. This assumption is coherent with the evolution of the Italian regulatory framework, recently enabling the participation of DERs with bids as small as 0.2 MW [6]

For this study, the simulations are performed on five batteries working in parallel. These five prosumers with similar profiles are part of an aggregated unit composed of domestic users only and do the same activity as before, self-consumption, and tertiary reserve. The total available energy by these five prosumers is scaled up to the total number of houses (assuming these five batteries are a representative sample of the whole aggregated unit).

This involves:

- Five batteries with their controllers that forecast the tertiary reserve available considering the expected SoC variation due to self-consumption;
- The total aggregated band needs to respect the threshold of the minimum bid size;
- Then the market model defines the quantity awarded.

The model does the same as the unconstrained case, and the available power for upward and downward is found for each prosumer and then is rescaled to find the total aggregated power.

This total aggregated power has a first constraint regarding the minimum bid size. In addition to this, the model compares the prices on the market with the bid's (Eq.12 and Eq.13) to identify the potential upward and downward allocated reserve. When compliance has been verified, the model follows the same strategy to choose between the upward and downward reserve offered to avoid SoC saturation. Then this selected tertiary reserve is requested to the batteries.

$P_{real,AC}$ is found for all the batteries where part of this real power is for SC and other for tertiary. By knowing the total real tertiary power of each prosumer, the aggregator computes the total aggregated real energy that should be equal or greater than 0.2 MW to be awarded.

III. Results

❖ **Behind-The-Meter**

In this case, the prosumer only bid on DAM. From Eq.1, it is known the difference of powers on the side of the prosumers. In Figure 1, it could be seen that whenever the prosumer has more load Power than PV power, the difference has a positive value: BESS is requested to discharge for that specific time. Meanwhile, when the prosumer has more PV Power than the consumption, it means that the prosumer can charges the battery.

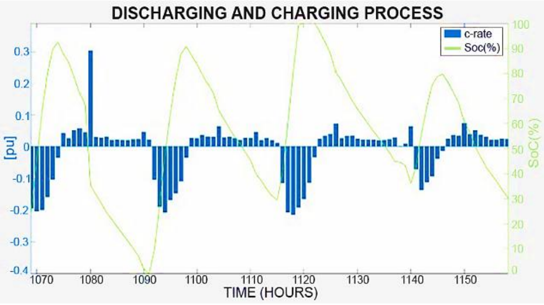

Figure 1 Discharging and Charging Process of Behind the Meter Case

If the battery reaches 100% of SoC, then there is not enough space to store the energy, so the prosumer needs to inject it into the grid. On the other side, if the prosumer has more consumption without having a generation of the PV Power, the battery reaches 0%, and then the prosumer withdraws from the grid. Both situations are considered imbalances to the prosumer (imbalance fee of 100 €/MWh).

❖ Unconstrained Case

In this case, along with SC, the prosumer also participates in ASM through tertiary reserves. It has been assumed a regulatory framework in which the prosumer could access on his own to the market and can bid everything available to the tertiary reserve without the restriction of the minimum bid.

If the prosumer provides an upward reserve to the market, by following Eq.12, it is only accepted when the price bid is lower than the one on the market as shows Figure 2. Only in that case, it provides upward regulation

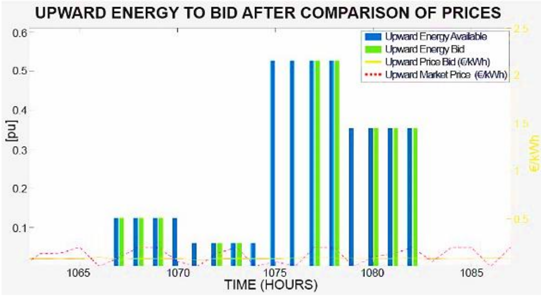

Figure 2 Upward Energy to Bid after comparison of Prices

Different from the upward reserve and following Eq.13, it could be seen in Figure 3 that prosumer is accepted for downward regulation whenever the price offered is higher than the one on the market (prosumer buys back energy).

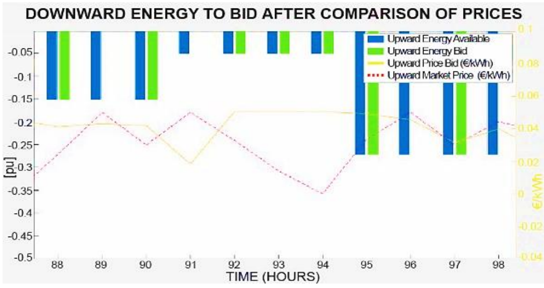

Figure 3 Downward Energy to Bid after comparison of Prices

The model follows the strategy explained in Section II, only offering downward energy when the SoC is low, upward when the SoC is high, with the purpose to keep the SoC far from saturation.

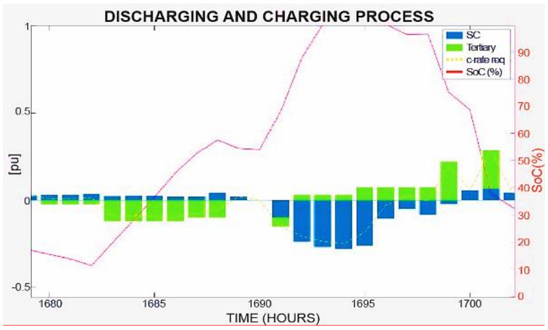

Figure 4 Discharging and Charging Process of Unconstrained Case

This tertiary bid, together with power requested for self-consumption (P_{diff}) gives the total power required (Figure 4).

❖ Aggregated Case

The aggregated case introduces in the market the constraint of the minimum bid size. Tertiary reserve bids are only accepted if their quantity is equal or greater than 200 kW. Again, upward bids are selected if offered price is lower than the one on the market, as shown in Figure 5.

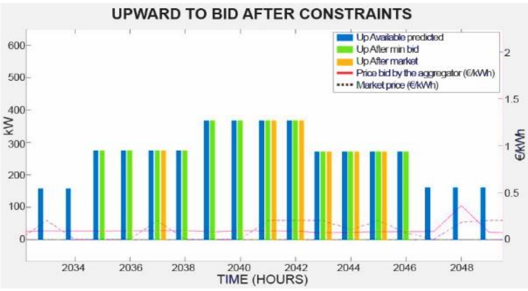

Figure 5 Upward to Bid after constraints

Downward reserve bid, in addition to the quantity constraint, are accepted when the price bid is higher than the one on the market, as in Figure 6.

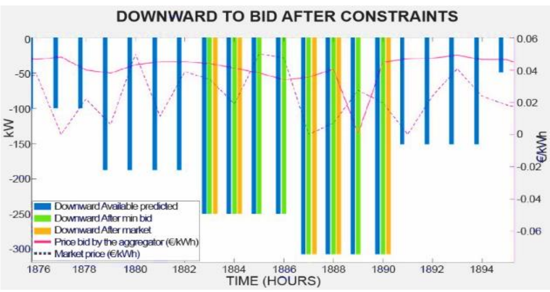

Figure 6 Downward to Bid after constraints

For the aggregated case, it is expected that the prosumer exchanges less energy for tertiary than in the unconstrained case because of the additional constraint on the minimum bid.

IV. Sensitivity Analysis

For each of the cases, it was tested the battery sizing and other parameters to have a large sensitivity analysis. It was studied EPR= 2.5 h, 3 h, 3.5 h, 4 h, and for the Nominal Power of the battery, P_n= 1.5 kW, 2 kW, 2.5 kW, 3 kW.

❖ Behind-the-Meter (BtM)

Figure 7 shows that when EPR increases, the injection is decreasing a little, but decreases the most when P_n increases.

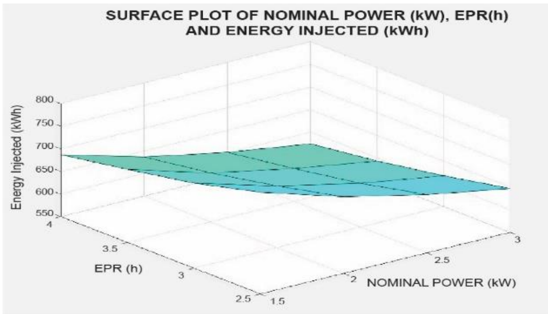

Figure 7 Surface Plot of P_n, EPR and Energy Injected in Behind-The-Meter

Figure 8 shows that at 1.5 kW and EPR=2.5 h has high numbers of withdrawn energy, then there is a minimum point of the withdrawn energy around 2-2.5 kW and EPR=3-3.5 h, that gives the highest self-consumption for battery sizing and after these points, it starts increasing again for larger EPR and nominal power.

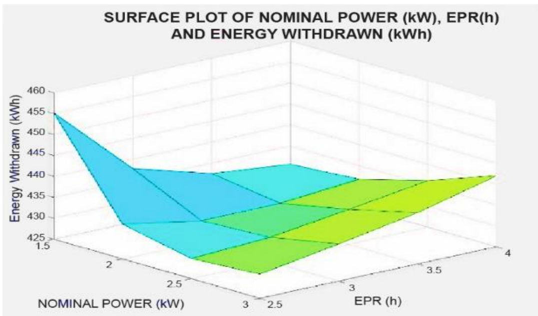

Figure 8 Surface Plot of P_n, EPR and Energy Withdrawn in Behind-The-Meter

Figure 9 shows that largest BESS are not financially advantageous because as EPR and P_n increase, there is no return on the investment and this is due to the high CAPEX for larger batteries.

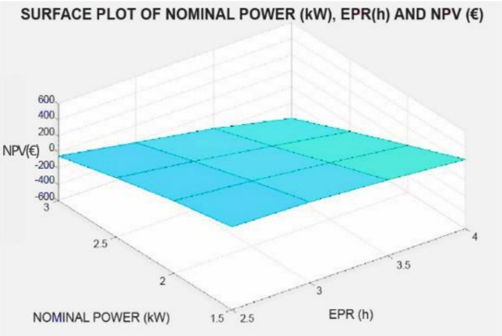

Figure 9 Surface Plot of P_n, EPR and NPV in Behind-The-Meter

❖ Unconstrained Case

For this analysis, it has been considered one prosumer with its battery providing tertiary and SC. For the available tertiary, the model has applied a safety factor to change the ratio of bid quantity with respect to available quantity (so, the market risk). In figure 10, it could be seen that by increasing power and EPR, the self-consumption of the prosumer increases, also with respect to BtM case: introducing the ASM has an increasing benefit to the prosumer.

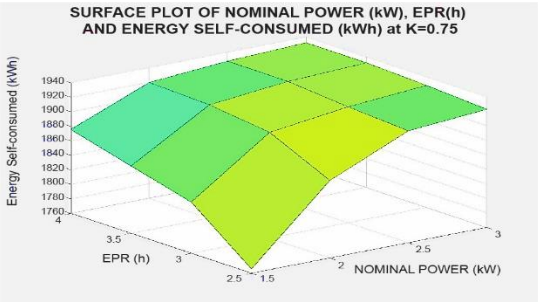

Figure 10 Surface Plot of P_n, K_s =0.75 and Self-consumption

It can be appreciated in Figure 11 and Figure 12 that as it is increased the nominal power of the battery and K_s , the prosumer exchanges more energy in the market.

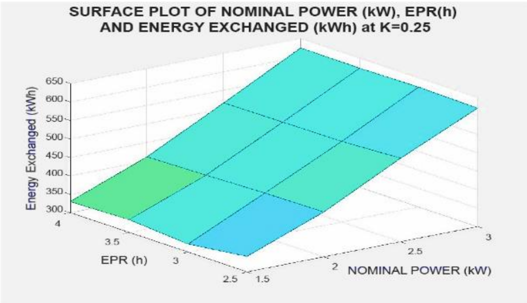

Figure 11 Surface Plot of P_n, Energy Exchanged, EPR at constant K= 0.25 in Unconstrained Case

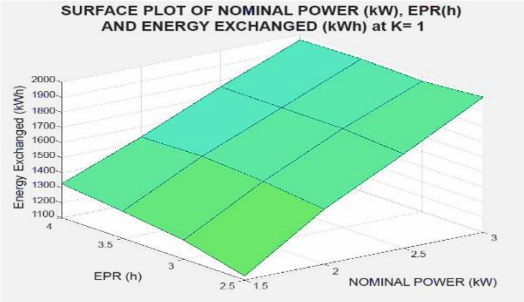

Figure 12 Surface Plot of P_n, Energy Exchanged, EPR at constant K=1 in Unconstrained Case

NPV generally increases in this case, but still the increasing CAPEX let smaller batteries be more attractive than larger batteries from an economic point of view (Figure 13).

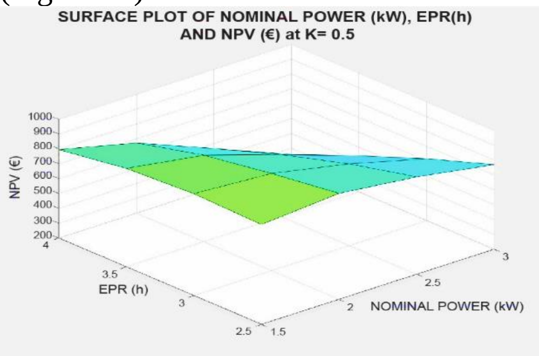

Figure 13 Surface Plot of P_n,NPV, EPR at constant $K_s = 0.5$ in Unconstrained Case

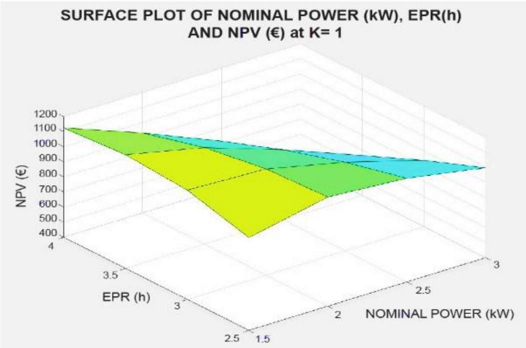

Figure 14 Surface Plot of P_n,NPV, EPR at constant $K_s = 1$ in Unconstrained Case

A larger K_s increases CAPEX (Figure 14). However, as the power is approaching 3 kW and EPR is greater than 3.5 h, it shows a decrease in the NPV, since CAPEX is predominant. A BESS with P_n = 2 kW and EPR = 3 h gets the maximum NPV.

❖ Aggregated Case

The minimum bid size for the aggregation in Italy is 200 kW, so that prosumers can only bid if aggregated. It was considered aggregated units composed by domestic prosumers only. A sensitivity analysis is proposed for different aggregator sizes. As in the previous cases, it is studied the perspective of a prosumer. EPR is constant and for all the cases K_s = 1. In Figure 15, it could be seen see that the highest energy exchange is in larger batteries.

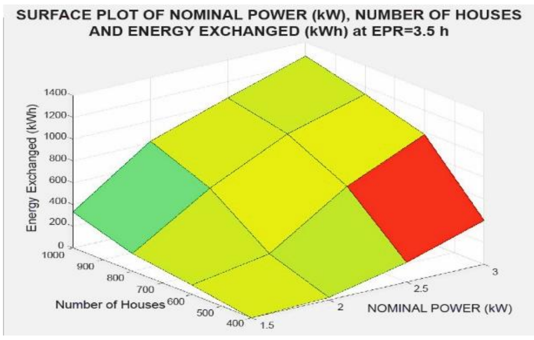

Figure 15 Surface Plot of P_n, houses and Energy Exchanged at EPR=3.5 h in Aggregated Case

One thing that it should be appreciated is that when P_n= 1.5 kW and there are 400 houses aggregated, there is never exchange of energy on ASM. Instead, by increasing P_n and houses, the energy exchanged increases more and more, therefore, biggest NPVs are observed when the prosumer is aggregated in 1000 houses. By having small batteries, it could be seen that is not of a big benefit to the prosumer to bid on ASM if the houses aggregated are smaller. One of the significant evolutions of ASM include the decrease in minimum bid size. A sensitivity analysis is performed on the minimum bid size. It has been considered the actual bid size of 200 kW, and the tested minimum bid sizes are 50 kW, 100 kW, and 150 kW. By reducing the minimum bid size, it is possible to bid more tertiary energy on the market (Figure 16) and this reflects higher NPV with respect to the other bid sizes.

Figure 16 Surface Plot of P_n, minimum bid and Energy Exchanged at EPR=4h in Aggregated Case

V. Conclusion

The scope of this work was to discover if, through the effective management of aggregated energy storage systems at the domestic level, a prosumer was able to provide benefit to itself by maximizing the

self-consumption and to the system by providing flexibility.
The outcome of this study shows that participation in the ASM allows prosumers to increase self-consumption and to increase revenues (Figure 17) and, thus, the BESS investment interest. NPV was more attractive in case of higher safety factors, meaning that as a prosumer it is better to provide all or almost all the band of tertiary power available. It was noticed that when the prosumers have smaller batteries there is not much energy exchanged. On the other hand, this is different with larger batteries, where it is exchanged more energy with ASM but since all the costs related to the investment are higher than for small batteries, it does not show good results in terms of NPV. For smaller batteries and a lower number of houses aggregated with the minimum bid size of 200 kW, it could be seen as not convenient to participate on the ASM since there is not exchanges of energy on the market. The best study case was when there was no minimum bid size since it was evident that energy self-consumed was higher than for the other cases and this case also presented the highest revenues among all the cases.

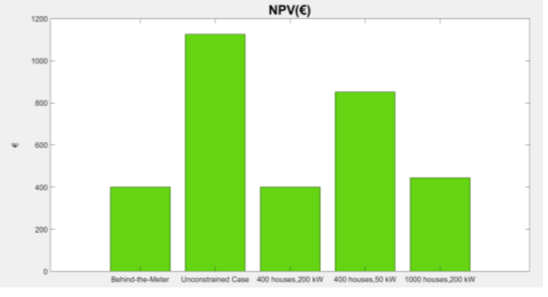

Figure 17 NPV of the cases studied

Future improvements could be to study the impact of the payment and profit-sharing between the aggregator and the prosumer. Furthermore, the imbalance impact on revenues is relevant. Thus, a topic to be considered could be developing a strategy aiming at reducing this factor.

[1] European Environment Agency, "European Environment Agency," 16 December 2019. [Online].Available:https://www.eea.europa.eu/data-and-maps/indicators/renewable-gross-final energy-consumption-4/assessment-4. [Accessed 29 August 2020].

[2] T. D. Corsatea, S. Giaccaria, C. F. Covrig, N. Zaccarelli and M. Ardelean, "RES diffusion and R&D investments in the flexibilisation of the European electricity networks," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 1069-1082, 2016.

[3] J.-M. Glachant, J. Vasconcelos and V. Rious, "A conceptual framework for the evolution of the operation and regulation of electricity transmission system towards a decarbonised and increasingly integrated electricity system in the EU," 2015.

[4] ARERA, "Delibera 05 maggio 2017 300/2017/R/eel," 2017.

[5] G. Rancilio, A. Lucas, E. Kotsakis, G. Fulli, M. Merlo, M. Delfanti and M. Masera, "Modeling a large-scale battery energy storage system for power grid application analysis," *Energies*, vol. 12, no. 17, p. 3312, 2019.

[6] ARERA, "Orientamenti relativi alla Partecipazione del veicoli elettrici al mercato per il servizio di dispacciamiento, per il tramite delle infrastrutture di ricarica dotate di tecnologia: Vehicle to Grid," 2020.

Table of Contents

Introduction **1**

Chapter 1 The Domestic User: from Consumer to Prosumer **5**
- 1.1 Photovoltaic System 6
  - 1.1.1 Growth and Trends Worldwide 6
  - 1.1.2 Growth and Trends in Italy 9
- 1.2 Battery Energy Storage Solutions (BESS) 12
  - 1.2.1 BESS Technologies 14
  - 1.2.2 BESS for Stationary Applications 16
  - 1.2.3 Basic Layout of the BESS 17
  - 1.2.4 From Electrochemical to Physical components 28
  - 1.2.5 BESS Modelling 30
- 1.3 Exploring PV and Energy Storage Synergy 33
  - 1.3.1 Services provided by PV+BESS 33
  - 1.3.2 Business Models 35

Chapter 2 Electricity Markets in Italy **37**
- 2.1 Wholesale Market 39
- 2.2 Ancillary Services Market 41
- 2.3 Market Evolution 45
  - 2.3.1 Opening to DERs 46
  - 2.3.2 Acknowledgment of peculiarities and limits of BESS 49

Chapter 3 Aggregation **52**
- 3.1 Overview of Aggregators 52
  - 3.1.1 United States of America (USA) 54
  - 3.1.2 Australia 55
  - 3.1.3 Europe 56
- 3.2 Types of Aggregators 60
  - 3.2.1 Aggregator as Retailers 60
  - 3.2.2 Aggregator as BRP 61
  - 3.2.3 Aggregator as a Service Company 61
  - 3.2.4 Aggregator as Third-Party 63
  - 3.2.5 Prosumer as Aggregator 63
  - 3.2.6 DSO as Aggregator 64
- 3.3 Revenue Models 65

Chapter 4 Proposed Methodology 67
4.1 Reference case: the domestic prosumer.. 68
4.1.1 Energy Flows Computation... 68
4.2 Behind-the-meter Case 68
4.2.1 BESS Model.. 69
4.2.2 Energy Flows Computation... 72
4.3 Behind-the-meter case and flexibility services... 74
4.3.1 The Controller 75
4.3.2 Energy Flows Computation... 75
4.3.3 Loss of Regulation 82
4.4 Aggregated case... 84
4.4.1 The Controller 85
4.4.2 Energy Flows Computation... 86
4.5 Economic Model... 89

Chapter 5 Data Acquisition 95
5.1 Domestic Load Profiles 95
5.1.1 Appliances in the Project Micene.. 96
5.1.2 Appliances not in Micene... 99
5.1.3 Production of the Load Profile 100
5.2 PV Power Profile.. 100
5.2.1 From Irradiation data to PV Power 100
5.3 Simplified Machine Learning Method 101
5.4 Input Data to the Controllers 102
5.5 Market Data... 104
5.6 Economic Data 107

Chapter 6 Numerical simulations and Results 109
6.1 Results 109
6.1.1 Behind-the-meter Case.. 110
6.1.2 Unconstrained Case... 111
6.1.3 Aggregated Case 114
6.2 Simulation Layout for Sensitivity Analysis... 118
6.2.1 Behind-the-meter Case.. 119
6.2.2 Unconstrained Case... 122
6.2.3 Aggregated Case 126
6.2.4 Comparison of the study cases 130

Chapter 7 Conclusions 133

Acronyms 135

Bibliography 137

List of Figures

Figure 1.1 Solar PV Growth in 2018 [12] 6
Figure 1.2 Solar PV Capacity and Additions in 2018 [12] 7
Figure 1.3 European Annual Solar PV Installed Capacity [11] 8
Figure 1.4 Segmentation of the Capacity in some countries [11] 8
Figure 1.5 EU28 Total Solar PV Installed Capacity [11] 9
Figure 1.6 Installed Power and Number of PV Plants in Italy [13] 11
Figure 1.7 Energy self-consumed in 2018 [13] 12
Figure 1.8 Trends of Lithium-ion Battery Price [21] 15
Figure 1.9 Lithium-ion components [20] 18
Figure 1.10 Discharging/Charging in Li-ion Batteries [20] 18
Figure 1.11 OCV vs SoC for Li-ion battery [34] 20
Figure 1.12 Discharge Capacity, Voltage and c-rate of a battery [38] 21
Figure 1.13 One cycle from 0 to 100% [45] 24
Figure 1.14 Different types of battery cycle [46] 25
Figure 1.15 Cause and effect of degradation mechanisms [50] 26
Figure 1.16. Components of BESS [57] 28
Figure 1.17. The composition of the battery [57] 29
Figure 1.18 Peak load shaving strategies [68] 34
Figure 2.1 Electricity Market in Italy [117] 38
Figure 2.2 Day-ahead market clearing price [129] 39
Figure 2.3 Intraday Market [75] 41
Figure 2.4 Timeframe of the Reserves [79] 45
Figure 2.5 Innovation in Ancillary Services [95] 46
Figure 2.6 Evolution of the electricity markets in Italy [95] 47
Figure 2.7 Timeline of the Pilot Projects 48
Figure 3.1 Benefits of the use of aggregators [95] 53
Figure 3.2 Aggregator as Retailers [89] 61
Figure 3.3 Aggregator as BRP [89] 61
Figure 3.4 Aggregator as Service Company [89] 62
Figure 3.5 Prosumer as Aggregator [89] 63
Figure 3.6 DSO as Aggregator [89] 64
Figure 4.1 Components of the BESS model and their main variables 69
Figure 4.2 Simulink Model for the Prediction of Tertiary reserve and bid on the Market. 75
Figure 4.3 Different prosumers in an aggregated unit 85
Figure 5.1 Example of correlation of Real and Forecasted PV Power 102
Figure 5.2 Example of PV Power produced in one year 102
Figure 5.3 Example of Load Consumption in one year 103
Figure 5.4 PV Power Profile of the aggregated users 103

Figure 5.5 Load Power Profile of the Aggregated Users 104
Figure 5.6 Average Downward Prices in 2019 105
Figure 5.7 Average Upward Prices in 2019 105
Figure 5.8 Average annual zonal prices in the DAM market [127]................................ 107
Figure 6.1 Difference in Power between Load and PV Power in the ends of February and beginning of March 110
Figure 6.2 Discharge and Charge Process in the middle of February for Behind the Meter Case 111
Figure 6.3 Tertiary Power Available after Prediction 112
Figure 6.4 Upward Energy to bid After Comparing the Prices.. 112
Figure 6.5 Downward Energy to Bid after comparing the prices 113
Figure 6.6 Criteria Selection for Tertiary Reserve in Unconstrained Case...................... 113
Figure 6.7 Discharge and Charge Process of Unconstrained Case 114
Figure 6.8 Upward Available for prosumer and aggregator 115
Figure 6.9 Downward Available for prosumer and aggregator 115
Figure 6.10 Upward Available to Bid after constraints 116
Figure 6.11 Downward Available to bid after constraints 116
Figure 6.12 Discharge and Charge Process in Constrained Case 117
Figure 6.13 Tertiary Reserve Awarded after respecting the minimum bid...................... 117
Figure 6.14 Surface Plot of Nominal Power, EPR and Energy injected.......................... 120
Figure 6.15 Surface Plot of Nominal Power, EPR and Energy Withdrawn..................... 121
Figure 6.16 Surface Plot of Nominal Power, EPR and NPV in Behind the Meter Case .. 121
Figure 6.17 Capex of the batteries considering EPR and Power 122
Figure 6.18 Plot of Energy Self-consumed, Nominal Power and EPR with constant Ks . 123
Figure 6.19 Frequency of the State of Charge in Unconstrained Case 124
Figure 6.20 Plot of Energy Exchanged, Nominal Power and EPR with constant Ks 124
Figure 6.21 Effect of Safety Factor on LoR and Energy Exchanged............................... 125
Figure 6.22 Plot of NPV, Nominal Power and EPR with constant Ks............................. 125
Figure 6.23 Effect of Safety Factor on LoR and NPV 126
Figure 6.24 Number of Houses studied for aggregation 127
Figure 6.25 Plot of Energy Exchanged, Nominal Power and Houses with constant EPR 128
Figure 6.26 Plot of NPV, Nominal Power and Houses with constant EPR 128
Figure 6.27 Plot of Energy Exchanged, Nominal Power and Minimum bid with constant EPR.. 129
Figure 6.28 Plot of NPV, Nominal Power and Minimum bid with constant EPR........... 130
Figure 6.29 BESS life of the different cases 131
Figure 6.30 Energy Self-consumed of all the cases 131
Figure 6.31 NPV comparing all the cases 132

List of Tables

Table 1.1. PV Plants installed in 2017 and 2018 [13] 10
Table 1.2. Number of PV Plants and the total Power [13] 10
Table 2.1. ASM ex-ante sessions 42
Table 2.2. MB sessions 43
Table 3.1. Overview of the type of aggregator 65
Table 4.1. Auxiliary Power with respect to T_{amb} and P_{grid}^{AC} 70
Table 4.2. Efficiency with respect to $c\text{-}rate_{req}^{tot\ AC}$ and SoC 72
Table 5.1. Economic Parameters used in the simulations 108
Table 6.1. Parameters studies on sensitivity analysis for SC 118
Table 6.2. Parameters studies on sensitivity analysis for unconstrained case 118
Table 6.3. Parameters studied on number of houses aggregated 119
Table 6.4. Parameters studied on the minimum bid for aggregation 119

Introduction

One of the most critical changes to electrical systems is the increasing penetration of Renewable Energy Sources (RES) into the distribution network [1]. This increase is a consequence of the energy transition from fossil fuel-based generation towards energy sources, which creates less environmental damage and pollution. Higher diffusion of RES into distribution networks increases the needs of power reserves [2] for ensuring system stability since the intermittent and unpredictable production dramatically affects the security and reliability of the system. This need for flexibility implies substantial changes in the way energy systems and markets are handled [3].

Consequently, the power system requires new resources of flexibility, characterized by constant and rapid availability to vary their power exchanges with the network. The aggregate impact of significant variable RES on the grid suggests the need for modifications, as already said, to current procurement mechanisms and ancillary services market designs and rules.

One of these changes to the electrical systems and the most significant around the world has been the rapid expansion of distributed energy resources (DERs), which are electricity-producing resources or controllable loads that are connected to local distribution [4]. The use of DERs, such as distributed photovoltaic (PV), energy storage systems (ESSs), and demand response (DR), combined with innovative smart grid technologies (SGTs), has been growing every year. DERs can offer more excellent customer choice and may also present opportunities to optimize overall system investments and provide a range of grid services [5].

Recently, the electricity market has been opening up to generation sources that previously were not considered able to provide balancing services, such as DERs, and due to digitalization, the technical possibilities to integrate small- and medium-sized prosumers are continuously expanding, and one of these possibilities is the integration of energy storage [6].

The new electricity market could rely on efficient and affordable energy storage technologies to manage a large share of intermittent resources. One of these storage technologies is lithium-ion batteries that are an excellent example of electrical energy storage technologies. However, not all technologies are widely available and economically feasible. Cost, specific energy, power, safety, performance, and the lifetime of ESSs still need improvements [7] and should be considered carefully for ESSs to become widely adopted in the distribution grid and, thus, increase the flexibility of variable DG.

Regulators are moving in the direction of more inclusive markets, where participants provide more resources at a lower cost. The implementation of RES aggregation through entities known as Virtual Power Plants (VPPs) is one of the most recent and effective ways to achieve this, and thanks to the concept of aggregation, regulators are opening up Ancillary Services Market (ASM) to RES and DERs participation. For instance, this is gradually happening in Italy [8].

This study addresses the issue of increasing the flexibility resources of the Italian electricity system through the participation of the demand in the market, focusing the analysis at a domestic level.

The scope of this work is to verify the performance of the Battery Energy Storage System (BESS) of providing grid services, from both technical and economic points of view at a domestic level. The study will focus on different strategies that the customer could integrate to guarantee the increase of self-consumption, but also the participation in the market for frequency regulation. These domestic users equipped with ESS, used as sources of flexibility, will participate in Day-Ahead Market (DAM) and in the ASM, where Tertiary Reserve (TR) is offered.

The thesis here proposed evaluates BESS integration in the Italian ASM framework, as said before. Considerable attention will be dedicated to representing the regulatory framework correctly, and some assumptions will be introduced to represent a likely future regulatory scheme and to obtain results that can be generalized. The role of all the involved parties, such as the Balance Responsible Party (BRP) and Balancing Services Provider (BSP), will be described and will be technically and economically modeled.

The analysis focuses on Li-ion BESS, which is the most widespread electrochemical storage device. A model of the battery already validated [9] will be modified to accurately model small-scale BESS and applied to a set of cases simulating BESS behaviors. The model to be selected will show truthfulness in representing the states of the battery performing power cycles simulating services provision. The cell model will receive as input the PV and load data each hour and will link these parameters to the power requested to the battery that will give back efficiency, an update of the state of charge (SoC), and the real energy provided by the battery. The model will also include the rest of the system linking the battery to the grid and managing the battery.

Since this work aims to deal with products traded on the market, a simulation of the market itself is vital to evaluate when the battery is selected for provision. On the other hand, a multi-service strategy should intent to perform SoC restoration by having a balance among services. It will be developed a strategy that will keep as far from the limits of saturation of the SoC of the battery, i.e., the maximum SoC and the minimum SoC.

To assess how the different parameters affect the effectiveness and the economic sustainability of the solution, a sensitivity analysis between two main parameters of BESS will be carried out: nominal power (P_n) and Energy to Power Ratio (EPR) to find the optimal point. The results obtained highlight the economic return of the investment through the Net Present Value (NPV).

Thesis Layout

The organization of this thesis is the following:

Chapter 1 describes the photovoltaic systems, its development during these years, and what are the expected numbers in the future. It also presents what a Battery energy storage system is, the leading technologies used for energy storage, the layout of the batteries to outline which parameters characterize its design and behavior. Further, it focuses on the photovoltaic system together with storage, all the functions that are possible to exploit, and the central business models proposed by battery providers.

Chapter 2 outlines the Electricity Markets in Italy, focus on Wholesale Market and Ancillary Services Markets. A description of primary grid services is given, focusing on services considered in this study, starting with the wholesale market to give a brief explanation about the avoided cost that is possible to have by performing self-consumption. In the Ancillary services, it is described part of the services that are provided, but with focus on frequency regulation that is the scope of the study. Part of the chapter is dedicated to the evolution of the market, future trends, and some barriers.

Chapter 3 shows a definition of aggregator, an overview of what is happening in capacity and services delivered in countries working on this concept. Additionally, the types of aggregators that are possible to work with and the main functions that they could have as an aggregator are detailed. Together with all those mentioned above, it is described a brief explanation of revenue models.

Chapter 4 is dedicated to the representation and explanation of the methodology proposed for this study. Here, all the descriptions and the reasons for the choices taken for all the models done are included. The comprehensive procedure developed and used for the implementation of services is explained together with the description of energy flows.

Chapter 5 explains how the data were selected, why some decisions were made, and in what framework was preferable to work.

Chapter 6 contains the report of simulations and results found. It starts with the results of each of the cases and then there is a sensitivity analysis by going through changes in nominal power and EPR to show a description of the behavior of the BESS for each study case. A comparison and examination of the results in terms of performance and economic return of the investment are performed.

Chapter 7 includes a conclusive summary of the work done on the thesis and the outcomes achieved, with possible recommendations.

Chapter 1
The Domestic User: from Consumer to Prosumer

Energy production and consumption remain a critical focal point in global efforts to address climate change. Climate strategies that set targets for partial or complete decarbonization can establish indirect mechanisms for scaling growth in the renewable energy sector.

Solar Photovoltaic (PV) has become the world's fastest-growing energy technology, with gigawatt-scale markets in an increasing number of countries. Demand for solar PV is spreading and expanding as it becomes the most competitive option for electricity generation in a growing number of markets for residential and commercial applications and increasingly for utility projects [10].

This chapter shows a description in section 1.1 about the PV system and its growth worldwide with a focus on European Region, especially in Italy. Section 1.2 will introduce the concept of Battery Energy Storage Solutions (BESS) and the technologies that have been developed and used over the years. BESS could be used for mobile or stationary applications, but this study only focuses on stationary. Together with the abovementioned, it will be shown the Basic layout of BESS and description of some important parameters that will help in the study of the storage. Section 1.3 will show the synergy of PV and storage and will explain the utilities and the business models.

1.1 Photovoltaic System

Photovoltaic technology is an integrated assembly of modules and other components that allows to directly transform solar energy into electricity to provide a particular service, either alone or in combination with a backup supply through the photovoltaic effect, i.e., the property of some semiconductor materials to generate electricity if affected by light radiation. Silicon, a common element in nature, is the primary material for the photovoltaic cell. Several cells are electrically connected and encapsulated in a structure to form the module. Several modules, connected in series and parallel, form the sections of a system whose power can reach thousands of kW. Downstream of the photovoltaic modules is the inverter, which transforms the direct current generated by the cells into alternating current, which can be directly used by users or transferred to the grid. The modules are towards the sun on fixed structures or on structures capable of following their movement to increase solar uptake, which have a tracking system.

The main applications of photovoltaic systems are:

- systems for users connected to the low voltage network;
- electricity production plants connected to the medium or high voltage grid;
- integration with a storage system for users isolated from the network.

1.1.1 Growth and Trends Worldwide

Despite its relatively low, one-digit year-on-year growth, as shown in Figure 1.1, solar was again the power generation technology with the most significant capacity additions globally in 2018, and more solar was deployed than for any other single technology [11].

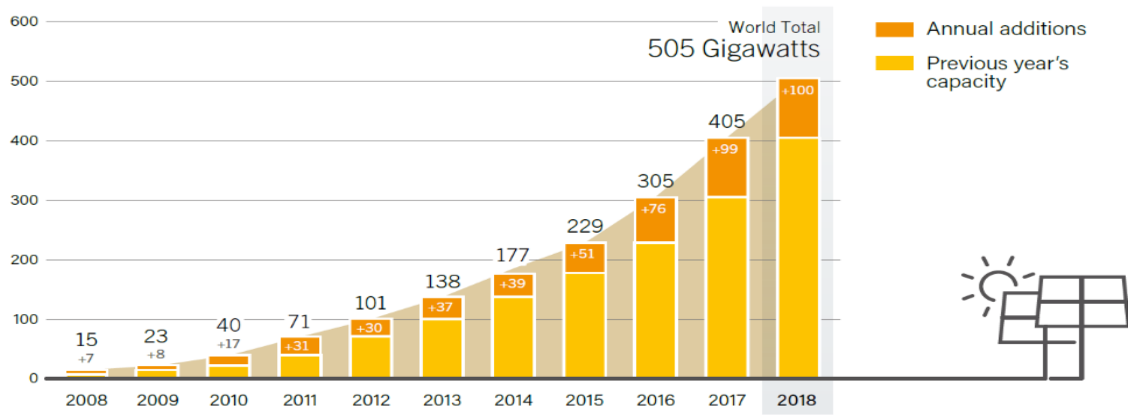

Figure 1.1 Solar PV Growth in 2018 [12]

The annual global market for PV increased only slightly in 2018, but enough to surpass the 100 GW (direct current) level (including on- and off-grid capacity) for the first time. Cumulative capacity increased approximately 25% to a year-end total of 505.5 GW; this compares to a global total of around 15 GW only a decade earlier (Figure 1.1.) [12]

In 2018, solar PV had another strong year for new additions(Figure 1.2), boosted by growth in emerging markets [12]. Solar also added more capacity than all renewables combined—including large hydro—and had twice as much installed than wind power. This high demand in emerging markets and Europe was mainly due to ongoing price reductions, compensated for a substantial market decline in China that had consequences around the world [12].

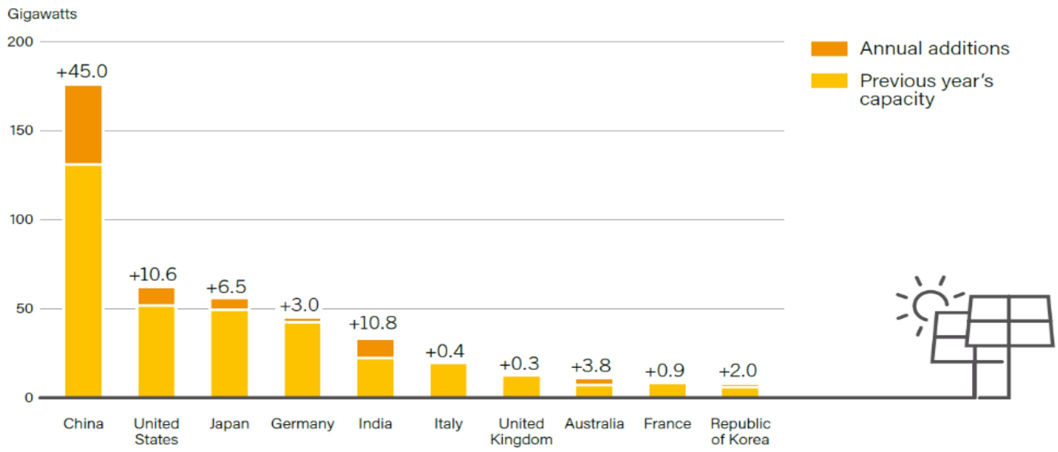

Figure 1.2 Solar PV Capacity and Additions in 2018 [12]

By 2018, nearly all countries and many sub-national jurisdictions had adopted some form of renewable energy target. Several new or revised renewable energy targets were established in 2018, including the European Union (EU). For example, in 2018, the European Commission outlined its strategy for reaching a zero-carbon economy across the region by 2050, and individual EU member countries were required to establish national energy and climate plans to meet EU-wide 2030 targets [10] where the goal was meeting at least 32% (revised upwards from 27%) of its final energy consumption from renewable sources.

Europe seems like one of the solar growth regions. Driven by the EU's binding national 2020 targets, the continent added 11.3 GW in 2018(Figure 1.3), a 21% rise over the 9.3 GW installed the year before [11].

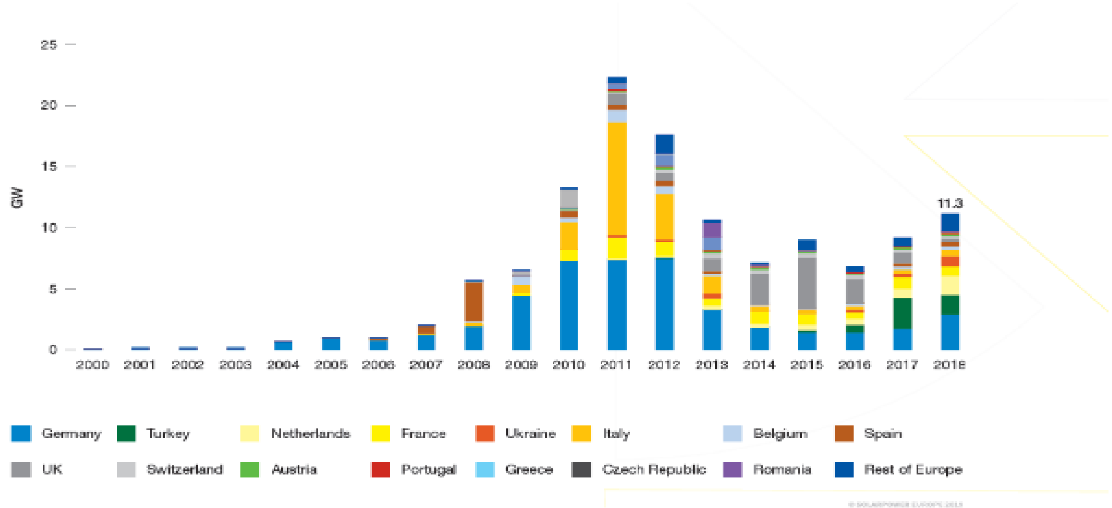

Figure 1.3 European Annual Solar PV Installed Capacity [11]

The European Union seems well prepared for the coming years when it comes to solar because the majority of the EU's 28 member states still have some way to meet their national binding renewables targets in 2020, and increasingly an option for low-cost solar [11].

While support schemes of some kind are still needed for solar PV in most countries, interest in purely competitive systems is multiplying. Self-consumption remained an essential driver of the market for new distributed systems in some regions, and corporate purchasing of solar PV expanded considerably, particularly in the United States and Europe [12].

By focusing only in Europe Region by 2018, 19% of Europe's cumulative PV system capacity was installed on residential rooftops, about 30% on commercial roofs, while the industrial segment accounted for 17% and the utility market for 34%. [11] Figure 1.4 shows the distribution for each country.

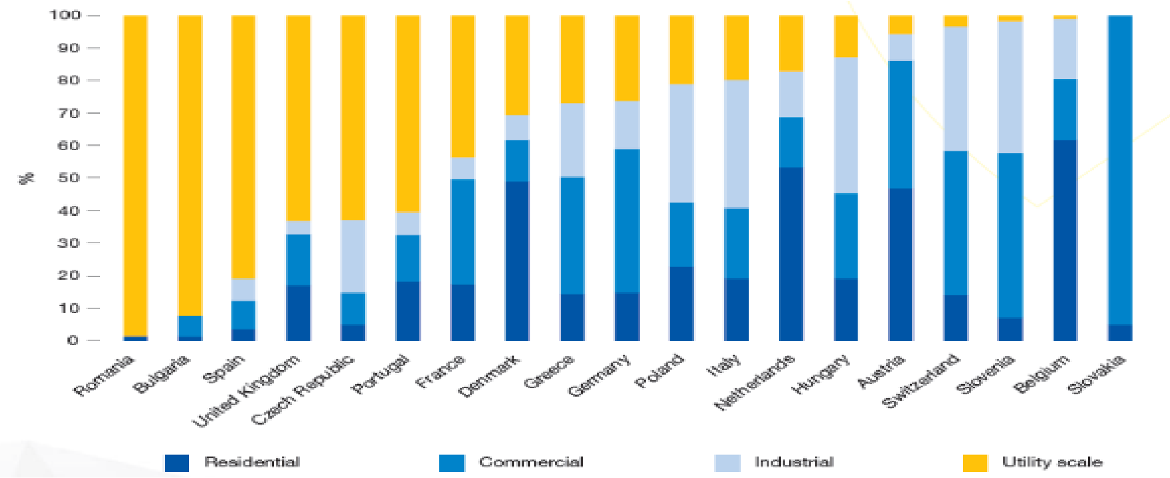

Figure 1.4 Segmentation of the Capacity in some countries [11]

1.1.2 Growth and Trends in Italy

The picture of total European solar installed capacities shows that Germany remains Europe's largest solar power plant operator with 45.9 GW of full installed capacity, followed by Italy with 19.9 GW. Again, Germany (36.5%) and Italy (15.8%) were home to over half of Europe's solar power generation capacities [11].

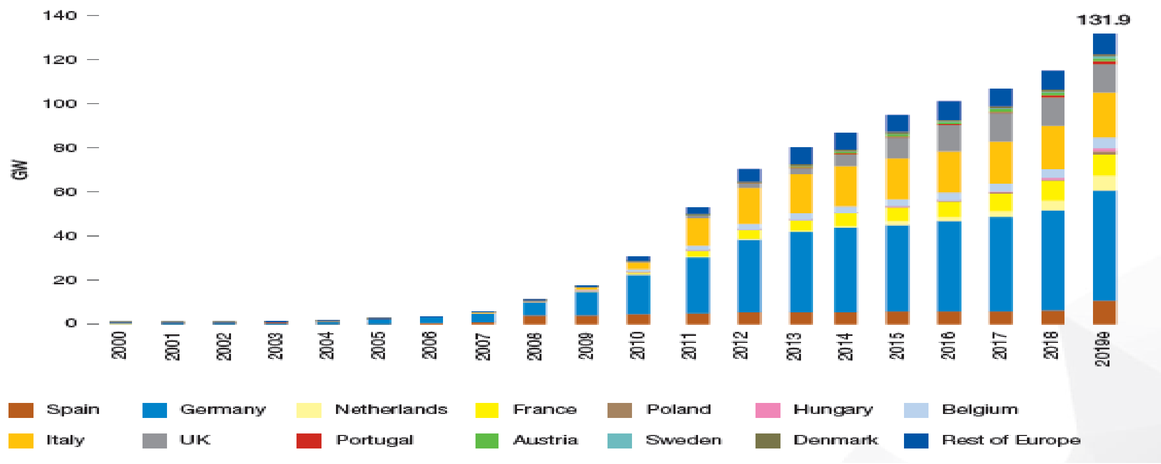

Figure 1.5 EU28 Total Solar PV Installed Capacity [11]

The scope of the study is focused on Italy that, thanks to its geographical position, has a significant amount of the solar source that has allowed exponential growth in the installation of photovoltaic systems in recent years.

By the year 2018, Italy had already reached the goal they were set. Italy has been working in projects to increase the hosting capacity of the grid with more renewables with the use of smart technologies but also storage systems. Generally talking about photovoltaic-related projects and experiences, there has been the introduction of smart metering, increasing solar in residential, commerce, and industries.

In Italy, in 2018, around 440 MW of photovoltaic systems were installed, mainly adhering to the on-the-spot trading (that implements the net metering system) with an increase of power of 6.3% [13], as shown in Table 1.1

Classi di potenza (kW)	Installati nel 2017		Installati nel 2018		*Var % 2018/2017*	
	n°	MW	n°	MW	*n°*	*MW*
1<=P<=3	17.160	43,4	17.400	43,5	*1,4*	*0,2*
3<P<=20	25.364	163,5	29.049	178,5	*14,5*	*9,2*
20<P<=200	1.280	89,7	1.626	121,6	*27,0*	*35,6*
200<P<=1.000	125	50,0	148	67,7	*18,4*	*35,5*
1.000<P<=5.000	2	3,9	1	1,0	*-50,0*	*-74,1*
P>5.000	5	63,1	1	27,5	*-80,0*	*-56,4*
Totale	**43.936**	**413,6**	**48.225**	**439,8**	***9,8***	***6,3***

Table 1.1. PV Plants installed in 2017 and 2018 [13]

By the end of 2018, 822,301 photovoltaic systems were installed in Italy, for a total capacity of 20,108 MW (+ 2.2% compared to 2017), which during the year generated 22,654 GWh (-7% compared to 2017, mainly due to worse irradiation conditions) [13]. Small plants (power less than or equal to 20 kW) make up approximately 90% of the total in terms of number and 21% in terms of power; the average size of the plants is 24.5 kW [13].

Classe di potenza	2017			2018		
	Numero	Potenza (MW)	Produzione Lorda (GWh)	Numero	Potenza (MW)	Produzione Lorda (GWh)
1<=P<=3	262.214	716	826	279.681	760	806
3<P<=20	447.332	3.267	3.762	476.396	3.445	3.636
20<P<=200	52.591	4.123	4.625	54.209	4.244	4.375
200<P<=1.000	10.739	7.353	9.367	10.878	7.413	8.548
1.000<P<=5.000	950	2.335	3.094	948	2.328	2.813
P>5.000	188	1.890	2.703	189	1.917	2.476
Totale	774.014	19.682	24.378	822.301	20.108	22.654

Table 1.2. Number of PV Plants and the total Power [13]

As already said, Italy has been working to increase hosting capacity and has been showing a phase of rapid growth between 2008-2013, within a multi-year incentive framework based on feed-in premiums and feed-in tariffs, named Conto Energia. Then, the dynamic evolved into a more gradual development.

Figure 1.6 shows the evolution of the number and installed power of photovoltaic systems in Italy in the past years until 2018. The plants that came into operation during 2018 were mostly installations serving residential users.

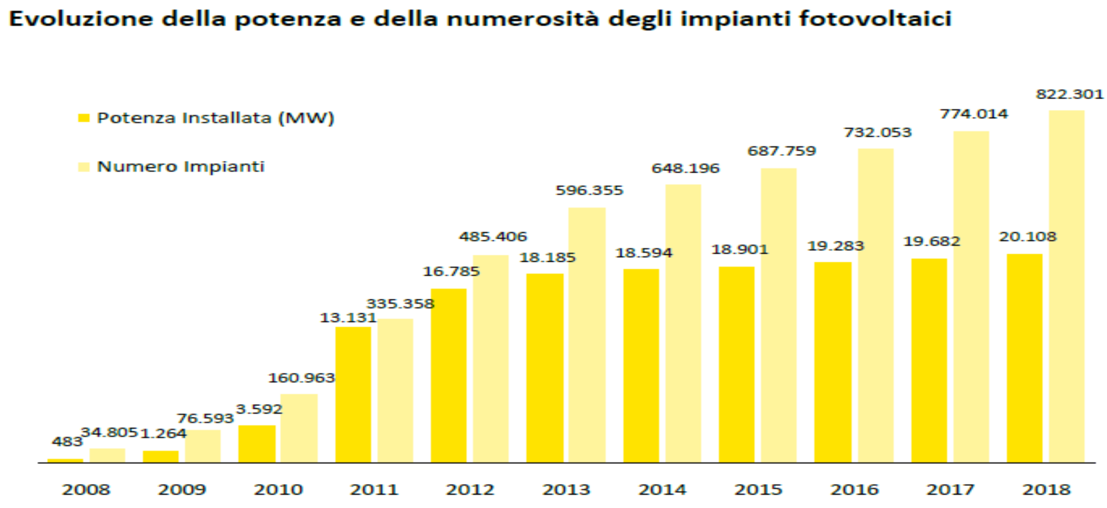

Figure 1.6 Installed Power and Number of PV Plants in Italy [13]

At the end of 2018, approximately 81% of the 822,301 systems installed in Italy belong to the domestic sector; the largest share of total power (49%) is concentrated in the industrial area.

In terms of numbers, a broad diffusion of small domestic systems is observed, mainly between 3 kW and 20 kW, followed by those with power up to 3 kW. Most of the installed power is concentrated in the industrial sector, in particular in production sites with plants of power between 200 kW and 1 MW [13].

Self-consumption

By self-consumption, it is meant the electricity produced, which is not fed into the transmission or distribution network of electricity as it is directly used by using, onsite, all or part of the electricity generated by their system.

According to Italian law, a self-producer is generally defined as the "physical or legal person producing electricity mainly for their use." Shared or collective self-consumption in Italy is not allowed at the moment, and only individual direct use of electricity produced (individual self-consumption) is possible. However, legislation is now slowly opening to grid services offered by PV operators [14].

In Italy, self-consumption in 2018 amounted to 5,137 GWh (equal to 22.7% of the total production of photovoltaic plants and 38% of the production of only plants that self-consume), a higher value than in 2017 (20.1%). The highest level of self-consumption was recorded in July (Figure 1.7), at the peak of production.

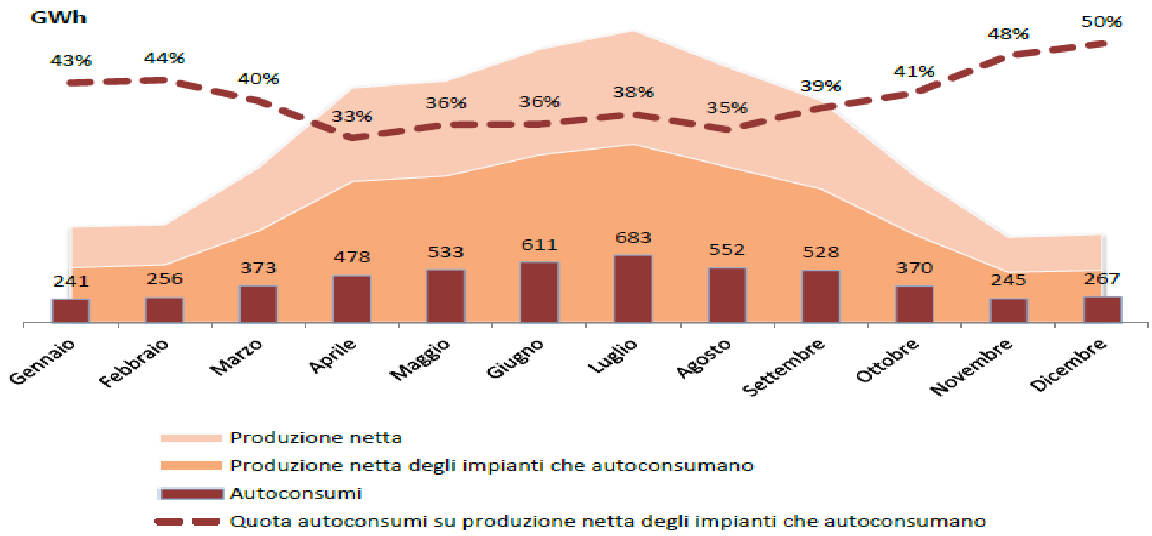

Figure 1.7 Energy self-consumed in 2018 [13]

The industrial sector was the one characterized by higher self-consumption (43% of the 5,137 GWh self-consumed in Italy during 2018), followed by the tertiary sector (27%), the domestic (21%), and the agricultural sector (9%) [15].

1.2 Battery Energy Storage Solutions (BESS)

A battery converts chemical energy into electrical energy. It is typically made of three major parts: an anode, a cathode, and an electrolyte, each made of a different material.

The chemical reactions between the materials generate energy and mainly occur when the battery is plugged into an external circuit that connects the anode and cathode, for example, when it is placed into a mobile phone. The reactions cause electrons and ions to build up at the anode. [16] The electrons flow towards the cathode through the external circuit, where they provide electrical power (to the phone or car, for instance). The ions also flow towards the cathode, but through the electrolyte, which separates the anode and the cathode. The ions and electrons recombine at the cathode to complete the circuit and keep the reactions running [16].

As the transformation of energy systems continues in many countries, policymakers have focused on the development and deployment of enabling technologies to facilitate the integration of renewable energy technologies such as energy storage.

Energy storage has been a critical component in enabling the grand transition and continues to gain momentum globally. The transformation of power networks, pushed by the electrification of energy systems, requires additional energy storage capacity to address the new flexibility needs of electric grids [17].

Storage can provide a range of grid services at different timescales.

- Energy storage provides valuable services to all stakeholders across the value chain;
- Energy storage is critical for unlocking intermittency of renewables and enabling the grand transition;
- Energy storage needs to be considered as part of energy flexibility in general and planned as part of distributed energy resources (DER). Even if energy storage will always be the more expensive option, it is essential to consider energy storage holistically alongside energy flexibility options in general;
- Flexibility: With an increasing thrust towards renewable integration across the globe, energy storage has the potential to manage demand and supply dynamics;
- Efficiency: Pairing energy storage with the right assets can significantly reduce delivery losses.
- Resilience: Energy storage applications like black start facilities enable the maintenance of critical functions leading to a quick recovery [17].

However, prominent barriers to storage deployment can be traced to the speed in which the market for storage technologies and their applications are evolving [17].

Some of the critical challenges that need to be addressed are:

- Perception of performance and safety: Grid operators have to be confident that energy storage systems will perform as intended within the more extensive network. Advanced modeling and simulation tools can facilitate acceptance — mainly if they are compatible with utility software;
- Cost-Effectiveness: Actual energy storage technology contributes around 30%- 40% [17] to the total system cost; the remainder is attributed to auxiliary technologies, engineering, integration, and other services;
- Regulatory and market guidelines: It is critical to remove the rules that are distorting the market and crippling investment. Energy storage systems provide different functions to their owners and the grid at large, often leading to uncertainty as to the applicable regulations for a given project. Regulatory change poses an investment risk and dissuades adoption.
- Cooperation from multiple stakeholders: Energy storage investments require broad collaboration among electric utilities, facility, and technology owners, investors,

project developers, and insurers. Each stakeholder offers a different perspective with distinct concerns.

Energy storage is overgrowing globally. Falling costs and new deployment incentives are fueling record investments in energy storage. The prices of storage have decreased dramatically in the last decade. Lithium-ion batteries, which are the most diffused type of storage batteries, fell from 1,000 USD/kWh in 2010 to 200 USD/kWh in 2017. [18] Remarkably, the potential for further cost reduction is substantial; by 2030, prices could fall by more than 60% compared to current levels [18]. At the same time, the existence of many different storage technologies able to match different performance requirements suggests that there is intense competition on performance and costs.

Also, environmental consideration and the benefits of smaller distributed generation resources are another driving force behind the integration of BESS into the energy segment. While the specific drivers to develop energy storage markets vary by region and market segment, the overarching goal of ESS deployments is to make the electricity grid more efficient, resilient, secure, cost-effective, and sustainable, as well as to expand the menu of available electricity market services. As a result, renewable installations paired with energy storage are expected to continue to rise into the future [18].

1.2.1 BESS Technologies

Battery technologies for energy storage devices can be differentiated based on energy density, charge, and discharge (round trip) efficiency, lifetime, and eco-friendliness. Energy density is defined as the amount of energy that can be stored in a single system per unit volume or unit weight. Lithium secondary batteries store 150–250 watt-hours per kilogram (kg) and can store 1.5–2 times more energy than Na–S batteries, two to three times more than redox flow batteries, and about five times more than lead storage batterie [19].

Charge and discharge efficiency are a performance scale that can be used to assess battery efficiency. Lithium secondary batteries have the highest charge and discharge efficiency, at 95%, while lead storage batteries are at about 60%–70%, and redox flow batteries, at about 70%–75% [19]. One crucial performance element of energy storage devices is their lifetime, and this factor has the most significant impact on reviewing economic efficiency. Another primary consideration is eco-friendliness or the extent to which the devices are environmentally harmless and recyclable.

Energy storage systems provide a wide array of technological approaches for managing power supply to create a more resilient energy infrastructure and bring cost savings to utilities and consumers. Storage technologies include mechanical (for example, flywheel, compressed air, pumped hydro), electrochemical (for example, lithium-ion, flow battery), and thermal (for example, ice, phase change materials). Individual technologies are tailored to different applications. The power system is dominated by pumped hydro energy storage (PHES), well established for decades. BESS and, in particular, Li-ion batteries currently dominate the interest of the market, due to their modularity and decreasing costs. Also, a diverse blend of battery technologies is beginning to be deployed. Thermal energy storage using molten salt is also being widely used in connection with concentrated solar power (CSP) projects [20].

Various technology options exist for BESS, as said before. Some technologies are already well established on the market (lead-acid, lithium-ion, nickel-based), also serving the stationary storage market, while others are still at the starting point of deployment or in a demonstration phase. The most spread in the world are Li-ion and NaS because of competitive cost and long life compared with the price.

Lithium-ion batteries are commercially available batteries with relatively good performance and a compact size. The availability of the raw materials is seen as a potential risk factor of the technology. Improvements in production technology, the use of low-cost materials (e.g., partial replacement of cobalt with nickel), the increase of the specific energy, and the increase in life duration (cycle life and calendar life) are crucial in lithium-ion battery-related research [16] This technology is also prevailing because of its multiple advantages at storing and releasing energy and upcoming decrease in price [21], as shown in Figure 1.8, that opens it up to a broader range of potential applications.

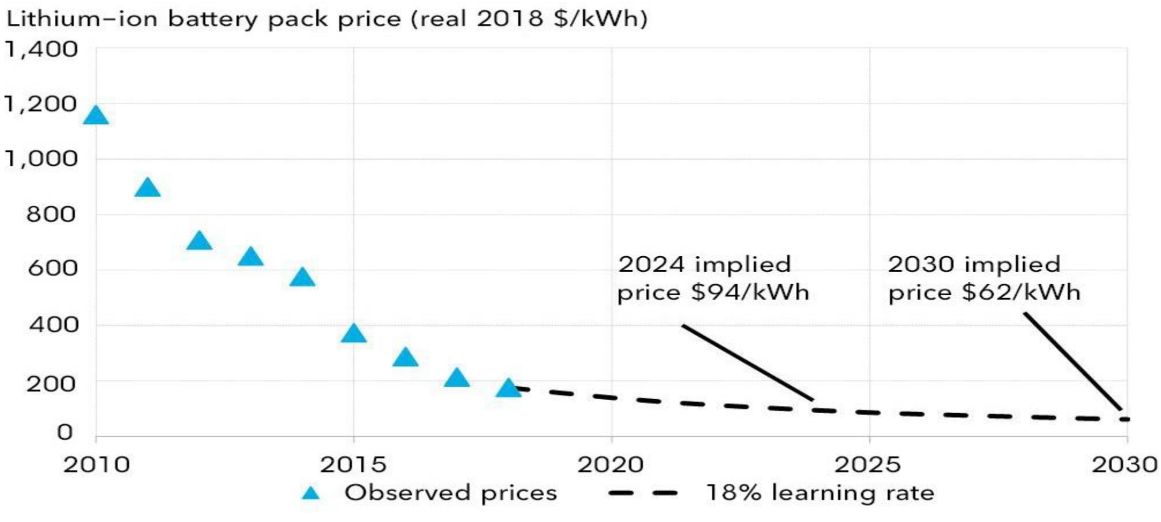

Figure 1.8 Trends of Lithium-ion Battery Price [21]

Another type of battery is the flow battery, which is a form of rechargeable battery in which electrolyte flows through an electrochemical cell that converts chemical energy directly to electricity. The additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell (or cells) of the reactor. Flow batteries can be rapidly “recharged” by replacing the electrolyte liquid (in a similar way to refilling fuel tanks for internal combustion engines) while simultaneously recovering the spent material.

The significant advantage of this type of battery is that power is not coupled in the same way as other electrochemical systems, which gives considerable design latitude for stationary applications. Additional advantages are good specific energy and recharge efficiency, low environmental impact, and low cost. The disadvantages of this battery technology are system complexity and high initial self-discharge rate [16].

One more type of technology is Molten salt batteries, also known as liquid metal batteries with low costs and high availability of materials. Examples are sodium-sulfur (NaS, molten salt) and sodium-nickel-chloride. A sodium-sulfur battery has a high energy density, relatively high roundtrip efficiency (89-92%), long cycle life, and is fabricated from inexpensive materials. However, because of the operating temperatures of 300°C to 350°C and the highly corrosive nature of the discharge products, such cells are primarily suitable for large-scale, non-mobile applications such as grid energy storage [16].

1.2.2 BESS for Stationary Applications

During the last decade, the trends in the overall worldwide rechargeable battery market have been mostly driven by the electric vehicles sector. The mature lead-acid battery technology is, by far, the essential battery market in volume and will remain so in 2025 (about 550 GWh) [16]. Of this installed lead-acid battery capacity, 79% can be found in cars as starting, lighting, and ignition batteries while only a share of 9% is installed in stationary systems to support telecom (4,2%), as UPS (3,5%) or to deliver other energy storage services (1,3%) [16].

With the shift in 2012 of almost all carmakers towards lithium-ion battery technology for the production of their (hybrid) electric vehicles, this battery market increased from an installed capacity below 2 GWh in 2000 to 90 GWh in 2016 [16] . While the original demand was for 100% originating from the portable electronics industry, this saw a decrease to 35%, reserving a share of 50% for electric mobility (i.e., cars, buses), 10% for applications like power and gardening tools as well as electric bicycles, and the remaining 5% for stationary energy storage services [16]. The use of lithium-ion in the market is showing an increase, but it also could be seen that the percentage used for stationary, even if it is small compare to mobile applications, it is also increasing.

Other potential customers of storage besides telecom that will increase more the percentage of stationary applications include power generation unit owners, grid operators, and industrial and residential consumers and prosumers. All of them seek to operate their system most cost-effectively and.

Energy storage is indeed proliferating globally. The deployment of battery has led to a push for mandates and incentives promoting this deployment both in front of the meter (i.e., utility-scale) and behind the meter (i.e., residential users). Further decreasing costs has also offered a reduction of regulatory hurdles and new business cases.

One of these forward-looking changes has been the legislative landscape on Battery Energy Storage that is evolving in Europe thanks to the proposal of the European Commission on the Clean Energy Package for all Europeans [22], which includes several positive measures to fasten the deployment of storage systems. As a result of this, Europe saw a growth of 49% in 2017 compared to 2016, with the installation of about 600 MWh electrical energy storage (primarily taken by battery systems). Continuous growth is foreseen for 2018 (about 850 MWh) and 2019 (1150 MWh), resulting in an installed capacity of 3.5 GWh (excluding pumped hydro storage), coming from 0.6 GWh in 2015 [16].

It is good to point out that for every field of application, suitable battery technology can be identified for both power-intensive as well as energy-intensive applications. For example, utility-scale batteries are being built to indirectly enable higher variable renewable energy(VRE)shares by broadly supporting greater grid flexibility and resilience mainly to support the grid centrally by providing ancillary services such as frequency regulation or by relieving transmission or distribution congestions locally. However, smaller-scale energy storage solutions are growing at a faster pace than utility-scale.

1.2.3 Basic Layout of the BESS

BESS are modular systems that can be deployed in standard shipping containers. Until recently, high costs and low roundtrip efficiencies prevented their mass deployment. However, increased use of lithium-ion batteries in consumer electronics and electric vehicles has led to an expansion in global manufacturing capacity, as explained in the section before, resulting in a significant cost decrease that is expected to continue over the next few years.

The low cost and high efficiency of lithium-ion batteries have been instrumental in a wave of BESS deployments in recent years for both small-scale, behind-the-meter installations and large-scale, grid-level deployments, which made them the most widely deployed type of batteries used in stationary storage applications today. Li-ion rechargeable batteries consist of two electrodes, anode and cathode, immersed in an electrolyte and separated by a polymer membrane (Figure 1.9) [23].

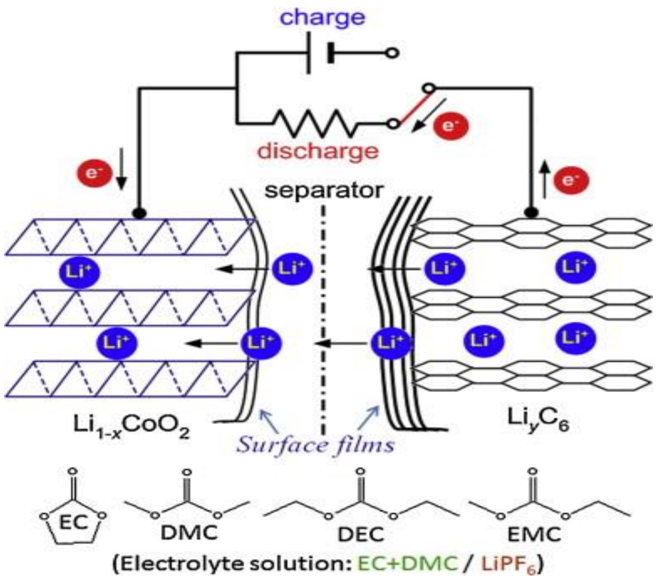

Figure 1.9 Lithium-ion components [20]

Li-ions, the working ionic component of electrochemical reactions, are transferred back and forth between the anode and the cathode through the electrolyte [23]. While the concentration of lithium ions remains constant in the electrolyte regardless of the degree of charge or discharge, it varies in the cathode and anode with the charge and discharges states [23] . The storage of lithium ions in electrodes occurs via three main electrochemical reactions [24] in intercalation [25], alloying [26], and conversion [27].

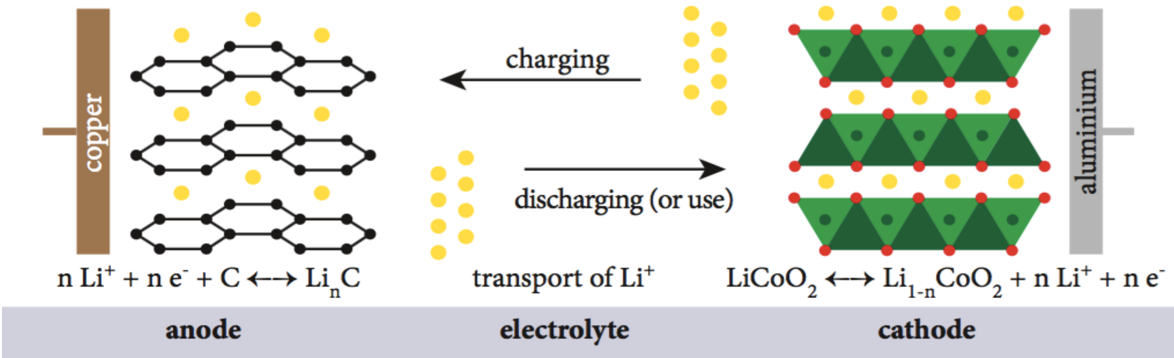

Figure 1.10 Discharging/Charging in Li-ion Batteries [20]

Electrochemical intercalation reactions(Eq. 1.1) are widely applied in Li-ion batteries for both anodes, such as graphite [28] , and cathodes, such as $LiCoO_2$ [25] and $LiFePO_4$ [29].

$$Li_{x_i}[cathode] + \left(x_j - x_i\right)Li[anode] \leftrightarrow \; Li_{x_j}[cathode] + [anode] \qquad (1.1)$$

Where x_i and x_j indicate the concrete solubility limits of the intercalation reaction.

There are a variety of BESS technologies, differentiated by their reaction chemistries. Chemistry type affects the power and energy of a BESS [30]. The nominal power (P_n), in kW, measures the instantaneous demand requirement they can supply, and the nominal energy (E_n), in kWh, establishes the total amount of energy that the module can deliver over time.

By dividing the nominal energy (in kWh) by the nominal power (kW), it is obtained the duration (in hours, minutes, or seconds) that a module can operate while delivering its rated output. This correlation is the energy to power ratio (EPR) that sometimes is also called the discharge time.

$$EPR(h) = \frac{E_n\ (kWh)}{P_n\ (kW)} \qquad (1.2)$$

State of Charge (SoC)

The SoC of a battery is defined as the ratio of its current capacity to the nominal capacity C_n (Eq. 1.3) which demonstrates the maximum amount of charge that can be stored in the battery [31] (SoC of 100% means that the BESS is fully charged, whereas it is considered to be empty at 0%).

$$SoC = \frac{C_{n-}\, C(t)}{C_n} = \frac{Remaining\ capacity}{Nominal\ Capacity} \qquad (1.3)$$

Various experimental methods, models, and algorithms, of estimating the SoC of a battery have been proposed and developed, each having its advantages and disadvantages [32] .One of the most common methods of SoC estimation is direct measurement [33]. Frequently used direct measurement methods are the Open Circuit Voltage (OCV) method, terminal voltage method, impedance method, and impedance spectroscopy method [33]. Open circuit voltage (OCV) is a very accurate method and is described as the thermodynamic battery potential under a no-load condition with a nonlinear relationship with SoC for a lithium-ion battery [34] [35], as shown in Figure 1.11

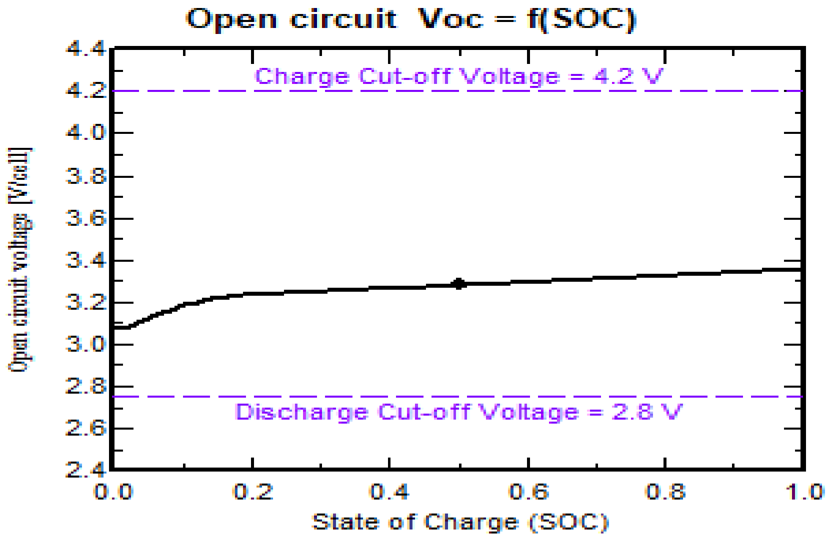

Figure 1.11 OCV vs SoC for Li-ion battery [34]

For Li-ion technology, the mid-voltage is usually around 3.3 V, and the slope around 0.15 V / SoC, as it is shown in Figure 1.11, has some limits of voltages in 2.8- 4.2 V.

The state of charge in BESS must be bounded within a given range, which can be formulated as:

$$SoC_{min} \leq SoC_t \leq SoC_{max} \tag{1.4}$$

Where SoC_{max} and SoC_{min}, are the maximum and minimum states of charge of the BESS.

Furthermore, SoC estimation can be used to regulate over-discharging and over-charging of the battery, which leads to a reduction in battery life, explosion or flame, accelerating aging, and permanent damage to the cell structure of batteries [36].

Another variable widely used in the literature is the depth of discharge (DOD), which describes the emptiness of battery (complement of the SOC) [37], and for utility-scale, the maximum DOD should be limited to 80% to prolong battery life

$$DoD(t) = 1 - SoC(t) \tag{1.5}$$

To model the effect of other operating conditions (e.g., temperature) on the BESS behavior, the SoC can be formulated by introducing the concept of equivalent current. Indeed, it has been empirically formulated by Peukert for lead-acid batteries at the end of the nineteenth century that the discharged capacity is related to the c-rate [37].

C-rates govern charge and discharge rates of a battery, which is related to SoC and, therefore, to the OCV. The capacity of a battery is commonly rated at 1C [38], meaning that a fully charged battery rated at 1Ah should provide 1A for one hour.

$$i[A] = \frac{C_n\,[Ah]}{1\,[h]} \tag{1.6}$$

In describing batteries, the discharge current is often expressed as a c-rate to normalize against battery capacity, which is often very different between batteries. A c-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current discharge the entire battery in 1 hour.

$$c - rate = \frac{i}{C_n}\,\left[\frac{1}{h}\right] \tag{1.7}$$

Since the OCV is approximated to the output voltage of the battery [39], from Figure 1.12, it could be seen that the c-rate is proportional to this voltage. As voltage decreases, also decrease the c-rate and, in the same way, for increasing voltage.

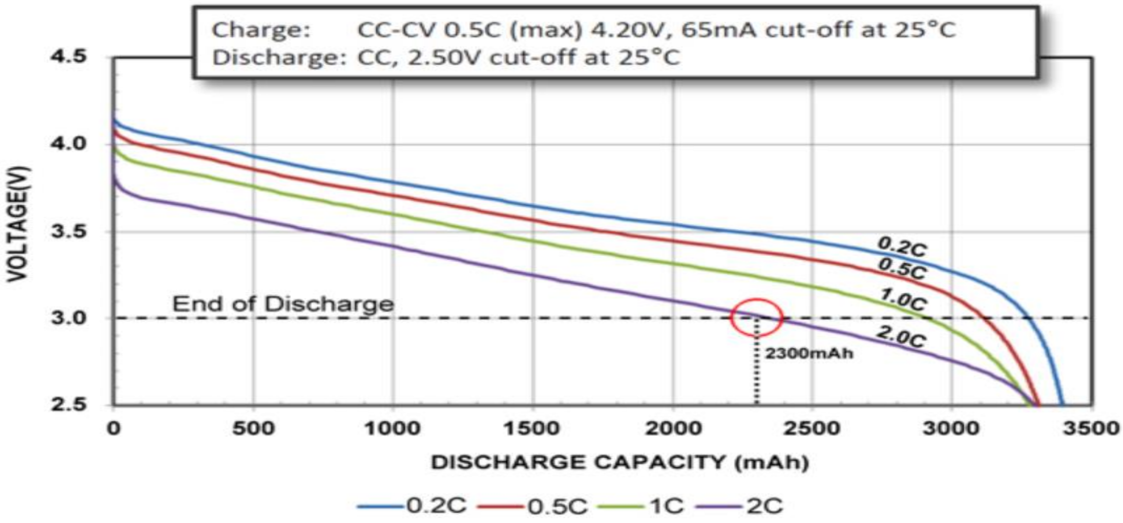

Figure 1.12 Discharge Capacity, Voltage and c-rate of a battery [38]

C-rate is inversely proportional to the battery's capacity, so as you move up with capacity, you can move down in C [40] . The exploited capacity depends on c-rate (Figure 1.12), and this capacity is lower when the c-rate is greater than 1C.

Efficiency

The battery efficiency is the ratio of the energy retrieved from the battery to the energy provided to the battery when coming back to the same SoC state. All batteries have losses. The energy retrieved after a charge is always less than what had been put in. The parasitic reaction that occurs within the electrochemistry of the cell prevents the efficiency from reaching 100 percent [41].

The efficiency factor is commonly measured by coulombic efficiency. A coulomb is a unit of electric charge, one coulomb equal one ampere-second (1As) [41]. Coulombic efficiency (CE), also called faradaic efficiency or current efficiency, describes the charge efficiency by which electrons are transferred in batteries. CE is the ratio of the total charge extracted from the battery to the total charge put into the battery over a full cycle.

Li-ion has one of the highest CE ratings in rechargeable batteries. It offers an efficiency that exceeds 99 percent. This efficiency, however, is only possible when charged at a moderate current and cool temperatures [41].

While the coulombic efficiency of lithium-ion usually is better than 99 percent, a more common efficiency is Roundtrip Efficiency, defined as the ratio of the discharged energy removed to the regeneration energy returned during the process [42].

$$Round\ trip\ efficiency = \frac{watt\ x\ hours(discharge)}{watt\ x\ hours(regen)}\ x\ 100 \tag{1.8}$$

Note that only the discharging energy efficiency of the battery could be calculated from the above equation and that the regeneration energy is not equal to the internal chemical energy gained by the battery itself because of the occurrence of polarization during the charging process [43].

The roundtrip efficiency is usually known as energy efficiency, and generally, three types of energy efficiency are defined according to the different battery working conditions [43]: energy efficiency under charging (η_{ch}), energy efficiency under discharging (η_{dis}), and energy efficiency under charging-discharging (η_{batt}).

η_{ch} is the ratio of chemical energy gained by the battery during charging, i.e., the net energy (ΔE_{batt}), over the energy extracted from power sources to charge the battery (ΔE_{in}).

$$\eta_{ch} = \frac{\Delta E_{batt}}{\Delta E_{in}} \tag{1.9}$$

The proposed equation for ΔE_{batt} [44] is:

$$\Delta E_{batt} = \int_{SoC(0)}^{SoC(t)} V_{OCV}\, C_n\, dSoC \tag{1.10}$$

The value of ΔE_{in} is calculated as:

$$\Delta E_{in} = \int_{SoC(0)}^{SoC(t)} V_{ch}\, C_n\, dSoC \tag{1.11}$$

In Eq. 1.11, V_{ch} is the battery's close circuit voltage (CCV) during charging, C_n is the nominal capacity, $SoC(0)$ is the battery's state of charge in terms of capacity when the charging starts and $SoC(t)$ is the SoC when the charging is completed.

η_{dis} is calculated similarly, as the ratio of discharged energy from the battery (ΔE_{out}) over ΔE_{batt}.

$$\eta_{dis} = \frac{\Delta E_{out}}{\Delta E_{batt}} \tag{1.12}$$

The value of ΔE_{out} is calculated using the following equation:

$$\Delta E_{out} = \int_{SoC(0)}^{SoC(t)} V_{dis}\, C_n\, dSoC \tag{1.13}$$

In Eq. 1.13, V_{dis} is the battery's CCV during discharging, $SoC(0)$ and $SoC(t)$ are the battery's SoC when the discharging starts and completes, respectively.

η_{batt} is calculated as the ratio of ΔE_{out} over ΔE_{in} when the battery is under the charging-discharging cycle.

$$\eta_{batt} = \frac{\Delta E_{out}}{\Delta E_{in}} = \frac{\int_{SoC(0)}^{SoC(t)} V_{dis}\, C_n\, dSoC}{\int_{SoC(0)}^{SoC(t)} V_{ch}\, C_n\, dSoC} = \frac{\bar{V}_{dis}\, \bar{C}_n \Delta SoC}{\bar{V}_{ch} \bar{C}_n \Delta SoC} = \frac{\bar{V}_{dis}}{\bar{V}_{ch}} \tag{1.14}$$

By using roundtrip efficiency, it is taken into consideration energy losses from power conversions and parasitic loads (e.g., electronics, heating and cooling, and pumping) associated with operating the energy storage system [19]. This metric is a crucial determinant of the cost-effectiveness of energy storage technologies. Among energy storage options, compressed-air energy storage (CAES) has the lowest reported efficiency (40%–55%), and Li-ion batteries have the highest (87%–94%). For energy storage, coupled with photovoltaics, efficiencies of less than 75% are unlikely to be cost-effective [19].

Cycling

The efficiency is a function of the type of cycle. One first definition of a cycle in a battery is the process where the battery has been discharged 100% of its battery's capacity [45]. Another way to define the battery cycle is as the process in which the battery can go from an initial SoC value to an equal final SoC value [46].

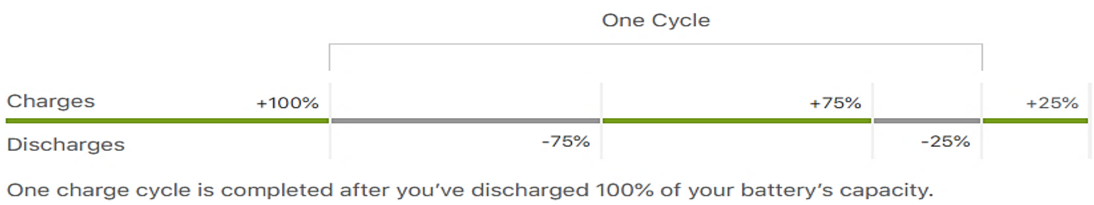

Figure 1.13 One cycle from 0 to 100% [45]

Following the same concepts, it could be seen that there are different ways (Figure 1.14) in which it is possible to describe a cycle, but usually is the process of charging a rechargeable battery and discharging it as it is required.

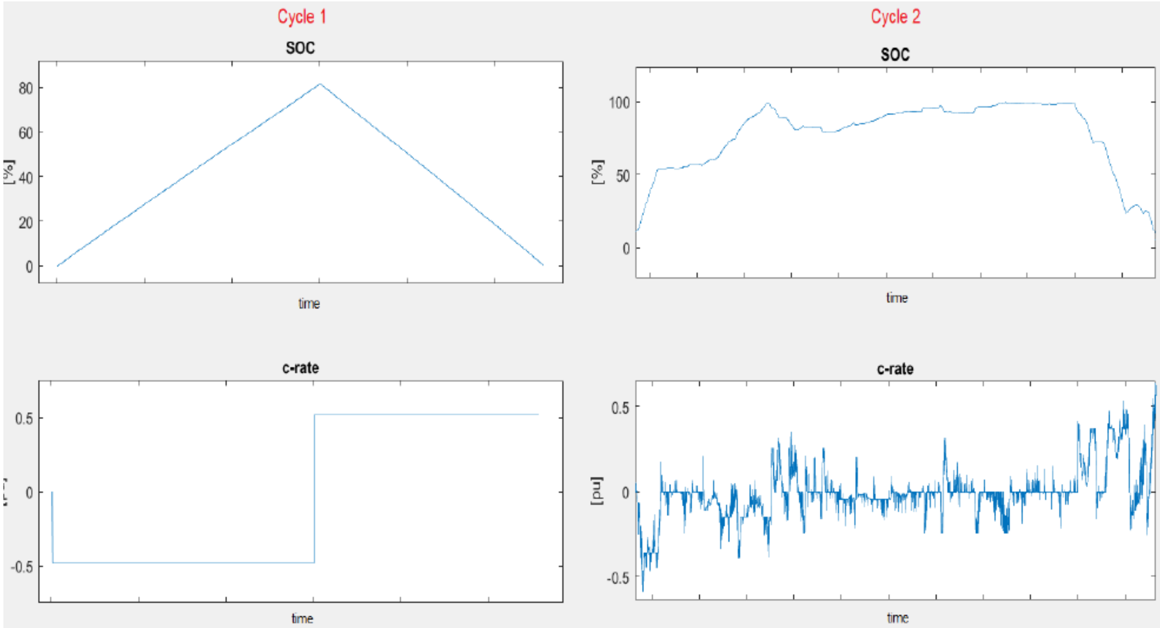

Figure 1.14 Different types of battery cycle [46]

Equivalent Life cycles are the number of complete charge/discharge cycles that the battery can support before that its capacity falls under a certain percentage of its original capacity**.** Generally, this means the number of charge/recharge cycles before a battery starts to reduce its performance visibly.

$$equivalent\ cycles = \frac{E_{gross}}{2 * E_n} \tag{1.15}$$

Where E_{gross}, is the gross energy flown through battery taken with its absolute value (positive and negative energy furnish both positive contributions to this summation). At the denominator, there is energy flew in a standard cycle (c-rate = 1, constant) at DOD: two times nominal energy [46].

Each charge-discharge cycle, and the associated transformation cycle of the active chemicals it brings about, is accompanied by a slow deterioration of the chemicals [47] in the cell, which is almost imperceptible to the user. This deterioration may be the result of unavoidable, unwanted chemical actions in the cell. The battery cycle is one of the critical cell performance parameters that indicate the expected working lifetime of the cell.

Aging and Lifetime

Battery life is a measure of battery performance and longevity before a meet a threshold.

The key factors determining battery lifetime [48] are:

- Average Depth of Discharge (DoD)
- Frequency of discharge (cycles)
- Average temperature
- Typical discharge and charge routine
- Storage state and conditions
- Amount of appropriate monitoring and maintenance conducted

Accurate battery lifetime prediction is critical for the quality evaluation [49] and long-term planning of battery management systems. This prediction is based on the study the battery degradation.

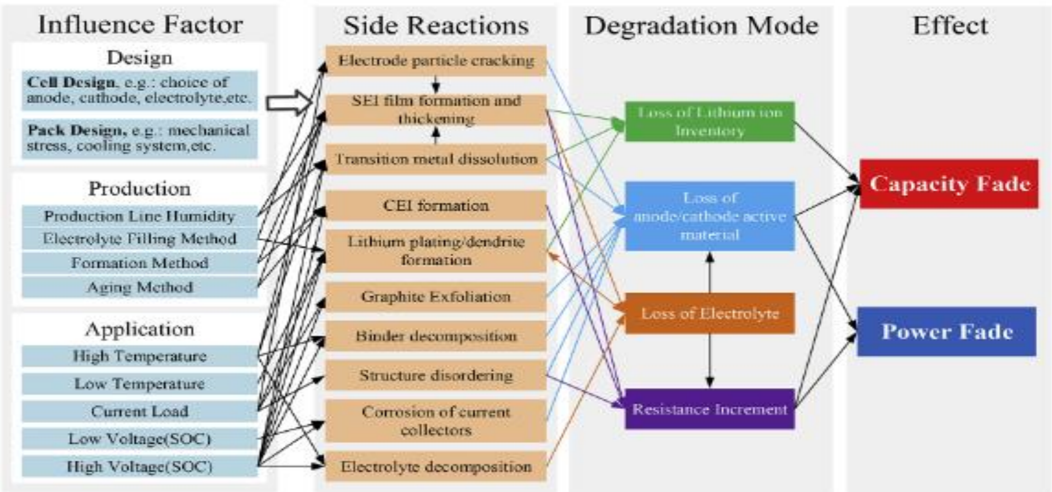

Figure 1.15 Cause and effect of degradation mechanisms [50]

Thus as shown in Figure 1.15, the battery degradation effects are usually represented by the decay of the battery-electric performance, especially the capacity and power [50]:

- Capacity fade: is caused by a loss of active electrode material (loss of storage medium): For example, if the cathode material becomes unstable at high potentials, it can no longer store lithium [51].
- Power fade: results from electrolyte decomposition and solid electrolyte interface (SEI) deterioration on the surface of electrode materials [52].

These fades, in principle, are related to calendar aging (shelf life) and cycle aging.

Calendar aging describes cell degradation during storage [53], i.e., without applying a current to the cell, while cycle aging describes cell degradation, which occurs during the charging and discharging of batteries. This differentiation assumes that there are aging mechanisms that occur independently of whether the cell is cycled and additional mechanisms that only arise if the cell is operated.

Like all battery chemistries, Li-ion degrades with each charge and discharge cycle. Cycle life can be maximized by maintaining battery temperature near room temperature but drops significantly at high and low-temperature extremes [54]. Cycle life is also dependent on DOD and current, or c-rate. Cycle depth and SOC-level must be wisely chosen to ensure the most extended lifetime.

Lifetimes of 500 to 1200 cycles are typical. The actual aging process results in a gradual reduction in capacity over time. When a cell reaches its specified lifetime, it does not stop working suddenly. The aging process continues at the same rate as before so that a cell whose capacity had fallen to 80% after 1000 cycles will probably continue working to perhaps 2000 cycles when its effective capacity has fallen to 60% of its original capacity. There is, therefore, no need to fear a sudden death when a cell reaches the end of its specified life [55]

A common criterion to consider the end of life (EOL) of a battery when its capacity drops to less than 20% of the initial nominal capacity [37]. This limit of 20% has been initially set because of the behavior of lead-acid batteries: where the capacity fade was showing quite linear until 20% [37], and then there was a sudden drop of capacity. Of course, all the batteries do not exhibit this significant decrease of capacity; this is why some projects such as the second life of batteries have been created (old batteries that do not fulfill the automotive requirements are reused in stationary projects)

End-of-life (EOL) is defined when the battery degrades to a point where only 70-80% of the beginning-of-life (BOL) [54], capacity is remaining under nameplate conditions. Usually, the aging of batteries is monitored by measuring the nominal capacity and comparing it to the initial nominal capacity $C_n(t_0)$. In this case, and replacement cell purchase should be considered when the battery reaches 70-80% of its useful life (in cycles) to avoid degradation of performance.

By considering all the above, the battery reaches its EOL when the state of health (SoH) goes below 70-80%:

$$SoH(t) = \frac{C_n(t)}{C_n(t_0)} \tag{1.16}$$

1.2.4 From Electrochemical to Physical components

In a more physical description, a BESS contains several primary components grouped according to function required for reliable system operation, and includes:

- the battery pack,
- a power conversion system (PCS)
- monitoring, control systems, and auxiliary systems.

Cell-based batteries consist of multiple individual cells connected into modules and then into packs. Monitoring and control systems, referred to as the battery management system, ensure safety and maximize performance. The battery management system (BMS) prevents individual cells from overcharging and controls the charge and discharge of the battery, which is important for safety and performance. There is a component that controls the temperature of the cells according to their specifications. Auxiliary systems include all the systems for guaranteeing the correct operation of the BESS (e.g., fire safety, HVAC system, mechanical ventilation).

Battery cells and component monitoring may vary to some degree, in that different types require an emphasis on issues. For instance, lithium-ion battery packs must emphasize thermal monitoring and controls, given a tendency to overheat [56].

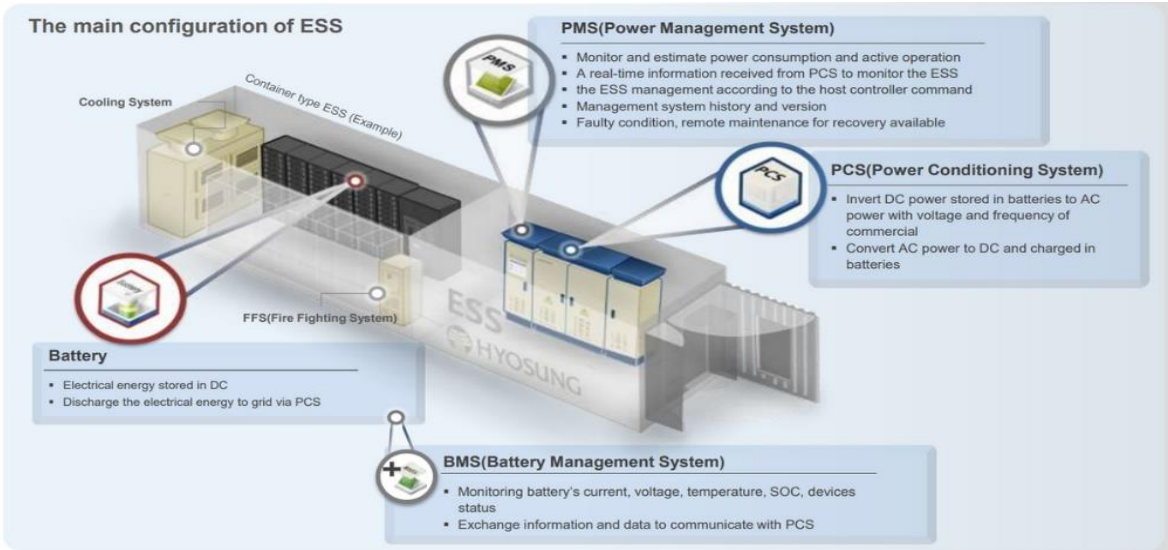

Figure 1.16. Components of BESS [57]

The battery is the basic building block of an electrical energy storage system. The composition of the battery can be broken into different units (Figure 1.17)

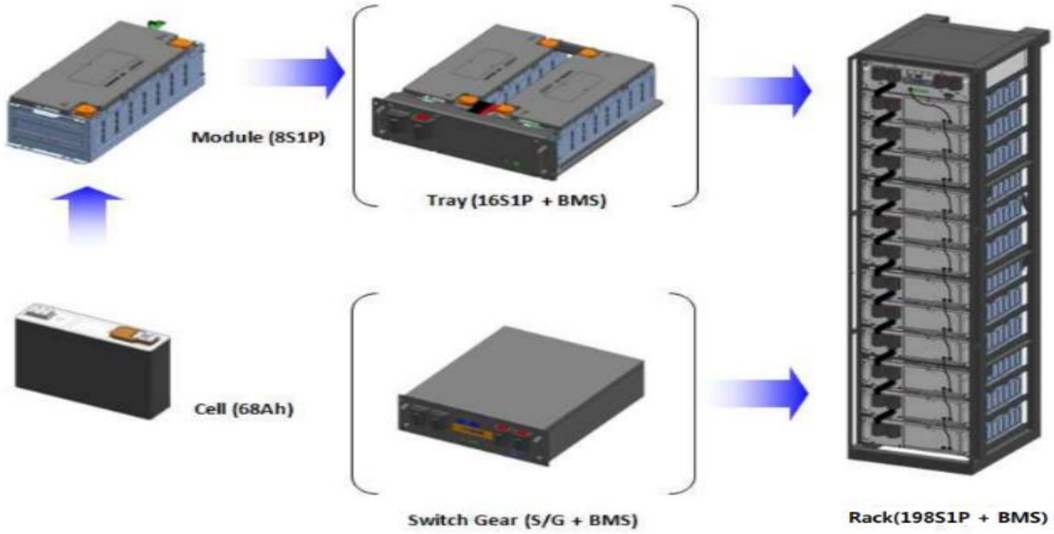

Figure 1.17. The composition of the battery [57]

At the most basic level, an individual battery cell is an electrochemical device that converts stored chemical energy into electrical energy. Each cell contains a cathode, or positive terminal, and an anode, or negative terminal [57]. An electrolyte promotes ions to move between the electrodes and terminals, which allows current to flow out of the battery to perform work. A cell is effectively the smallest, packaged form a battery can take. These battery cells are combined in a frame to form a module.

Energy Storage Systems are structured in two main parts. The power conversion system (PCS) handles AC/DC and DC/AC conversion, with energy flowing into the batteries to charge them or being converted from the battery storage into AC power and fed into the grid. It also includes required control and monitoring components, voltage sensing units, and thermal management of power electronics components such as fan cooling.

BESS also requires a battery management system (BMS), as stated before, to monitor and maintain safe, optimal operation of each battery pack. BMS is a core component of any Li-ion based ESS and performs several critical functions. The primary job of the BMS is to protect the battery from damage in a wide range of operating conditions to reduce the causes of degradation. It does so by ensuring that the battery cells work within their prescribed running windows for the state of charge, voltage, current, and temperature.

1.2.5 BESS Modelling

For the study of the battery, the behavior is it necessary to study several conditions (meaning every value of c-rate, SOC, DOD, and current profile of each possible cycle) [46] Since it is impossible to experiment all the possible operating conditions, a cell could undergo while working, a model is necessary to simulate battery operation.
Battery modeling plays an important role in the approximation of battery performance and design. For most applications using battery models, it is generally important to accurately predict the characteristics of the battery, but it could be complex.

One of the first approaches in modeling is the different types of models given the level of the system, i.e., the number of the components are taken into account [58] such as:

- Material-level, in which materials of the cell (electrodes, electrolytes, separators, current collectors) are investigated [59] .Usually, this level does not include the whole cell, but just the part involved in the phenomenon studied [46].
- Cell-level, this type of level is modeled one by one or as a whole but outputs of the model show the overall effects at terminals [46].
- Module-level, in which a stack of cells together with the BMS is considered. This system allows us to study the whole operation of the cells during cycling since the BMS can treat saturation cases in SoC, voltages, or power that usually occur in battery cycles [46].
- System-level: present an integration of stack of cells, BMS, and inverter. All the systems and their interface with the external environment are modeled, which allows a complete study of performance in common operation for BESS.

The second type of categorization, which deals with the level of simplification of the working principle, is the following (from the most accurate to the least) [60]:

1. Electrochemical models
2. Electric models
3. Analytical models

When a battery is modeled, two aspects should be considered:

- State of Charge (SoC): correct estimation of battery SoC allows us to understand the amount of charge and hence energy that can be stored or provided by the battery.
- State of Health (SoH): An accurate evaluation of batteries' SoH allows us to account for the rate of degradation process inside the cell of the battery.

Some models take into account both SoC and SoH simultaneously, but most of the models have a focus on one of the two quantities, depending on their application [46].

1. Electrochemical: electrochemical modeling is usually based on equations for mass, energy, and momentum transport of each species for each phase and component of the cell. It typically involves a system of coupled partial differential equations that must be solved in time and spatial dimensions.

Electrochemical models can predict the local distribution of concentration, electrical potential, current, and temperature inside the cell, besides current and voltage at the external terminals. Therefore, they tend to be relatively complex and time-consuming. They typically have various parameters to determine through several experiments [61]. To make the system numerically solvable, the structure of the cell needs to be simplified. The most common approaches utilized to model lithium-ion cells are the following:

- Pseudo two-dimensional model (P2D): It is called pseudo-two-dimensional since it has a real dimension on the x-axis, in the normal direction concerning layers, and a pseudo-dimension of the spherical particle representing its radius. Electrodes are assumed to be composed of a lattice of identical spherical particles. Li-ions can move through two spatial coordinates: a radial coordinate r, across the spherical particles of active materials in the electrodes, and a linear coordinate x, going across the cell from the negative to the positive electrode.

  Doyle, Fuller, and Newman where among the first authors to have been developed a model based on these assumptions [62] They developed Dualfoil [63], which is a Fortran program based on their electrochemical model. This model is by far the most widespread among battery researchers [64], when the aim is a theoretical study and deep design of cells.

- Single-particle model (SP): cell is composed of electrodes and electrolyte which have no spatial extension and no potential difference at interfaces. [65] Electrodes are assumed to be composed of one single spherical particle whose area is equivalent to the surface area of solid active material in a porous electrode. Porosity is neglected, and lithium ions surface concentration is assumed constant along the x-axis of the electrode. The solid-phase potential is hence only a function of time t. The solving process is much faster than the P2D model, but the model is less accurate.

2. Electrical: batteries can be represented by equivalent electric circuits that aim to model as accurately as possible battery operation, especially the terminal voltage and current characteristics at the external terminals. These models could be very simple, comprising few circuital elements (e.g., voltage source to represent energy stored and a resistance in series to take into account losses), or more complex, depending on the number of circuital elements related to a precise physical phenomenon occurring in the cell. Due to the wide spectra of possible equivalent circuits, these models and applications in a broad range of sectors, comprising battery monitoring and design [60].

Depending on the working principle of each model, electric models can be divided into [66]:

- Thévenin-based models (time-domain models).
- Impedance-based models (frequency-domain models).
- Runtime models.
- Combined models.

3. Analytical: The battery is described by analytical equations that do not consider electrochemical processes, but that is empirical. Few simple equations are used to describe battery behavior. The values of parameters can be empirically found by experimental data or by manufacturers' datasheets. In most cases, there is no direct reference to the voltage variation of the battery, and the SoC is computed through charge or energy balances. These models usually focus on the evaluation of the SoC of the battery based on energy or current balances. The voltage characteristic of the battery is normally neglected.

Analytical models' complexity can vary, but they are, in general, simpler than other model categories: for this reason, they are often used in dimensioning tools [60]. Their simplicity comes; however, at the expense of accuracy, and errors in predicting battery performance could be relatively high. In the following paragraphs, four different approaches to growing complexity are presented.

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) [58]:

$$SoC = SoE(t) = SoE(t-1) + \frac{\Delta E}{E_n} \tag{1.17}$$

Where t and t-1 are two subsequent time-steps in discrete-time simulation, and ΔE is the variation of energy as a function of power requested to the cell, time-step, and efficiency of the cell.

Another empirical model is based on round trip efficiency defined as the ratio of energy provided by the battery during discharge over energy absorbed during charge, at a given c-rate and SoC variation.

Knowing the total power required or provided by users to the battery, energy entering or exiting the batteries depends on the efficiency. Energy entering or exiting the batteries is the integral of power over time, and it must be multiplied by the efficiency when power is provided to the battery and divided by the efficiency when released.

Efficiency can be considered constant or function of c-rate as following:

$$\eta_{RT}(c - rate) = 1 - \sum_{i}^{n} k_i * (c - rate)^i \tag{1.18}$$

Where *ki* is an experimental coefficient and n is the degree chosen for approximating polynomial.

1.3 Exploring PV and Energy Storage Synergy

As a highly versatile and low-cost power generation source, solar is expanding rapidly across the world and has already reached notable penetration shares in the most advanced energy markets. But for solar to become the backbone of the future energy system, it is necessary to move one step forward and exploit its great synergy with energy storage. Energy storage can enable higher penetration of VRE by improving system flexibility, reducing curtailment, and minimizing costs.

Batteries allow consumers and prosumers to take control of their energy ecosystem increasingly. Battery energy storage solutions may be the accelerator that facilitates variable renewables cost-effectively and flexibly. Plus, solar and storage make the perfect match, as storage allows to bring in the benefits of solar fully and has a wide range of applications and technologies to meet different needs and functions.

1.3.1 Services provided by PV+BESS

The integration of BESS has brought many benefits not only for the consumers but also for the grid. The following paragraphs explain some of them.

Energy Arbitrage

Generating energy is quite expensive; storing it can both increase the efficiency of a system and optimize it economically. The main goal of energy arbitrage (or energy shifting) is to store energy during lower-priced hours and to sell it during higher-priced hours.

Peak Shaving

Peak shaving is installed to cover the peak load, and so reducing peak demand, and does not have an economic target, as energy arbitrage does. In a grid where the amount of RES is solid, the energy is stored when the generation exceeds demand (off-peak period), and it is injected during periods of shortages.

Cost reduction by matching supply and demand perfectly. Since peak occurs occasionally, it is economically not feasible to design a generation system much bigger than the capacity needed. With peak shaving, the efficiency of the system is increased, as it allows plants to save in fuel and maintenance costs, as well as the use of the transmission and distribution (T&D) system [67].

Peak shaving(Figure 1.18) is also important for end-users as residential and industrial customers can save their electricity bills by shifting peak load from peak periods (when the energy price is high) to the off-peak period (when the energy price is low). They may also save in connection charges and capital costs for the distribution system.

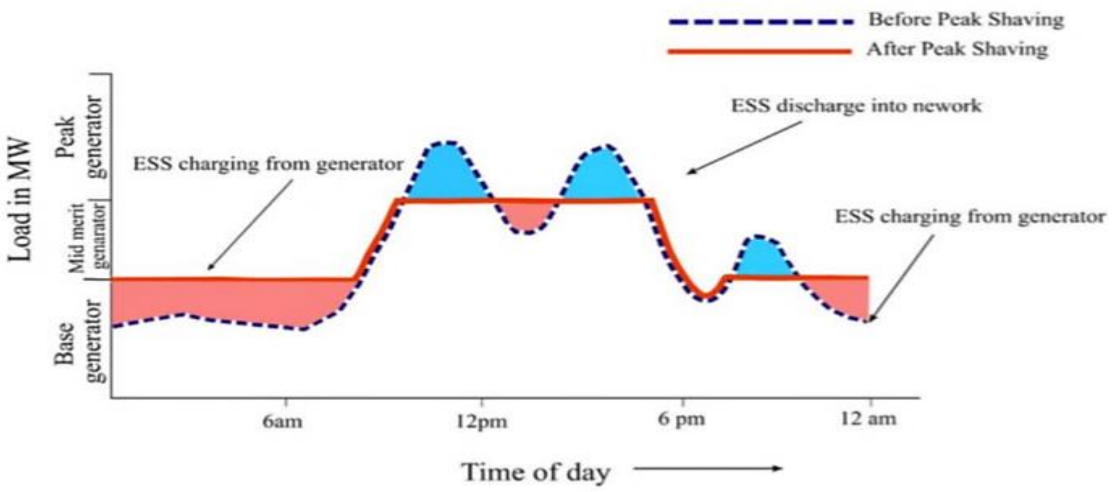

Figure 1.18 Peak load shaving strategies [68]

Behind the Meter

BESS is an excellent solution to increase the self-consumption of the PV solar plants and could be of a benefit to industries, commerce, and residences that are not directly connected to the grid.

Behind the Meter (BTM), energy storage can also allow for much higher levels of renewable energy penetration due to the decrease of RES unpredictability. These two factors help reduce costs and improve resiliency for commercial and industrial, or residential customers.

Participation in electricity markets

With the addition of storage, the potential of solar is fully tapped: solar energy can be dispatched at any time of the day and can provide the same or better services and reliability than conventional power plants. These systems can also automatically respond to grid signals to correct frequency, voltage, and reactive power, thereby significantly improving grid stability and reducing barriers and objections to increasing deployments of distributed renewables.

They can enable higher penetration of VRE in some power systems by improving system flexibility, reducing curtailment of VRE, and, in some cases, driving down overall system costs supplying during periods of high net demand, and avoiding curtailment during periods of negative net demand. Policymakers are promoting the ancillary grid services offered by enabling technologies and, to a lesser extent, by renewable energy. Now prosumers can also offer ancillary services to grid operators: these services can also be aggregated and managed by third parties [22] trough aggregation that will be explained later on in Chapters 2 and 3.

1.3.2 Business Models

Some business models could exist between a prosumer and the Energy storage provider that also could affect the benefit that customers could have.

These options are explained below:

Direct Purchase

In the Spot Sale or direct-purchase business model, the client buys the system outright with upfront, on-hand cash, and can choose to pay to the provider for ongoing Operation and Maintenance(O&M). The battery storage providers give the storage solution to the ones who already have the PV system, but some batteries providers could also give the whole system(PV+storage), and this is coming together with a control system that guarantees optimal management. Clients cover all costs as already said, and the ownership is kept for them who benefit from 100% of savings in the utility bill and revenue generated by the battery. This business model could assure the highest returns for clients, but at a higher risk associated with the initial capital investment.

Benefit Share

In this business model, the provider invests its capital by installing a storage system and operation of the battery system by featuring control management at the client's site. Savings on the utility bills and revenues generated by the battery are to be shared between the battery storage provider and the client, based on a predetermined split and this allows the provider to recoup its initial investment. This model contributes clients with the advantage of benefiting from savings and revenues with no capital investment and no tariffs for O&M services.

Since there is no initial investment on the client-side, the risk profile is considerably lower than the direct purchase model, but with returns that are consequently lower. This model brings about another advantage since the provider guarantees the system behaves at its best to secure the maximum return on its investment.

Lease

As the benefit share, the provider invests its capital by installing a storage system and operation of the battery system by featuring control management at the client's site. The client agrees to pay a fixed annual/monthly leasing fee to use the system, as well as O&M services, benefiting from 100% of the savings and revenues generated by the battery.

Site Lease

On the other side, the site lease business model is similar in the fixed fee, but in this case, the provider is the one to pay the client a monthly/annual fee to use the system, thus benefiting from 100% of the savings and revenues generated by the battery.

Chapter 2 Electricity Markets in Italy

For Italy, the electricity supply is a strategic service. It was historically provided by a public company acting as a monopolist. In 1999, the path towards the creation of a liberalized market started [68]. At this moment, electricity markets guarantee the competition [69] in production, import, export, purchasing, and selling of electricity.

The electricity market is the place where transactions involving electricity are conducted, and this was set up in Italy as a result of Legislative Decree no. 79 dated March 16, 1999 ("Bersani Decree") as part of the implementation of the EU directive on the creation of an internal energy market (Directive 96/92/EC repealed by Directive 2003/54/EC) [70].

The electricity market is divided into:

- Day-Ahead Market (DAM)
- Intra-Day Market (MI)
- Ancillary Services Market (ASM)

Gestore dei Mercati Energetici (GME) administers the Italian Power Exchange (IPEX), a platform dedicated to the wholesale trading of gas, electricity, and energy efficiency certificates. The IPEX is not mandatory, so that eligible purchasers and wholesalers may also sign bilateral contracts for the exchange of electricity with producers.

Precisely, GME organizes and manages:

The Forward Electricity Market, where forward electricity contracts with delivery and withdrawal obligations, are traded.

The Spot Electricity Market that is subdivided in:

- DAM, an auction market where hourly energy blocks are traded for the next day, and participants submit bids by specifying the Quantity and the minimum/maximum price at which they are willing to sell/purchase.

- MI, which allows participants to modify the schedules defined in the DAM by submitting additional supply offers or demand bids.

Moreover, GME manages, on behalf of Transmission System Operator(TSO) in Italy, referred to as Terna S.p.A., both the ASM through which it collects offers and communicates the results, as well as a platform registering the transactions carried out over the counter. On this platform, the parties that have concluded contracts outside the IPEX register their trade obligations and set forth the relevant electricity input and output plans, committing to perform these contracts [71]. Figure 2.1 shows a more definite division of the Italian Market. This provisional program derived from the organized Pool market, and the bilateral transactions are then presented to TERNA [72].

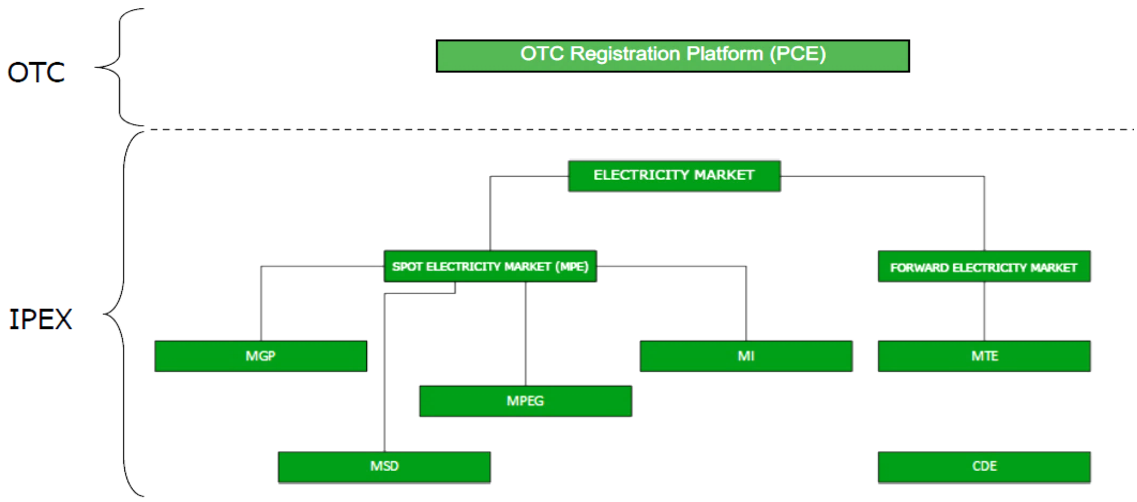

Figure 2.1 Electricity Market in Italy [117]

Since the scope of the study focus on optimizing the domestic level, and two different services will be provided which belong to different markets, it is presented a brief description of these markets to give a clear view of what happens in each one. Section 2.1 explains the wholesale markets in Italy, whereas Section 2.2 focuses on the ancillary services market that is needed to balance the system and will explain how these services are a trade-off.

Section 2.3 then describes the evolution that has been taken place in the Italian market, with all the new decrees or expected projects that will guarantee to have a better system, mainly the opening to DERs and the barriers that BESS could have as it is introduced this to DERs.

2.1 Wholesale Market

Day-Ahead Market

DAM is an auction market with an ex-ante time frame for scheduling bids and offers where most of the electricity sale and purchase transactions referred to hourly energy blocks take place. Here market participants start to submit their offers (bids) with quantity and minimum price at which they are willing to sell for generators and the maximum price they are willing to purchase on the side of consumers (Figure 2.2)

It opens nine days before the delivery day, and it closes every day at 12.00 [73] . After that, the economic merit order criterion and the transmission capacity limits between zones are considered to accept both offers and bids.

In the daily market, the trading of purchase and sale offers for each hour of the following day is carried out.

- Bids/Offers for each of the 24 hours of the next day.
- Bids/offers consisting of one or more "quantity/price pairs" for each hour (simple or multiple bids/offers)

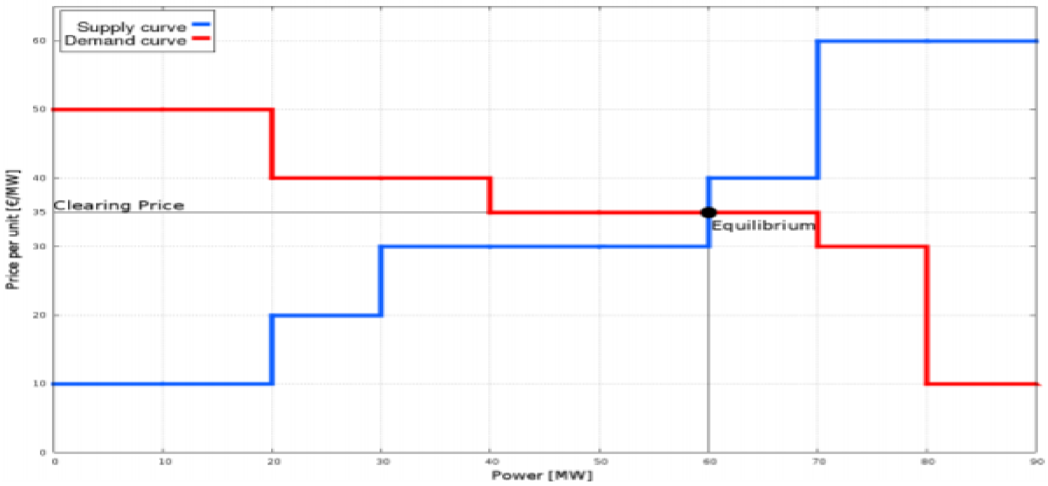

Figure 2.2 Day-ahead market clearing price [129]

In the DAM, the price and volume of each hour are established from the point of equilibrium between supply and demand, as Figure 2.2. In Italy, there are six geographical zones as a part of the national network; there are currently six active zones [74], and it must be highlighted that all the accepted supply offers are evaluated at the clearing price of the zone to which they belong. whereas the accepted demand bids referring to units of consumption belonging to Italian geographical areas are evaluated at the single national price (PUN), which is the average of the zonal prices weighted by zonal consumption and represents the purchase price for end customers in these zones(Eq. 2.1)

$$PUN = \frac{\sum(P_i \times Q_i)}{\sum Q_i} \tag{2.1}$$

Where:
i = zone
$Q =$ Bought Quantity
$P =$ Zonal Price

If there is no zonal congestion, there is only one zonal price, which coincides with PUN.

Intra-Day market

Intraday markets are an essential tool for market parties to keep positions balanced as injections and/or off-take may change between the day-ahead stage and real-time. They are managed with the same rules applied for the DAM. In the same way as DAM, the intraday market is organized in the form of implicit auctions and accounts for the same zonal representation. Participation in MI is voluntary and open to all agents pre-qualified to operate on the GME platform.

In the intra-day market, electricity purchase and sale offers are traded for each hour of the next day, which modifies the program resulting from the daily DAM market (Figure 2.3). The intra-day Market is also marginal. Unlike the daily market, all matched offers, both purchase and sale, are valued at the settlement price of the area. The intra-day market takes place in seven sessions: MI1, MI2, MI3, MI4, MI5, MI6, and MI7 [75].

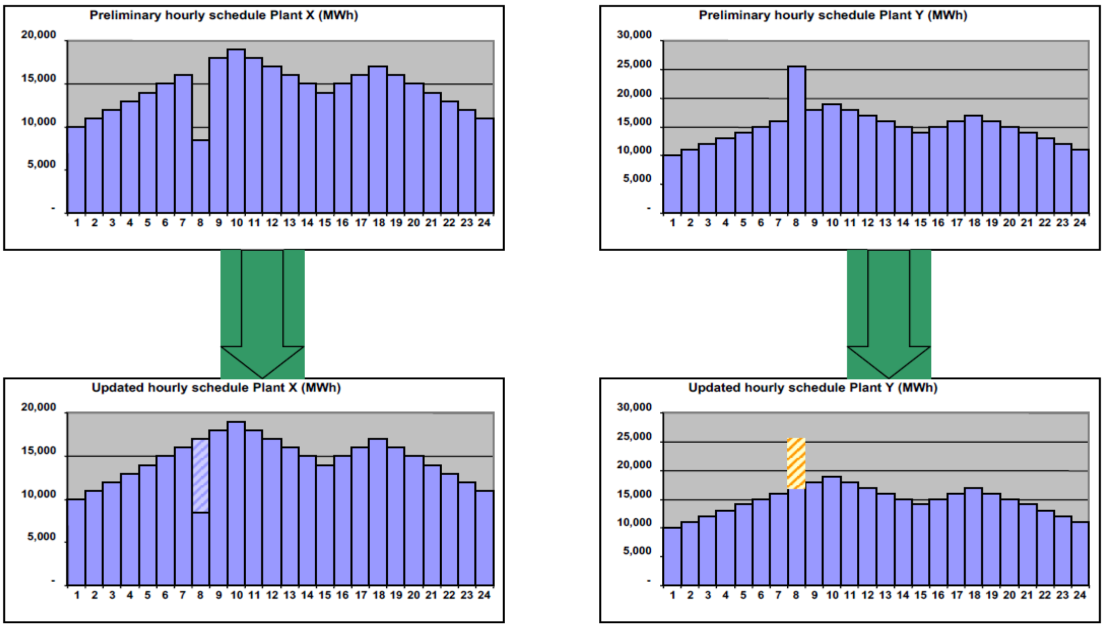

Figure 2.3 Intraday Market [75]

2.2 Ancillary Services Market

Only after the clearing of the day-ahead and intraday markets, the TSO runs the ancillary service market to ensure system reliability on a nodal basis, especially the procurement of reserve margins and re-dispatch actions [76].

The ancillary service market (ASM), in Italian Mercato del Servizio di Dispacciamento, is subdivided into ASM ex-ante and balancing market (MB). Through ASM, the Italian TSO, Terna S.p.A procures the ancillary services needed to manage, operate, monitor, and control the power system and to solve the inter-zonal congestions by creating reserve margin and balance injections and withdrawals in real-time.

Separately in ASM ex-ante, Terna mostly reliefs congestions and procures reserve margins, while in MB, Terna selects the bids/offers mainly for balancing purposes.

In doing this, Terna accounts for a more realistic nodal representation of the network and considers all the security constraints of the system and, to some extent, technical constraints of generation units. ASM ex-ante functions in a corrective logic from the day-ahead and intraday market schedules (up and downward offers).

In this market, bids/offers must refer to offer points authorized to provide ancillary services in the ASM, and these have to be submitted by the respective service providers. Directly bids are selected as the output of an optimization algorithm on a nodal basis is run by the

TSO, considering complex bids, and taking into consideration the results from the day-ahead market. This algorithm deals with re-dispatching, reserve procurement, balancing energy, and consider system constraints as boundary conditions. Note that, for each demand bid accepted in the ASM and on withdrawal points, GME manages the ASM market on behalf of TERNA and determines the non-arbitrage fee that the participant has to pay, if negative, or receives, if positive.

The ASM is cleared through a pay-as-bid algorithm that means that the energy is paid at the offered price. Terna is the central counterparty which accepts bids/offers from market participants related to different reserve and balancing services [77].

The market is divided as stated before into:

• ASM ex-ante: 4 sub-sessions, where Terna trades energy and balancing services to release congestions and to create reserve margins (secondary and tertiary reserve).
• Balancing Market, MB: 5 sub-sessions, where Terna trades real-time balancing services to restore secondary/tertiary reserve and to maintain the balance of the grid.

Since February 11, 2015, ASM ex-ante consists of four scheduling sessions: MSD1, MSD2, MSD3, and MSD4 [76] that are organized as the indicated table below.

	MSD1 (D-1)	MSD2 (D)	MSD3 (D)	MSD4 (D)
Gate opening time	12:55 (D-1)	Bids/offers MSD1	Bids/offers MSD1	Bids/offers MSD1
Gate closure time	17:30 (D-1)			
Trading hours	1-24 (D)	8-24 (D)	12-24 (D)	16-24 (D)
Definitive results	21:10 (D-1)	6:15 (D)	10:15 (D)	14:15 (D)

Table 2.1. ASM ex-ante sessions

As shown in Table 2.1, bids/offers can be submitted and selected in the MSD1 only. This session opens at 12:55 of the day before (D-1) the delivery day and closes at 17:30 of (D-1). The results of the MSD1 are made known by 21:10 of the day before (D-1) the delivery day (D). Following the national network code, GME provides participants with the individual results (bids/offers accepted by Terna) of the session of the MSD2 within 6:15 of the delivery day. MDS3 and MDS4 are organized similarly. In these markets, individual results were informed by GME, respectively, at 10:15 and 14:15 of the delivery day (D).

Whereas MB takes place in real-time and it is subdivided into five different sessions as indicated in Table 2.2

	MB1 (D)	MB2 (D)	MB3 (D)	MB4 (D)	MB5 (D)
Gate opening time	Bids/offers MSD1	22:30 (D-1)	22:30 (D-1)	22:30 (D-1)	22:30 (D-1)
Gate closure time		7:00 (D)	11:00 (D)	15:00 (D)	21:00 (D)
Trading hours	0-8 (D)	8-12 (D)	12-16 (D)	16-22 (D)	22-24 (D)

Table 2.2. MB sessions

The MB1 takes into consideration the valid bid/offers that participants have submitted in MSD1. The other MB sessions open at 22:30 of the day before delivery (D-1) and all close in real-time (D) one hour before the first hour that may be negotiated in each session. In the MB, Terna accepts energy offers to activate secondary control and to balance energy injections and withdrawals into/from the grid in real-time. Moreover, for each of the five MB sessions, GME publishes market results of each accepted bid/offer and notifies participants within the fifteenth day of the month M+2. This lag takes into account the time needed for the distribution system operator (DSO) and the TSO to access to metering data and perform all the procedures according to the settlement rules as defined by energy authority(ARERA), and specified into the national network code.

Each plant admitted to the market must provide bids and offers for each of the following services:

- Secondary Reserve.
- Tertiary Reserve.
- Start-up.
- Shut down.
- Change of plant configuration.

Other ancillary services not traded in ASM are:

- Primary Reserve
- Primary and Secondary Voltage regulation
- Black-start capability
- Load rejection
- Remote disconnection

- Load Interruptibility Service

This work deals with an aggregate that provides only Tertiary Reserve services, but still, it is provided a brief description of the primary and secondary reserve.

Primary Reserve

The primary frequency control is automatic and based on the primary reserve, guaranteed by the synchronous generators connected to the electric grid and running that have to vary the power supplied to restore the energy balance and to bring the frequency to a value closer to the nominal one (50Hz) whenever an impair on the equilibrium of generation and demand cause a frequency deviation. Primary reserve and regulation are currently not traded in ASM, but it is a mandatory requirement for all relevant units [78].

Secondary Reserve

The secondary control is automatic and based on the secondary reserve provided by generators connected to the grid. They must vary their power supply to restore the nominal value of the frequency. The function of the secondary reserve is to restore cross-border power exchanges to their set-point values and to restore the system frequency to its set-point value at the same time [79].

Tertiary Reserve

Unlike the Secondary Reserve, Tertiary Reserve margins are activated by sending dispatching orders and not using an automatic control mechanism.

On ASM ex-ante, the requested resources are divided into:

- tertiary reserve to rise: margin to increase the injected energy;
- tertiary reserve to decrease: margin to decrease the injected energy.

The tertiary frequency control is based on a set of different tertiary reserves, which are active power reserves used for restoring the necessary Frequency Restoration Reserve (FRR) as well as to cope with forecast uncertainties and/or unexpected events.

There are two types of tertiary control reserve:

- Spinning tertiary control reserve, fully delivered within 15 min, to restore the secondary reserve. It can be activated manually, and it corresponds to the European manual Frequency Restoration Reserve (mFRR).
- Replacement tertiary control reserve fully delivered within 120 min and necessary to restore the tertiary reserve against shifts in demand. It corresponds to the European Replacement Reserve (RR).

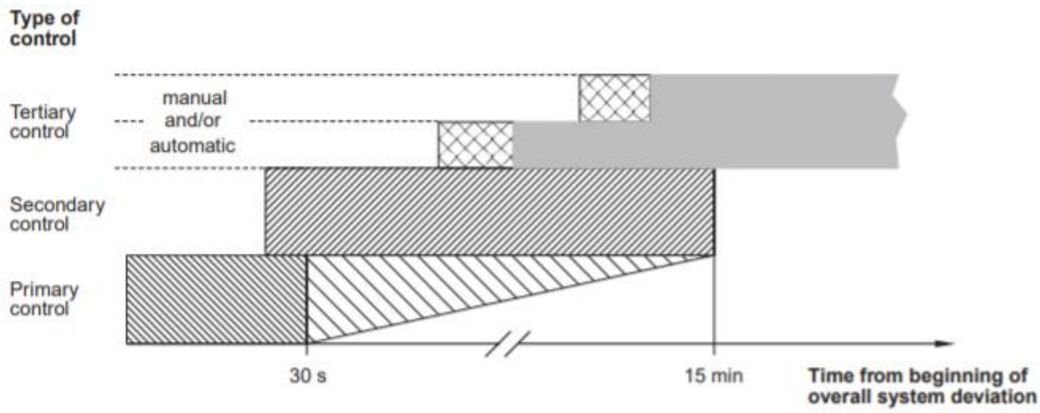

Figure 2.4 Timeframe of the Reserves [79]

2.3 Market Evolution

At the retail level, since 2003 (gas) and 2007 (electricity), consumers are free to choose the gas or electricity provider that applies the best economic and technical conditions, under the regulatory supervision of ARERA.

However, until July 1, 2020, consumers can choose to purchase electricity and gas under the tariffs laid down by ARERA.[6] Starting from July 1, 2020, the free market will be the only option available for energy consumers, meaning that ARERA will no longer regulate prices. The reform assumes that free competition between energy suppliers will result in lower prices for consumers [71].

In another view, the impact of increasing DER deployments will vary in different countries and regions around the world, and this will affect the market. However, it also has been seen that Distributed Energy Resources encompass a broad set of solutions that include systems and technologies designed to operate closer to customers on the electricity grid.

In this context, Terna is adding new ancillary services (Figure 2.5), and, in agreement with ARERA, it has launched a process for progressive opening of the ancillary services market [80] that is explained in the next section.

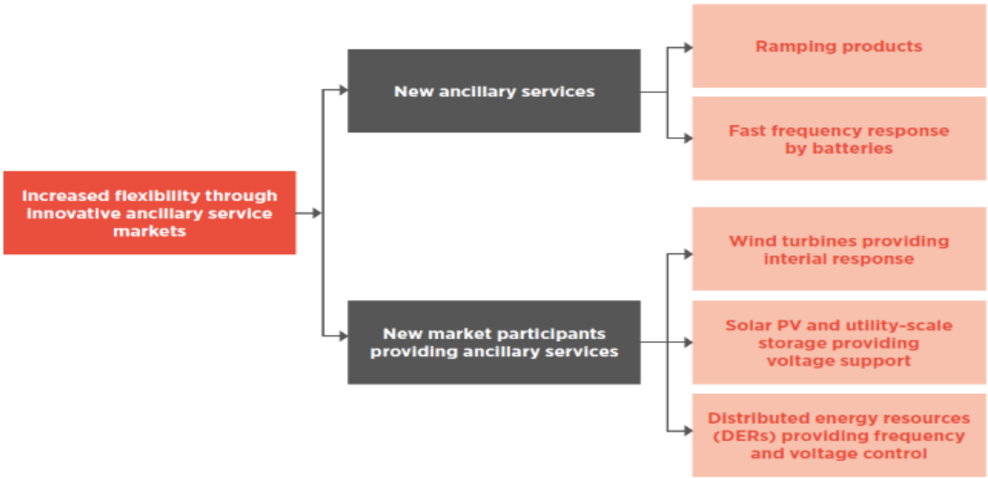

Figure 2.5 Innovation in Ancillary Services [95]

2.3.1 Opening to DERs

As explained in the previous section, TERNA and ARERA have launched a gradual process for opening the ASM to distributed resources, through the definition of pilot projects in which DERs and storage units can participate to a certain extent to the ASM. This principle is issued in the deliberation 300/2017/R/EEL [81], to measure the performance of these resources to launch an organic reform of this market ultimately. The term "pilot project" derives from the goal to test the function of the new resources and subsequently proceed, together with ARERA, with a complete review of the ancillary services market and Grid Code, under which such resources would be fully integrated into the ancillary services market [80]. This complete review of the electricity balancing to steadily integrate new units and provide innovative services to face the need for a distributed power system has begun with the publication of the general principle behind the Testo Integrato del Dispacciamento Elettrico (TIDE) [82].

The primary aim of pilot projects is, therefore, to immediately increase the number of resources available to guarantee the adequacy and security of the electricity system at a lower cost for the end-user, through procurement of reserve services and balancing and therefore moving from a traditional to a complex market as shown in Figure 2.6.

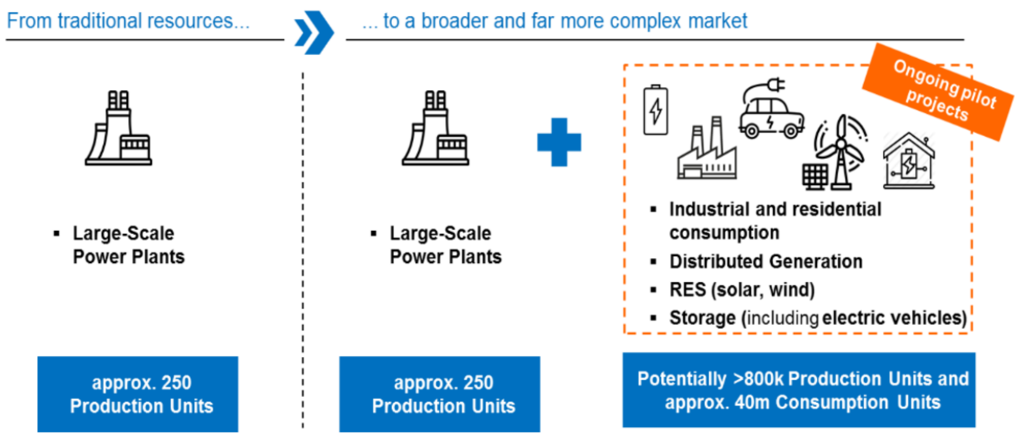

Figure 2.6 Evolution of the electricity markets in Italy [95]

It is substantial to clarify that Terna currently procures services from traditional thermal sources and that diversification of resources, launched through the pilot projects, can contribute to minimizing overall costs for the electricity system.

The authority said that pilot projects for storage and renewables would be selected following “harmonized procedural criteria” by Terna and operators from the energy sector [83].

Via these pilot projects, also distributed resources that do not meet the minimum requirements defined by the Grid Code may be enabled to provide certain ancillary services, such as congestion management, balancing, and tertiary reserve services. These resources cannot, however, at least in the initial phase, provide other services such as secondary reserve [80].

Terna was proposed to proceed to update its own Network Code, to introduce enabled virtual, mixed production/consumption units (UVA). The UVA is composed of aggregations of consumption and/or generation points and storage systems (including e-mobility charging stations) that are connected to the grid at any voltage level and fall within the scope of aggregation defined by Terna. For the first time in Italy, the figure of the aggregator had been introduced [80].

In June 2016, the authority set out the guidelines concerning the first phase of the comprehensive reform of the rules governing electricity dispatching services. The authority had proposed to maintain separate aggregates for input and withdrawal. The first phase of the reform excludes all consumption and production not handled on an hourly basis since the participation of profiled users would be hazardous for dispatching users.

The primary aim was to open the ASM to participation on the demand side and production units powered by non-programmable renewable resources.

Terna also identified the following pilot projects as being particularly innovative [80]:

- Virtually Aggregated Consumption Units (UVAC)
- Virtually Aggregated Production Units (UVAP)
- Virtually Aggregated Mixed Units (UVAM)
- Relevant Production Units (UPR) not subject to mandatory participation

Starting from aggregating only consumption points (UVAC) and only production points (UVAP), the projects identified by Terna evolved towards mixed aggregations (UVAM).

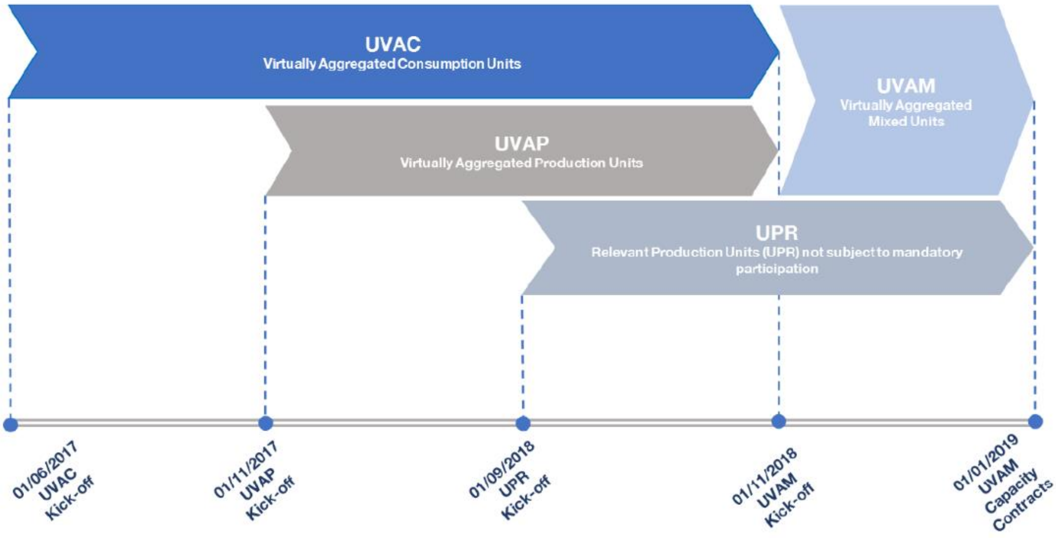

Figure 2.7 Timeline of the Pilot Projects

In November 2018 was launched the UVAM pilot project, enabling consumption and production units as well as storage systems in these aggregations. They are connected in MV and even aggregated up to the same market zone could start providing tertiary reserve by putting their offer directly on the ASM for both upward and downward tertiary reserve. They are paid pay-as-bid, as the relevant units, and also could get a fixed yearly remuneration 30 000 €/MW/year if they respect some requirements: they have to offer upward reserve for at least two consecutive hours in peak hours (working days from 2 to 8 PM) always throughout the year; they must offer the upward reserve below a strike price of 400 €/MWh [84].

2.3.2 Acknowledgment of peculiarities and limits of BESS

Technical Barriers

One of the most significant barriers is related to the current coordination level between the TSOs and the DSOs, which is regarded as quite weak and cannot serve for the efficient provision of ancillary services. This bad coordination is because the numerous DERs within the distribution systems are not visible and controllable by the TSOs.

In this context, not even the DSOs know the dynamic capabilities of the DERs within their distribution grids, simply because this is not part of their business, at least, not until now [85].

The TSOs and DSOs should clearly define the data they need from each other, schedule the system planning, define the connection requirements for DERs and end-users, and develop coordinated network codes.

A significant challenge is also the installation of a proper Information and Communications Technology (ICT) infrastructure to exchange the necessary data for monitoring, accounting, and control of the ancillary services provided by distribution entities (i.e., DERs, flexible loads) to the transmission system [86]. Some barriers in this regard include the not-so-clear specifications for enabling security while transmitting data through existing communication standards.

Regulatory Barriers

Policymakers and regulatory authorities can have a significant effect on the way ancillary services will be provided to the power system in case of increased DERs penetration. At the same time, they can undoubtedly facilitate the establishment of an ancillary services market at the distribution system level. However, until now, obstacles appear at the regulatory framework of most countries that discourage the establishment of new ancillary services and prevent DERs operators from offering their services.

More specifically, technology and size limitations imposed by the present regulations are referred to as one of the main reasons why DERs units and loads are excluded from the ancillary services markets, even though they could potentially provide the requested services [85]. Another possible barrier is the lack of separation between BRP, the entity responsible for the RES management on DAM (i.e., the imbalances), and the ones responsible for the provision of the services, BSP. This regulatory barrier could also lead to a techno-economical barrier.

Financial Barriers

As more and more DERs are going to provide ancillary services to both the distribution and the transmission system level, a proper remuneration scheme must be introduced, based on the value estimation of each service. According to reference [87], the electricity markets should be developed accordingly, so that the value of the flexible resources is more visible in market prices and proper investment signals are sent.

Finally, following the aforementioned necessary investments regarding the ICT infrastructure and the measuring system that need to be installed at the transmission and the distribution level, an appropriate recovery scheme should be introduced so that the corresponding network operators can manage their costs [85].

Another barrier is the absence of incentives to deploy smart grids or smart planning for grid operators.

- Lack of incentives to develop smart and flexible solar installations in public tenders.
- Missing price signals in grid tariffs to incentivize flexibility and load shifting.
- Inadequacy of current grid tariff structures for self-consumption (i.e., increasing capacity-based elements, lack of grid tariff for collective self-consumption).

These barriers have implications in terms of which electricity storage technologies are most economically suited to provide this array of services. For instance, the contrast between (i) pumped hydro storage with very low "self-discharge" rates at idle that are well suited to longer storage durations and (ii) flywheels that have very high discharge rates at idle, but have high power ratings and can be distributed within the electricity system to provide high power/rapid discharge services, such as frequency or voltage regulation [18].

Ownership Barrier

The most significant overall barrier to energy storage in the current EU legislative landscape is the lack of attention paid to the storage itself. When the Electricity Directive (Directive 2009/72/EC) was approved in 2009, energy storage was not included in the picture, resulting in unintended barriers and bottlenecks in the legislation [88]. Because of this, Europe does not have a common regulatory approach to energy storage, and this creates essential differences between member states.

This lack of a proper definition of energy storage in the current EU legislation leads to a series of barriers, thereby creating an uncertain investment environment. Since energy storage was not included in the Electricity Directive, storage is often considered to be a generation system. It, therefore, falls under an ambiguous situation concerning ownership since, according to the unbundling principle, TSOs and DSOs cannot own or control generation systems.

In the EU landscape, a partial exception to the unclear ownership rights of energy storage systems is Italy [88] . Italy is working on solving this kind of limitation by launching grid-connected battery energy storage pilot projects. A first project was launched in 2011 and envisaged the construction of three storage systems in southern Italy (34.8 MW capacity) to ensure flexibility in the management of renewable power plants and to boost the transmission grid's capacity. A second 40MW project was launched in 2012 to increase the security of electricity systems in Sicily and Sardinia [88]

The Italian government supported Terna's projects and allowed TSOs and DSOs to build and operate batteries and storage systems under certain conditions (Italian decree Law 93/11, Art. 36, paragraph 4). After this overall decision, in the Italian network regulator, ARERA, approved a decision (574/2014/eel) to define network access rules for energy storage. Terna also foresees the introduction of annual auctions for reserve capacity [88].

Chapter 3 Aggregation

DERs, such as rooftop solar systems, behind-the-meter BESS, plug-in electric vehicles, and commercial and industrial loads, can provide ancillary services. Usually, to do this, they must be aggregated as Virtual Power Plants (VPP). This aggregation is aimed to reach the minimum bid size (in MW) that is requested in most of the electricity markets. However, aggregated DERs still face barriers in entering the electricity markets, and complete integration is still ongoing. Aggregators are entities of the market that enable DERs to the market. Further, the aggregator plays an essential role as the intermediary between decentralized actors and the market and can help small actors like renewable self-consumers, active customers, or small businesses to participate in the electricity market (demand response) offered locally or to the grid (wholesale market) and with VPPs it is possible to participate in the energy balancing market by employing the available DER units.

In Section 3.1, it is presented an overview of the concept of aggregation, and it is showed a summary of the countries where the aggregation is a more developed concept. This, to give a comparison of how advanced some countries in the aggregation are, the quantities of power that are aggregated, and mainly how it is their approach in terms of power and services delivered. Furthermore, it is dedicated a special section to study the regulation in terms of aggregation. Since there are different types of aggregators, Section 3.2 describes them. Another important thing that should be considered besides technical barriers that were already explained in Section 2.3.2 is how are the revenue models related to the provision of services on the market via aggregation.

3.1 Overview of Aggregators

The aggregator is a relatively new concept that is used to describe a new actor, a formal role, and an activity. The formal role of an aggregator describes the responsibilities, tasks, and functions of aggregators explicitly in legislation. The activity of aggregation, combining multiple customer loads or generation into a pool, is also used in describing the aggregator concept [89].

With the help of aggregation, it is possible in principle to reduce prices on control reserves and wholesale markets by combining several different units and optimizing their demand and supply behaviors. For consumers and prosumers participating in aggregation services, it will have the potential to lower balancing costs and decrease the energy bill. Aggregation is still state of the art, and the countries working on this are still in a transient regime.

Lastly, the descriptions of aggregators differ in the scope of flexibility. Flexibility is both present at the demand side (e.g., peak shifting) and supply-side (e.g., curtailment) [89]. However, the main descriptions of aggregation focus primarily on the demand response at the consumption side and do not include potential flexibility at the generation side. Several other descriptions have defined the aggregator as being active with RES, including generation flexibility. It is essential to recognize that aggregators can be involved in both demand response and flexibility on the generation side, for instance, by performing curtailment of solar or wind power.

Aggregators bundle DERs to engage as a VPP in power or service markets. They use a centralized IT system to control the DERs and optimize their operation remotely.

They can provide:

- Load shifting
- Balancing services to TSOs
- Local flexibility to DSOs

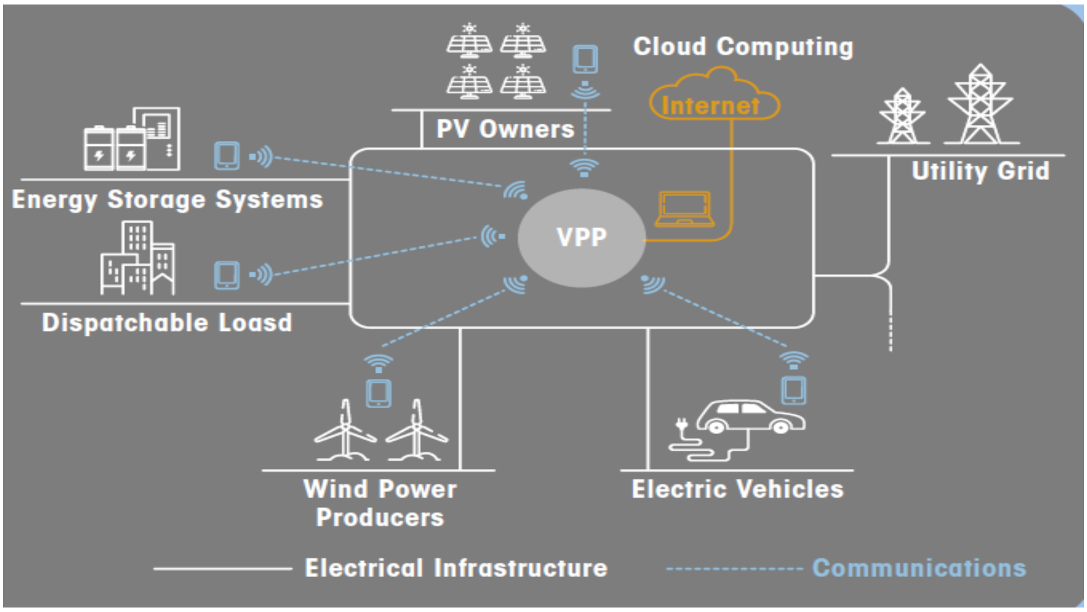

Figure 3.1 Benefits of the use of aggregators [95]

In the year 2014, in the USA, only demand aggregators were found (with some backup generators). The primary motivation to aggregation was the DR programs offered by system operators to decrease the peak loads and to increase the security of the systems. The customers involved vary; most of the aggregators were concentrating on the large customers, but some aggregators were also concentrating on residential customers with direct load control of air conditioning or water heaters. In Australia and New Zealand, one aggregator was found which had a business similar to that in the USA. In 2014, their idea was to include in the future also residential customers after the smart meters were installed. In Europe, the aggregator business is still in its infancy. Two main types of aggregators existed in 2014: generation aggregators (in Germany) and combined load and generation aggregators (in the UK). In some European countries like in France and the Netherlands experimental phase of aggregation had been initiated, but there are not yet real commercial activities [90].

From 2014 to nowadays, the business and the concept of aggregator has evolved in all these markets. The following paragraphs describe their main evolution and their business model.

3.1.1 United States of America (USA)

The first initiatives developed in the USA for aggregation in 2014 were to provide demand responses. Many companies still work on demand response, but there are other projects with other types of services.

As demand response, there are many aggregators that their focus is on providing demand response services to utilities and TSOs. The services offered range from remote measurement of consumer consumption to reducing the amount of consumed energy in a certain point of the network upon request of the utility.

Their portfolio is composed of commercial and institutional electric customers such as shops, schools, offices, hotels, water plants, not homes, and industrial businesses and organizations, utilities and grid operators, and regulators and policymakers to meet energy needs with demand response.

Another of the services provided, especially for residential and institutional, is energy management services, where they gain greater control over both their energy expenditures and assets, which in turn create new sources of revenue. The aggregator does this by helping the clients reduce the demand for electricity during periods of a system-wide peak by utilizing real-time data to optimize and manage energy consumption.

Some other projects deal with aggregation for different purposes from demand response by implementing artificial intelligence technologies that focus on behind-the-meter.

By aggregating energy storage systems in a VPP, and offering the following services:

- reduce the cost of electricity for commercial consumers. The batteries are charged when the cost of electricity is low and discharged when the cost of electricity is high (typically during peak demand period).
- •Use the software to reduce the net demand of its customers, thereby reducing the demand of the whole area when the existing supply system cannot supply in the local area [91].
- Use of energy storage units to help make the grid more reliable [92].

3.1.2 Australia

In Australia, the main reason for aggregation is the fast growth of peak demand compared to peak generation. There are short periods where the existing infrastructure of the electricity grid is too limited to supply enough electricity, which results in volatility and price spikes. Because this situation only occurs 1% of the time, it is not economical to build more infrastructure. The EUAA [93](End users association of Australia) conducted a trial [94]to demonstrate the benefits of a DR aggregation process. The primary purpose of this trial was to enable especially electricity consumers to respond to the extreme peaks and the final prices because of that. The trial comprised different case studies with various types of industries as potential DR providers. The outcome, in the form of an independent trial assessment conducted in 2004, estimated that the value of DR could be as much as $2 billion (1.2 billion euros) per year [90].

Recently, the South Australian government is developing the World's Largest VPP that will be a network of 50 000 household solar PV units connected into an aggregator. This network is expected to meet around 20 % of South Australia's average daily power demand (250 MW) [95]. Additionally, the new power plant is expected to lower energy bills for participating households. The wholesale price is estimated to drop around USD 3 per MWh for all customers, with each additional 50 MW of capacity that is brought onto the system via the aggregator [95]. The Australian VPP Tesla proposal could reduce the wholesale electricity price by around USD 8/MWh or USD 90 million per year across all South Australian customers, which means 30 % of the total energy bill [96].

Another type of aggregator in Australia consists of a network of behind-the-meter batteries providing a range of benefits to the household, the retailer, and the local network. The VPP aims to both cut consumer electricity costs and help maintain grid stability in South Australia.

3.1.3 Europe

The regulatory framework is essential for defining aggregators, as it gives legal boundaries to aggregators in the European Union. This framework includes both national legislation and regulation constructed by the institutions of the European Union (i.e., European Commission, Parliament, and Council).

The Energy Efficiency Directive (2012/27/EU) was the first European legislative document that described the aggregator. The main objective of this Directive is to establish a binding set of measures that ensure the EU reach its 20% energy efficiency target [97] and one of the described instruments for improving energy efficiency is demand response. It is argued that demand response could lead consumers to take actions on consumption and to reduce or shift consumption.

Still, the Directive describes aggregators in the context of demand response as enablers for flexibility. The Directive states that: "aggregator means a demand service provider that combines multiple short-duration consumer loads for sale or auction in organized energy markets" [97]. This definition describes aggregators as demand service providers. Unfortunately, no clear definition is given about the meaning of what demand services are. The aggregator is described in the context of demand response. Therefore, demand response is most like to be a form of demand service.

The European Commission has also ratified the role of aggregators across Europe through their new legislative package, the Clean Energy for All European Package. In this legislative package, which contains a revision of the Electricity Directive, the definition of aggregators is made in the broader context of giving customers (industrial, commercial, and households) access to the energy markets.

First, aggregators are not anymore defined as only "demand service providers," the new proposal for the Directive defines aggregators much broader as "market participants." [89]Secondly, this proposed revision of the Electricity Directive also includes a generation in its definition. Therefore, the definition of the concept aggregator has shifted in recent years in EU legislation. The concept of aggregator has been broadened by not only focusing on on-demand services and loads but expand it by including generation and define it as a market participant [89].

An overview in some European countries is developed on the following paragraphs:

Germany

In 2016, German market regulation was having significant barriers to most forms of Demand Response program types, including both those provided by retailers and independent aggregators. However, the government was aware of these barriers and since then has been undergoing a regulatory review to facilitate change.

Third-party aggregation was complicated in Germany, due to regulatory barriers that require independent service providers (e.g., aggregators) to ask the bilateral permission of multiple parties on particularly the scheduled exchange and compensation payments with the consumer's BRP and retailer [98]. There were no standards for this, and the BRP and retailer often have no interest in working with the aggregator to reach such an agreement.

The aggregation in Germany has been evolving, and more companies are becoming aggregators. In 2018, Germany had one of the biggest Virtual Power plant in Europe. Today the virtual power plant has more than 1300 wind farms in its system, in addition to 100 solar energy, hydropower and bioenergy producers. The total capacity of the virtual power plant exceeds 10,000 MW [99]. It is an entirely renewable plant that enables to sell the power and draws on the full flexibility of the plant.

The lower limit for participation in the balance power market today in Germany is 15 MW. Selling of balance power has a positive impact on the economic situation of the VPPs. Due to special requirements for VPPs, the Minute Reserve Market is the most important and promising one.

France

In 2016, France was the only Member State in Europe which had opened both the ancillary services markets and wholesale market to Demand Response and independent aggregators. This was made possible because the relationship between aggregators and retailers/BRPs had been regulated in 2013, and a standardized framework was put in place. It was also one of only 3 Member States (Finland, GB, and France) where residential consumers were also engaged.

However, the high mandated cost of the retailer's sourcing costs is continuing to block market growth within the wholesale markets, as almost all revenues earned must be paid back to the retailer by the aggregator and consumers. Since 2003, large industrial customers have participated in the balancing mechanism, and from 2007, the first pilots were run to introduce aggregated residential load to the mechanism.

One of the projects mentioned above was Voltalis, an experimental and transitory measure, in which the French TSO asked the regulator to allow the controlled active reduction of loads connected to the distribution grid where no responsible balancing party was supposed to be involved directly at this stage.

This followed exchanges between various players regarding the potential contribution of low voltage loads reduction to the national balancing mechanism, during which a startup called Voltalis to propose an experiment to demonstrate the advantages of such action.

The regulator accepted this measure. The purpose was to undergo technical evaluations in 2008, intending to propose a virtual contribution to the balancing mechanism by the end of the year. The cumulated power reduction was supposed to be between 10 and 100 MW, and the TSO needed to control every 10 minutes.

In 2014, for the first time, an industrial consumer provided its energy reduction as an FCR or Primary Reserve. This program, together with Secondary Reserve (FRRa), had been accessible to load participation since 1 July 2014. The NEBEF ("Notification d'Échange de Blocs d'Effacement") was launched in 2014, creating a mechanism that allows the curtailed load to bid as energy directly into the wholesale electricity market. However, the participation of Demand Response to FCR and FRRa is only possible through a secondary market. For this reason, consumers and aggregators must sign bilateral contracts with producers (generators) to sell them their products.

United Kingdom (UK)

The United Kingdom was the first country in 2016 to open several of its markets to consumer participation in Europe [98]. Today, all balancing service markets are open to Demand Response, and aggregated load is accepted.

Independent aggregation is enabled, and the aggregator is not required to ask for permission or to inform the retailer before load curtailment and has direct access to consumers. They may aggregate load from all over the country. The UK offers a range of opportunities for Demand Response and encourages market competition between providers. The consumer, however, is contractually obliged to inform the retailer about intended participation.

In the UK, few aggregators are active, namely, which offer various services to the national grid by aggregating resources from smaller sites.

The Netherlands

Demand Response and aggregation are allowed in Frequency Restoration Reserves (FRR) automatic and manual (it includes Regulating, Reserve and Emergency Power), and in Replacement Reserves. Primary Control does not allow load access and aggregation.

In the Netherlands, competition over demand-side services is not enabled. The offering is always bundled with the sale of electricity and by a BRP (the non-competitive portion of a Retailer). Consumers must either reject the entire service or accept the aggregator's/BRP combined offer or try to re-negotiate their entire retail contract with another retailer to access the Demand Response services they required. Aggregators in the Dutch Market offer portfolio optimization services to BRPs only, through trading on the day-ahead, intraday, and balancing markets. BRPs optimize imbalances through real-time dispatch and may act as balancing service providers. BRPs can act as aggregators, or they can hire a third-party aggregator for this service. In this context, a third-party aggregator is obliged to have an agreement with the consumer's BRP and with its retailer.

The aggregator can only work as the BRP's service provider. As in the other Member States, this creates a market entry barrier for new entrants. The pooled load has to fulfill requirements as an aggregate. This is a critical enabler of Demand Response as it allows the BRP-aggregator to act as a mediator for the consumer, protecting them from harsh technical pre-qualification measures, which they may not have the ability or knowledge to fulfill.

Italy

The concept of aggregation in Italy refers to putting together DERs in a Virtual Power Plant, as already was explained in previous chapters. Terna began its pilot projects intending to initiate this process and test the new resources. One of these was the UVAM project.

Terna targeted the deployment of 1000MW of resources in the UVAM pilot during 2019. Resources are allocated in A region (northern and central Italy) and B region (the south) [100]. The program allows resources of as small as 1MW to participate in balancing the grid’s demand and supply. This 1MW threshold is thought to be considerably lower than the capacities required for similar grid-balancing opportunities in France or the Netherlands.

Nowadays, there is a proposal of reducing the threshold from 1MW to 0.2MW, after the publication of consultation documents (DCO) on Vehicle to Grid(V2G) [101].

The economic regulation of UVAM differs from that of large plants because it involves not only ordinary remuneration linked to energy activated (€/MWh) but also remuneration for resource availability (€/MW). As said in chapter 3, the is remuneration 30 000 €/MW/year if they respect some requirements, with a particular reduction of 28000 €/MW/year on region A [100].

Currently, 27 different BSP [100]have already been assigned a capacity contract. According to a Terna factsheet, by June 2019, more than 120 UVAM, totaling more than 830MW capacity were qualified to provide ancillary services, with the vast majority (83%) holding capacity contracts that guarantee availability to the grid operator when needed [80]
Terna intends to continue with the implementation of further pilot projects with the following key aims [80]:

- experiment with participation of distributed resources in other services (e.g., voltage regulation)
- incentivize competition and increasing participation of resources in existing services
- leverage the experience gained through pilot projects to develop proposals for a complete redesign of the ancillary services market.

3.2 Types of Aggregators

The constructed typology explains the main principles of the different aggregator types. In this section, the aggregator typology is used in analyzing how the different aggregator types are supported within the current market design. The following paragraphs describe the market facilitation of each of the different aggregator types.

3.2.1 Aggregator as Retailers

A retailer can also assume the full role of an aggregator, taking advantage of his existing customers and retailers who offer real-time prices very much resemble aggregators. However, for retailers offering real-time prices is not a way to produce load response but a way to limit their price risk. These retailers do not make installations on customers' premises, which would allow automatic response to price signals. This business model is called the retailer model, and the aggregator can, in this case, be called an aggregator retailer.

If the customer's demand aggregator is identical to his retailer, specific problems related to balance calculation disappear [90]. Thus, the aggregator is a one-stop-shop that fulfills the roles of BRP, supplier and monetizes flexibility for the prosumer. Hence, the aggregator provides an integrated proposition to the prosumer.

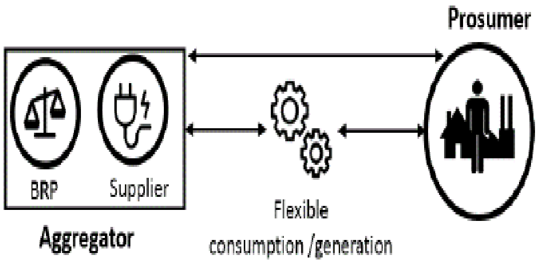

Figure 3.2 Aggregator as Retailers [89]

3.2.2 Aggregator as BRP

The third possibility is that BRP acts as an aggregator for customers whose retailers belong to its balance portfolio. A BRP has an existing relationship with retailers to whom he acts as a balanced supplier. The load changes are then automatically included in his consumption balance. Unfortunately, they are also included in the consumption accounts (calculated internally by BRP) of the respective retailers. Because load reduction is often activated when imbalance prices are high, in many cases, this would give free benefit to the retailer if the effect is not corrected by an agreement between the BRP and involved retailers.

In this type of aggregator, there are two BRPs on the same connection. Hence, the supplier has its BRP, and the aggregator has its BRP as well. Arrangements need to be made between the aggregator and supplier, as the aggregator may use electricity sourced by the supplier, and the aggregator could influence the imbalance position of the supplier's BRP. The aggregator sells the flexibility at its own risk on behalf of the prosumer.

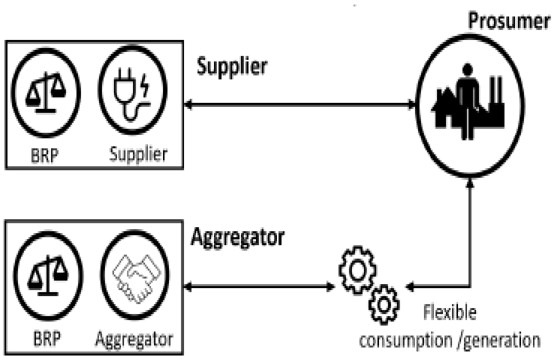

Figure 3.3 Aggregator as BRP [89]

3.2.3 Aggregator as a Service Company

Another possibility is that the aggregator acts as a service company to the retailer and has no independent position in the electricity market. In this case, he performs activities such as forecasting, scheduling optimization, and load control as usual, but the effect of load control is summed into the consumption balances of the respective retailers. The retailers can then sell this power forward, based on the aggregator's advice. The aggregator thus gets no direct benefit from the activity. However, the aggregator secured its income by making a service contract with the retailer [90].

The benefit of this model compared to the retailer model is that the aggregator is not limited to a specific group of customers, with whom he has a retail contract. However, the disadvantage is that he must first come into agreement with several retailers to take advantage of this fact.

An aggregator can also act purely as a service provider by only providing the means to access flexibility and not selling it at his own risk. The aggregator provides the means to access flexibility and offers this access as a service to other parties. This access to flexibility can be achieved by, for example, a software platform that can control decentral assets.

The aggregator, as a service provider, does not take the role of BRP or supplier. The aggregator could be perceived as not active in the traditional electricity value chain. Flexibility is not sold, but service is created that allows other market parties to unlock and use flexibility at prosumers.

Thus, this type of aggregator does not trade flexibility but solely collects flexibility from prosumers and organizes this as a service.

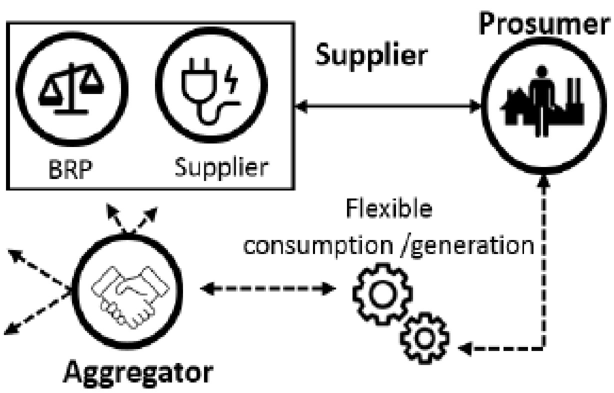

Figure 3.4 Aggregator as Service Company [89]

3.2.4 Aggregator as Third-Party

The aggregator could also be a third party, a company that does not have any existing relationship with the customers as far as the electricity business is considered. However, it could have a relationship in another field, such as facility management.

His balance account would be directly credited by load reduction or charged by load increase, caused by the control actions which he has exerted on the customers. In this, there could be difficulties in calculating the proper payments between the retailer and aggregator.

The retailer currently provides all energy which the end-users consume. This business model would require a change to this principle. The method of neutrally determining the energy provided by the retailer and that provided by the aggregator (which can be negative) is a challenge.

3.2.5 Prosumer as Aggregator

Prosumers could choose to adopt the role of an aggregator. They could aggregate a portfolio of flexible assets that they own. This portfolio could then be traded with other market players or at marketplaces.

The prosumer as an aggregator is not involved in the role of supplier or BRP but only aggregates flexibility from its resources. For large-scale prosumers rather than small consumers, it would be more convenient to adopt this aggregator type as the volume of flexibility is more likely to be present to aggregate into a pool.

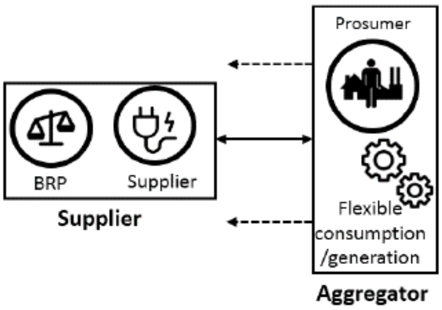

Figure 3.5 Prosumer as Aggregator [89]

The prosumer is an aggregator builds a portfolio of assets that are flexible and tries to trade this flexibility. However, the prosumer as an aggregator still has a contractual relationship with a supplier and BRP. Therefore, the contracts between the prosumer as an aggregator, the supplier, and the BRP should allow the prosumer to act as an aggregator.

3.2.6 DSO as Aggregator

The DSO can also act as an aggregator, which results in the DSO as an aggregator model. The DSO as an aggregator is not BRP or supplier and is only involved with the flexibility from the prosumer for congestion management.

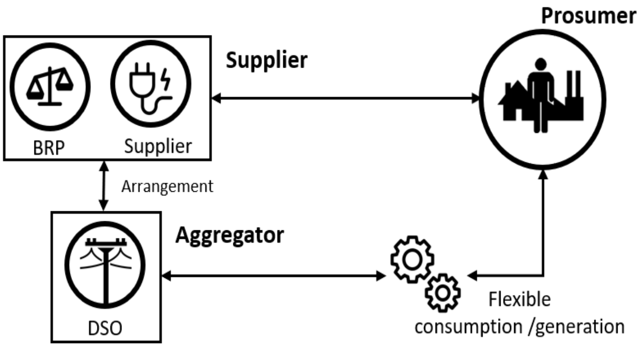

Figure 3.6 DSO as Aggregator [89]

An arrangement needs to be in place between the DSO as an aggregator and the supplier/BRP. Activation of flexibility by the DSO as an aggregator influence the supplier/BRP and procedures need to be in place to cope with the results of this activation.

Recently much discussion has been taking place on the role and possible additional activities of DSOs. DSOs acting as an aggregator is such new activity. Regulators have recently published their stance in this discussion. The Council of European Energy Regulators (CEER), an organization where Europe's national energy regulators work together, has recently published a report that presents the position of the CEER on flexibility concerning the DSO [102]. The benefits of using flexibility by DSOs are recognized by the CEER, for example, by using it for congestion management.

Type	Explanation
Aggregator as retailers	An integrated model where the aggregator both aggregates the flexibility and supply of electricity. There is only one BRP per connection.
Aggregator as BRP	The role of the aggregator is combined with the one of BRP. There are two BRPs on the same connection.
Aggregator as a service company	The aggregator provides the service to access flexibility. The aggregator does not trade flexibility but collects flexibility from prosumers.
Aggregator as Third-party	The aggregator does not have any existing relationship with the customer as far as the electricity business is considered.
Prosumer as Aggregator	Large-scale prosumers could choose to adopt the role of an aggregator.
DSO as Aggregator	DSO aggregates for congestion management.

Table 3.1. Overview of the type of aggregator

3.3 Revenue Models

Several business processes can be found inside the aggregator company, such as the customer acquisition process, settlement process. They can be defined in different ways. The purchasing process includes daily activities which concern themselves with buying services from the customers. However, it is difficult to separate from activities related to selling and buying power on the electricity market. Together they make up the core business of the aggregator and can be called the trading process. A large part of the aggregator's effective decisions is dealing with trading power either upstream (electricity market) or downstream (customers). The aggregator requires optimization and proper inputs to know when to sell or buy, how much, and from/to whom [90].

The relationship between remuneration and the customer's active participation can be tight. The customer's benefit could be based on dynamic tariffs provided by an aggregator retailer. Furthermore, the customer can be given a certain percentage of the aggregator's gross profit from selling DER to the market. A combination of the different payment components could be used to achieve a suitable risk and incentive level. It could also be noted that the customer may also get other benefits than direct payments from the aggregator. For example, the customer may receive as byproduct real-time power measurements and consumption monitoring, which help him achieve energy saving [90].

A significant obstacle to the development of prosumer business models is the availability of adequate smart metering systems and network tariff designs. Often energy storage facilities are charged twice when providing upward and downward flexibility services. In the EU, the new Clean Energy Package obliges member states to roll-out smart meters (based on a cost-benefit analysis) and removes the double charges on prosumers' storage used for flexibility.

Finally, the aggregator provides financial incentives to the customers to participate in demand response provision. These could take many forms, and there are many ways to set up the business. The customers could be rewarded by being offered an availability payment, call payment (payment for flexibility energy provided), or percentage of the aggregator's profits. The aggregator monitors the customer's performance and rewards him accordingly [90].

Chapter 4 Proposed Methodology

Previous chapters presented an overview of how a domestic prosumer can participate in the electricity markets. The analyzed framework includes the participation not only to the Day-Ahead Market (DAM) but also to the Ancillary Services Market (ASM). The inclusion of a BESS at the prosumer premises is considered an enabler for ASM. Furthermore, as already stated in Chapters 2 and 3, participating in the ASM is usually only possible via aggregation since there is a minimum bid size (in MW) to access the market.

This study aims to discover the effective management of aggregated energy storage systems at the domestic level by providing self-consumption but also providing frequency regulation through the ASM. It was proposed different case studies that show which is the optimum point where a prosumer could work. Battery operation is analyzed by the point of view of its operating parameters. For this, three different models of the BESS depicting different cases have been developed.

Section 4.1 describes the reference case where the user only owns a PV plant without the help of a battery. In section 4.2, it is introduced the concept of the battery only for the maximization of self-consumption. Since the scope of this study is not only the benefit of the user but also the benefit of the grid, it has been introduced the provision of a service included in ASM, the tertiary reserve. The participation in the ASM is proposed in section 4.3 in an unconstrained case. Unconstrained means that the constraint is relaxed on the minimum bid size. Therefore, the prosumer offers on ASM whatever is available for him, even below the minimum power threshold. Thus, the unconstrained case is adopted as an ideal model. In section 4.4, the aggregated case implements the minimum bid size in the model. Therefore, the single prosumer joins a virtual aggregated unit that is enabled to ASM. The aggregator works as BSP and offers the aggregated quantity on ASM. This chapter not only shows the BESS model according to each case but also the economic model in section 4.5. For each case, the energy and economic streams that are considered in terms of revenues and costs are described.

4.1 Reference case: the domestic prosumer

In this thesis, the reference case of the domestic prosumer includes a PV system and a domestic load. The energy that the load requires is not satisfied by the PV production is sold or bought from the grid. Since the reference case does not include a battery, there is no possibility of storage.

4.1.1 Energy Flows Computation

By having the power produced by the PV plant (P_{PV}) and the load consumption (P_{Load}), it is possible to compute the difference in power (P_{diff}).

$$P_{diff}[kW] = P_{Load} - P_{PV} \tag{4.1}$$

Knowing the difference in power and by considering the time of one hour, it is possible to identify the difference in energy. Since the sampling rate per power is per one hour, the absolute value of energy in kWh and power in kW are equivalent.

$$E_{diff}[\text{kWh}]=P_{diff}[kW] * 1\ [h] \tag{4.2}$$

If $E_{diff}[kWh] > 0$, this means that the prosumer has more consumption than the energy produced by the PV, then the prosumer will need extra energy from the grid to guarantee the load consumption for that hour, and then the prosumer withdraws energy from the grid E_{with}. On the other hand, if the prosumer has more energy produced than the required $E_{diff}[kWh] < 0$, the prosumer could inject energy $\left(E_{inj}\right)$ into the grid.

4.2 Behind-the-Meter Case

Storage is used in the PV system of the user to increase the amount of time that the PV system could be used to power a load by storing energy. The most common type of storage to be associated to a domestic PV system is a Li-ion battery that maximizes the self-consumption of the PV plant.

This model assumes that the prosumer only bids on DAM through the BRP, which is the one in charge of providing the injection/withdrawal program. This model considers that the BRP behaves ideally by incurring no errors in the program and that the imbalances paid by the prosumer are only in the case of BESS reaching the saturation limits due to an inadequate management.

4.2.1 BESS Model

A BESS numerical model was implemented in a Matlab Simulink tool suitable for analyzing the applications that could have its use in a Prosumer environment with the PV plant. This tool can simulate the runtime provision of grid services by the BESS and considering the energy flows exchanged with the network.

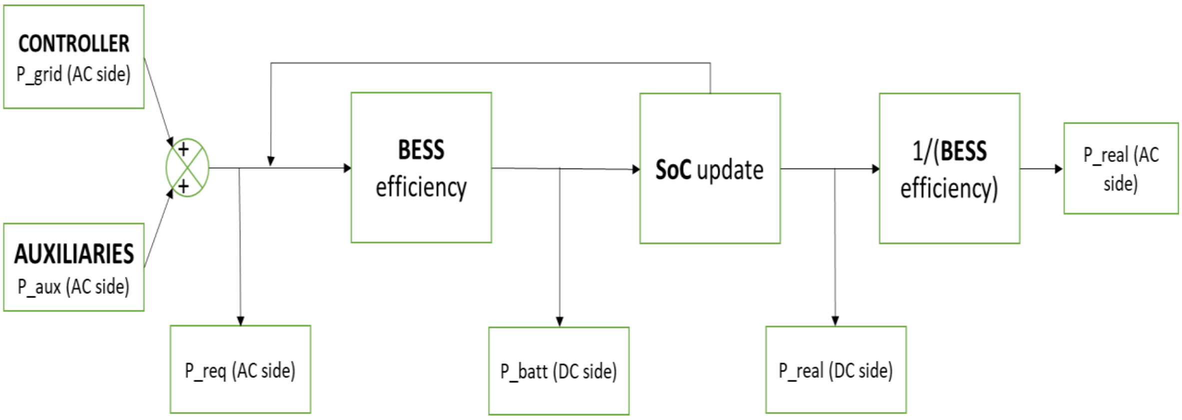

Figure 4.1 Components of the BESS model and their main variables

The model requires as inputs:

1. Energy to Power Ratio (EPR) for battery, defined as the ratio among nominal energy $E_n\ [kWh]$ and nominal power $P_n[kW]$.
2. The difference in power from load consumption and power produced, P_{diff} in Per unit base.
3. Saturation levels for SOC: SoC_{min}=0 and SoC_{max}=100, which are the thresholds for the BESS model.
4. Sampling-rate of 1/3600 Hz for all the cases since each step of the simulation is equivalent to an hour because the input data and the provided services are on an hourly timeframe, and this decreases the computational effort.

The main elements of the BESS model are:

1. Controller

A Controller implements the BESS operation strategy in runtime. Its inputs are the data of the user's choice related to PV and load profile of a domestic user. The sampling rate of the output can be configured. For a matter of study is considered as already stated above, in any case, depending on the user decision, this could be modified, and the model would also be set for the change in the sampling rate. The output from the controller is a power rate per unit, concerning the nominal power of the battery. A saturation block limits the power in the interval from -1 to 1 (thus, no power larger in absolute value than nominal power can be requested). Then, power is divided over the EPR to have the c-rate requested from the grid ($c_{rate\ req\ grid}$).

2. Auxiliary systems

For the BESS model, it is not only considered the difference in the power that is coming from the data of the users but also it should be considered some auxiliaries' power. BESS is kept in a constant ambient temperature by an HVAC system, including air conditioning and a heat pump. Therefore, the power requested depends on the thermal load of the BESS, i.e., the thermal dissipation of batteries due to their internal electrochemical process (proportional to battery power) and the heat exchange with the ambient (proportional with outdoor ambient temperature, T_{amb}) [9].

This auxiliary power varies concerning the power requested for performing the services, P_{gridAC} which is equal to $c_{rate\ req\ grid}$*EPR and T_{amb} as Table 4.1.

		Pgrid, AC						
		0	0,18	0,36	0,54	0,72	0,9	1
T amb(°C)	-5	908	801	951	1143	1224	1423	1831
	0	908	801	951	1143	1224	1423	1831
	10	558	567	874	1322	1423	1950	2188
	20	733	742	1050	1497	1598	2125	2363
	25	1092	1004	1408	1856	1957	2483	2721
	30	1197	1253	1683	2024	2125	2652	2890
	35	1341	1412	1703	2045	2146	2672	2910
	40	1516	1704	1749	2180	2281	2807	3045

Table 4.1. Auxiliary Power with respect to $\boldsymbol{T_{amb}}$ and $\boldsymbol{P_{gridAC}}$

The output of the lookup table is in [W], and it is referred to BESS in the Joint Research Centre (JRC) on which the whole model is validated. Since it is assumed that it is scalable on every battery, it is performed the following operations to obtain the power requested by the auxiliaries of the domestic battery as a function of the power requested from the grid and the ambient temperature (Table 4.1). First, it is divided the power by 10^3 to pass from W to kW. Then, it is divided by the nominal power of the JRC BESS (250 kW) and multiply by the nominal power of the battery in each simulation.

$$\text{Gain} = \frac{1}{10^3} * \frac{P_n[k]}{250} \tag{4.3}$$

Where P_n, is the nominal power of the battery in the simulation. The output from the auxiliary system block is $c - rate_{aux}$.

3. Efficiency

The overall efficiency of the BESS varies with the total c-rate ($c - rate_{req\ tot\ AC}$), given by the sum of auxiliary demand and power requested for providing the service, and the SoC. It is assumed that the overall efficiency is the same for charging or discharging the battery. The lookup table (Table 4.2) implemented in the model represents the roundtrip efficiency. The efficiency instant by instant is the square root of the roundtrip efficiency.

$$\eta_{BESS}(c - rate_{req\ tot\ AC}, SoC) = \eta_{ch} = \eta_{dis} = \sqrt{\eta_{RT}} \tag{4.4}$$

Where η_{BESS} is generally the efficiency of the charge (η_{ch}) or discharge (η_{dis}) process and η_{RT} , is the roundtrip efficiency.

From Table 4.2, it could be seen on the rows the $c - rate_{req\ tot\ AC}$ and on the columns the SoC. By observing this table, it is notable to say that at lower power, there is lower efficiency. Instead, by focusing only on SoC, it could be seen that the maximum efficiency is when SoC = 50%.

	SoC (%)				
c-rate-req-tot-AC	**0**	**15**	**50**	**85**	**100**
0	0,54	0,54	0,55	0,48	0,48
0,02	0,54	0,54	0,55	0,48	0,48
0,039	0,842	0,842	0,842	0,787	0,787
0,079	0,818	0,818	0,931	0,896	0,896
0,158	0,926	0,926	0,947	0,917	0,917
0,237	0,895	0,895	0,931	0,927	0,927
0,316	0,868	0,868	0,922	0,908	0,908
0,395	0,861	0,861	0,896	0,859	0,859
0,439	0,861	0,861	0,896	0,859	0,859

Table 4.2. Efficiency with respect to $\boldsymbol{c-rate_{req\ tot\ AC}}$ and $\boldsymbol{SoC}$

The efficiency block is necessary to pass from AC to the DC side and obtain the real power to update the SoC of the battery each step of the simulation.

4.2.2 Energy Flows Computation

By having the power produced by the PV plant (P_{PV}) and the load consumption (P_{Load}), it was possible to compute the difference in power (P_{diff}) as Eq. 4.1. For a matter of simplicity, all the values in the model are in PU, $\frac{P_{diff}}{base}$, where the base is the P_n of the battery and depending on the user's choice. This difference in power is transformed into c-rate and becomes the c-rate required by the controller in AC, $c-rate_{reqAC}$. By having this $c-rate_{reqAC}$ and then the $c-rate_{aux}$, the prosumer has the total in AC required to the battery($c-rate_{req\ tot\ AC}$).

$$c-rate_{req\ tot\ AC} = c-rate_{reqAC} + c-rate_{aux} \tag{4.5}$$

If $c-rate_{req,totAC}$ is positive, this means that the battery gets discharged at that moment, then the real power is:

$$c-rate_{totDC} = \frac{(c-rate_{req,totAC})}{\eta_{dis}} \tag{4.6}$$

Where: $c - rate_{totDC}$ is the total c-rate after the battery and have been transformed in this case with the discharge efficiency, η_{dis} which is fed with the actual SoC , $c - rate_{req,totAC}$ as explained in Eq. 4.4

Instead, if $c - rate_{req,totAC}$ is negative, means that the battery could be charged, then the real power is:

$$c - rate_{totDC} = c - rate_{req,totAC} * \eta_{ch} \tag{4.7}$$

Where η_{ch}, is the charge efficiency that just like η_{dis} depend on the $c - rate_{req,totAC}$ and the SoC.

$c - rate_{real,totDC}$, is the power that flows in the battery, after verifying feasibility with SoC saturation limits (Eq. 4.8). In this study, the limits are 0 and 100.

$$c - rate_{real,totDC} = \begin{cases} c - rate_{totDC}, \; SoC_{min} < SoC(t) < SoC_{max} \\ 0, \qquad SoC(t) < SoC_{min} or \; SoC(t) > SoC_{max} \end{cases} \tag{4.8}$$

If the prosumer is outside these limits, as shows Eq. 4.8, this means that the battery is not capable of providing what is requested, and this means that the prosumer will have an imbalance.

After computing $c - rate_{real,totDC}$, the prosumer needs to check that it is complying with the requirement for self-consumption(SC). For doing this comparison, it is needed the total required in AC($c - rate_{real,totAC}$) and for that $c - rate_{real,totDC}$ is converted from DC to AC.

For charging process,

$$c - rate_{real,totAC} = \frac{(c - rate_{real,totDC})}{\eta_{ch}} \tag{4.9}$$

For discharging process,

$$c - rate_{real,totAC} = c - rate_{real,totDC} * \eta_{dis} \tag{4.10}$$

After having $c - rate_{real,totAC}$, it is transformed to power:

$$P_{real,AC} = c - rate_{real,tot\ AC} * EPR \tag{4.11}$$

After having the real power and comparing with P_{diff}, it is possible to know how much the prosumer exchanged with the grid on the DAM. The entity responsible to provide the injection/withdrawal program is the BRP, that These imbalances could be due to saturation of SoC, but also when P_{diff} > P_n.

$$P_{gap} = P_{diff} - P_{real,AC} \tag{4.12}$$

if P_{gap} > 0, the prosumer needs to withdraw from the grid, because the real power available in the battery is not enough. But if the P_{gap} <0, the prosumer inject some energy into the grid.

4.3 Behind-the-meter case and flexibility services

Energy storage plays an important role in creating a more flexible and reliable grid system. The participation in ancillary services market is considered. Some of the rules of the market are neglected and it is considered an “unconstrained” market. One small battery can bid on its own on the market, without having a minimum bid limit. It is simulated tertiary control provision with regulating bands available after following self-consumption logic.

This model considers the function of BRP but as it is also providing flexibility services, there is the Balancing Service Provider (BSP) that is the one which provides services to the ASM.

4.3.1 The Controller

The controller, in this case, still takes care of the self-consumption logic but also introduce the participation to ASM and the consequent provision of tertiary reserve. This implies:

- the forecast of the power band available in the following market session for tertiary reserve, considering the expected SoC variation due to self-consumption;
- the market model for defining the quantity awarded in the market;
- the computation of the hourly setpoint for either upward or downward regulation and for the self-consumption logic.

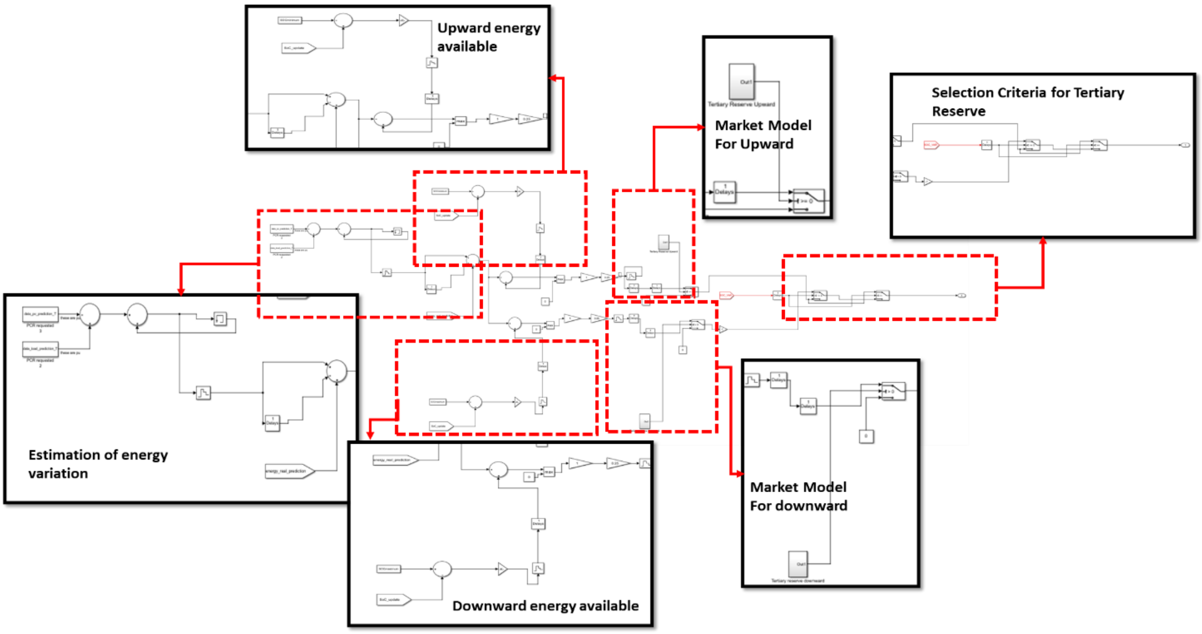

Figure 4.2 Simulink Model for the Prediction of Tertiary reserve and bid on the Market

Figure 4.2 provides part of the model in which the tertiary reserve is estimated and then is bid on the market. A detailed explanation of the process is proposed in section 4.3.2

4.3.2 Energy Flows Computation

As introduced in 4.3.1, there is an additional part on the controller that is related to the prediction of the energy available for the tertiary regulation. This model use predicted data for PV and Load Power to provide an estimation of the energy that will be required for the battery. The development of this predicted data is explained in section 5.3

In this market, since there is no constraint on the minimum bid size, the prosumer always bid the available quantity, whatever it is. The market model defines if the offer is either awarded or not, comparing the prices bid and the prices of the market taken from historical data.

Tertiary Prediction

To understand how much the available energy for the tertiary reserve is, the model estimates the energy variation for the whole market session due to all the services provided by the BESS. This energy variation allows estimating the final SoC at the end of the next market session without bidding for tertiary reserve. The gaps between SoC and the SoC thresholds (minimum and maximum SoC) are the available energy for bidding upward and downward. Since the market gate closure happens one hour before the delivery time (t-1) and the market session lasts 4 hours (from hour t to t+3), the prediction must involve five hourly energy variations. The hourly energy variation depends on:

- self-consumption and provision of the tertiary reserve as awarded in the previous market session (from hour t-1 to t);
- self-consumption only (for hours t to t+3).

The model uses the self-consumption logic, it is estimated the energy variation in the battery at the hour t-1 for the following 4 hours, and depending on the nominal energy and the initial state of charge, it is possible to estimate the tertiary energy available for upward or downward as detailed below.

The model first calculates SC and the provision of the tertiary reserve from the previous market.

$$\mathrm{E}_{t-1}\,[kWh] = \mathrm{Load}_{pred(t-1)} - \mathrm{PV}_{pred(t-1)} \pm \mathrm{E}_{real,TR(t-1)} \tag{4.13}$$

Where:

- E_{t-1} [kWh] is the total energy predicted at the hour before the delivery.
- $\mathrm{Load}_{pred(t-1)}$, $\mathrm{PV}_{pred(t-1)}$ are Load and PV energy predicted at the hour before the delivery.
- $E_{real,TR(t-1)}$ on the hour t-1 is the energy exchanged with grid based on the awarded quantity for hour t-1 in the previous market session, for upward or downward tertiary reserve.

For the market session,

$$\mathrm{E}_i\,[kWh] = \sum_{i=t}^{t+3} \mathrm{Load}_{pred(i)} - \mathrm{PV}_{pred(i)} \tag{4.14}$$

Where i is the hour of delivery, E_i [kWh] is the total energy predicted for each hour and $\mathrm{Load}_{pred(t)}$, $\mathrm{PV}_{pred(t)}$, are Load and PV energy predicted for each hour.

The total variation depends on the hourly predictions in (Eq. 4.13 and Eq. 4.14)

$$Tot\_E_{var,estimated}[kWh] = E_{t-1} + E_i \tag{4.15}$$

If $Tot\_E_{var,estimated} > 0$, this means positive energy that discharges the battery (load is greater than PV). If $Tot\ E_{var,estimated} < 0$, this means negative energy then the battery is charged (load is lower than PV). With this $Tot\_E_{var,estimated}$, it is possible to compute how much energy available the prosumer have for upward and downward services.

$$A\_E_{TR,up}[\mathrm{kWh}] = (SoC_{in} - SoC_{min}) * E_n - Tot\_E_{var,estimated} \tag{4.16}$$

Where: $A\_E_{TR,up}$[kWh] is the total available energy for upward, SoC_{in} is the actual SoC, SoC_{min} is the minimum value set for SoC, in this study is equal to 0% and E_n is the nominal energy of the battery.

The available power for the next hours is then evaluated considering an average efficiency (η_{avg}) of the system and a safety factor (K_s) that changes depending on how much the prosumer wants to provide of their energy available. This safety factor has this range:

$$0 < K_s < 1 \tag{4.17}$$

This margin will keep the battery farther from SoC saturation.

$$A\_P_{TR,up}[\text{kW}] = \frac{A\_E_{TR,up}[\text{kWh}]}{4[h]} * K_s * \eta_{avg} \tag{4.18}$$

Where: $A\_P_{TR,up}$[kWh] is total available energy for upward.

For the downward service, the model follows the equation:

$$A\_E_{TR,dn}\ [\text{kWh}] = (SoC_{max} - SoC_{in}) * E_n + Tot\_E_{var,estimated} \tag{4.19}$$

Where: $A\_E_{TR,dn}$[kWh] is total available energy for downward, SoC_{in} is the actual SoC, SoC_{max} is the maximum value set for SoC, which in the model is equal to 100%

And the available downward power ($A\_P_{TR,dn}$) for the following hours is:

$$A\_P_{TR,dn}[\text{kW}] = \frac{A\_E_{TR,dn}\ [\text{kWh}]}{4[h]} * \frac{K_s}{\eta_{avg}} \tag{4.20}$$

After the model have the available power for both services ($A\_P_{TR,dn}$, $A\_P_{TR,\text{up}}$), the model checks the power that is allowed to bid by comparing the prices that the prosumer bids and the one that is in the market. The market model explained in section 5.4, checks hourly the price bid where the award of the bid works as an on-off controller. For each hour, the bid is either awarded completely or rejected. For upward reserve, the prices that are accepted could not be greater than the one that set by the market (Eq. 4.21); differently for downward reserve, the quantity bid could be only awarded in case the price bid by the user is greater than the one that is on the market(Eq.4.22)

For upward reserve, the bid is accepted if:

$$p_{\ TR,up,bid} < p_{\ TR,up,mkt} \tag{4.21}$$

Where:

- $p_{\ TR,up,bid}$ is the price bid by the prosumer for the upward reserve
- $p_{\ TR,up,mkt}$ is the price set by the market for the upward reserve

In the case of the downward reserve,

$$p_{\ TR,dn,bid} > p_{\ TR,dn,mkt} \tag{4.22}$$

Where:

- $p_{\ TR,dn,bid}$ is the price bid by the prosumer for the downward reserve
- $p_{\ TR,dn,mkt}$ is the price set by the market for the downward reserve

In this model, there is a strategy to choose between the upward and downward reserve after it is selected the available power after the comparison of prices. The strategy is in the direction to avoid SoC saturation in the following 4 hours. Supposing an average roundtrip efficiency for the battery of 90%, at SoC=54%, the useful energy content of the battery is split in two equal parts. Therefore, if the SoC of the BESS is larger than 54%, upward energy is offered. If instead is smaller than 54%, a downward bid is presented.

This tertiary power available is the power required for tertiary reserve ($P_{req,TR}$), together with power requested for self-consumption (P_{diff}) give the total power required by the prosumer.

$$P_{req} = P_{req,TR} + P_{diff} \tag{4.23}$$

This power is transformed into c-rate:

$$c - rate_{req\ AC} = \frac{P_{req}}{EPR} \tag{4.24}$$

Then the model computes the total with the auxiliary part and finds $c - rate_{req\ tot\ AC}$ as Eq. 4.5. This is requested to the battery and in the same way, was done in Section 4.2, $P_{real,AC}$ is found. For discharge process, the model follows Eq. 4.6, 4.8,4.10, and 4.11, whereas for charge process Eq. 4.7, 4.8, 4.9, and 4.11.

By knowing $P_{real,AC}$, the model decides how much is given to the tertiary and the self-consumption. As already explained, The BRP proposes a "baseline" on the energy exchanged with the grid, which is always zero except when the battery hits the limits of saturation. Therefore, the prosumer must respect the program proposed by the BRP so that SC becomes the priority.

The model gives priority to self-consumption, but the model has different approaches to select between SC and Tertiary.by following Eq. 4.25 or Eq. 4.26.

$$P_{diff} * P_{real,AC} > 0 \tag{4.25}$$

or

$$P_{diff} * P_{real,AC} < 0 \tag{4.26}$$

1. $P_{diff} * P_{real,AC} > 0$

Whenever the model is in this position, the model checks how much the battery has of $P_{real,AC}$

If,

$$P_{real,AC} > P_{diff} \tag{4.27}$$

This means that real SC ($P_{real,SC}$) is exactly as the required, P_{diff}. Then,

$$P_{real,SC} = P_{diff} \tag{4.28}$$

When $P_{real,AC} > P_{diff}$, the model checks how much power is available for tertiary reserve ($A\_P_{real,TR}$) as follows:

$$A\_P_{real,TR} = P_{real,AC} - P_{real,SC} \tag{4.29}$$

The model chooses the tertiary real power ($P_{real,TR}$) as follows:

$$P_{real,TR} = \min\left(P_{req,TR}, A\_P_{eal,R}\right) \tag{4.30}$$

On the other hand, if,

$$P_{real,AC} < P_{diff} \tag{4.31}$$

SC is not respected, and there are imbalances. The model takes this gap of power in SC, transforms it into energy, which is equivalent to power because it is per one hour. This energy is injected or withdrawn, depending on the sign. Further, the model computes the energy no provided for tertiary reserve.

2. $P_{diff} * P_{real,AC} < 0$

If this is the result of the product, the model compares the self-consumption required and the real power to know how much the prosumer needs from the ASM market to comply with the SC and the battery.

$$D\_P_{real,TR} = P_{realAC} - P_{diff} \tag{4.32}$$

Where $D\_P_{real,TR}$, is the desired tertiary power from or to ASM.

This tertiary power needed is limited, since the prosumer cannot use more than the quantity that was already required since this was already communicated to be part of the bid. Then the real power for tertiary is:

$$P_{real,TR} = \min\left(P_{req,TR}, D\_P_{real,TR}\right) \tag{4.33}$$

Whenever the prosumer does not respect the SC requested, the model checks the gap, and then the prosumer injects or withdraws energy.

$$P_{diff} - P_{real,SC} > 0 \tag{4.34}$$

The sign positive means that the prosumer needs to withdraw from the grid.

On the contrary,

$$P_{diff} - P_{real,SC} < 0 \tag{4.35}$$

By having a negative sign, since the battery cannot absorb more energy, then the energy is injected.

4.3.3 Loss of Regulation

Ancillary services need reliable providers. Each provider must correctly follow the dispatching orders it receives. During this study, a parameter called Loss of Regulation (LoR) is introduced to indicate the performance of the provision: in particular, it describes the amount of energy not provided on the total energy requested. LoR must be minimized since it is linked to an economic penalty [€/MWh] applied to the BSP.

In this model, the energy not provided is analyzed hour by hour by the following:

$$P_{non-prov}(i) = P_{req,TR}(i) - P_{real,TR}(i) \tag{4.36}$$

Where $P_{non-prov}(i)$ is the power no provided and by multiplying per one hour is transformed to energy no provided ($E_{non-prov}$) that is associated with LoR.

Since the goal is to increase profits, BSP should be within the ranges accepted in LoR to avoid the penalty. This model allows a Loss of Regulation (%) with an acceptable range of 5-10%.

Considering this, the model decides that if the energy non provided by the battery (Eq. 4.37) is lower than 5%, there is no LoR for the tertiary reserve (LoR_{TR}) applied to the BSP.

$$Divergence(i) = P_{req}(i) - P_{real,\mathrm{AC}}(i) \tag{4.37}$$

Differently, in the case, this percentage is above 5%, then $LoR_{TR}(i)$ is exactly as Eq. 4.36.

$$LoR_{TR}(i) = P_{non-prov}(i) \tag{4.38}$$

To know the total value, the model considers:

$$LoR[kWh] = sum(abs(LoR_{TR}(i))) \tag{4.39}$$

The index of Loss of Regulation (LoR) is used to describe the ratio among the energy non-provided and the total energy requested to the battery of tertiary reserve.

$$LoR(\%) = \frac{sum(abs(LoR_{TR}(i)))}{sum(abs(P_{req,TR}(i)))} * 100 \tag{4.40}$$

4.4 Aggregated case

Most of the ASMs only accept bids larger than a minimum threshold (in MW). This minimum threshold limits the participation to ASM of DERs unless they aggregate together. The aggregated unit is managed by an aggregator that participates in ASM on behalf of DERs and works as BSP. In the framework of this study, it is adopted as reference a minimum size of 0.2 MW for both upward and downward reserve. This assumption is coherent with the evolution of the Italian regulatory framework, recently enabling the participation of DERs with bids as small as 0.2 MW [101].

The aggregated case introduces in the market the constraint of the minimum bid size. The single prosumer is inserted in an aggregated unit enabled to ASM via the aggregator. Therefore, it can provide services on the market only if the available power by the aggregated unit is greater or equal to the minimum bid. For this study, it has been simulated five prosumers doing the same activity as before, self-consumption, and tertiary reserve. The tertiary energy, however, is sold as an aggregated unit.

The simulations are performed on five batteries working in parallel. These five prosumers are part of an aggregated unit composed of domestic users only. Multiple scenarios are simulated, in which the total number of houses varies (some hundreds to one thousand prosumers aggregated). The total available energy by these five prosumers is scaled up to the total number of houses (assuming these five batteries are a representative sample of the whole aggregated unit). This solution to simulate only five batteries out of some hundreds is aimed to use a detailed BESS model without increasing the computational effort unsustainably. The use of a detailed model, also including the auxiliary systems, can increase largely the accuracy of modeling the BESS operation [103]. On the opposite, generalizing the behavior of a few users can lead to disregard some consumption patterns that are instead present in a large aggregated unit. It is validated since the PV systems show almost overlapping patterns for domestic users in the same geographical area. Besides the possibility of clustering in a few (4-5) groups, the domestic load profiles have already been shown by literature [104]. Furthermore, for an aggregated unit it is better to select similar power profiles, to maximize the available energy due to superposition effect. Using a database of many user’s profiles it has been decided to adopt similar load profiles to have an effective aggregation. For what just mentioned and limited to the purpose of this study, it can be argued that the benefit of adopting a more detailed BESS model overcome the drawbacks of generalizing few user’s behaviors.

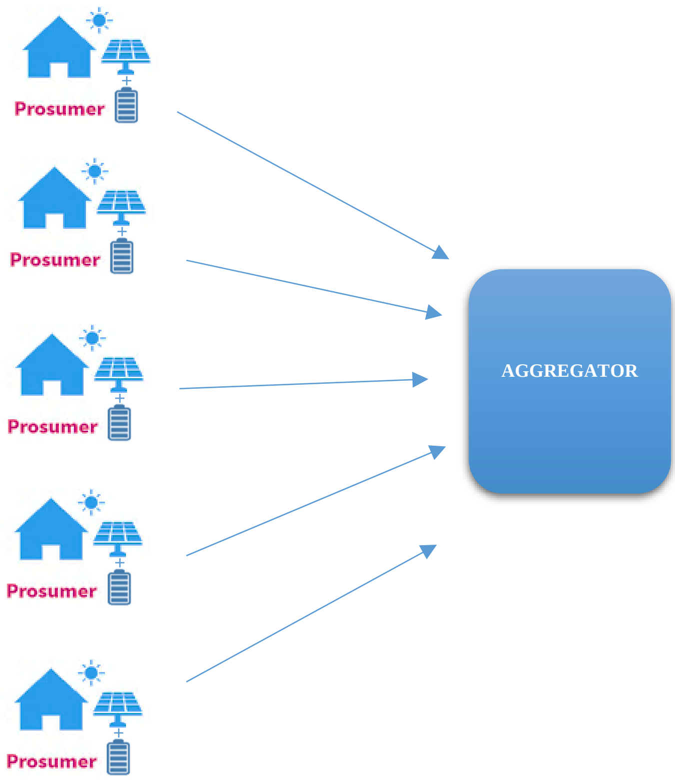

Figure 4.3 Different prosumers in an aggregated unit

4.4.1 The Controller

The controller for the aggregated market follows the same self-consumption logic and the provision of the tertiary reserve as stated for the unconstrained case, but in this case the model needs to aggregate several houses. For this study, the simulations are performed on five batteries working in parallel. These five prosumers are part of an aggregated unit composed of domestic users only and the total available energy by these five prosumers is scaled up to the total number of houses (assuming these five batteries are a representative sample of the whole aggregated unit).

This involves:

- That the model has five batteries with their controllers that do exactly the same forecast of the tertiary reserve available considering the expected SOC variation due to self-consumption;
- Since the model finds the available tertiary band provided by each prosumer, then it is possible to rescale it to have the total aggregated band;
- The total aggregated band needs to respect the threshold of the minimum bid size;
- Then the market model defines the quantity awarded in the market.

4.4.2 Energy Flows Computation

The model does the same as the non-aggregated case, in the calculation of $Tot\_E_{var,estimated}$ for each prosumer. Since the prosumers have similar profiles, it is expected this value to be similar. After the model have the total energy variation estimated for each prosumer then it is possible to compute how much available power the aggregator has for upward and downward services for each user.

The aggregated available upward power is:

$$Agg\_P_{TR,up} = \sum_{i}^{n(users)} A\_P_{TR,up,i} \tag{4.41}$$

Where: $Agg\_P_{TR,up}$ is the aggregated upward available power and $A\_P_{TR,up,i}$ is the individual upward power available of each prosumer studied.

And for downward power is:

$$Agg\_P_{TR,dn} = \sum_{i}^{n(users)} A\_P_{R,d,i} \tag{4.42}$$

Where: $Agg\_P_{TR,dn}$ is the total downward available power aggregated and $A\_P_{TR,up,i}$ is the individual downward power available of each prosumer studied.

SoC_{max}, SoC_{min}, K_s, η_{avg} and E_n are the same values for all the prosumers, but actual SoC is different, because even though the prosumers have similar profiles for PV and for load, it is not expected that the conditions are exactly the same ones for all the prosumers. Therefore, also the tertiary energy available is different for each prosumer. Since it is followed a constrained market with a minimum bid size, the model checks if the available power is larger or equal to the minimum bid size. This minimum bid size (i.e. 0.2 MW or 200 kW) needs to be respected, and since the model is performed in only five batteries, the model needs to rescale the quantity to find the actual power aggregated.

$$Tot\_Agg\_P_{TR} = \frac{houses_{agg}}{Batt_{sim}} * Agg\_P_{TR} \tag{4.43}$$

Where: $Tot\_Agg\_P_{TR}$ is the total power aggregated by the houses that are in the aggregation, $houses_{agg}$ is the number of houses aggregated, $Batt_{sim}$ is the number of batteries in parallel simulated in the model and $Agg\_P_{TR,up}$ is total power aggregated considering the number of batteries that are in the model.

This total power aggregated for tertiary could be for upward or downward services. The condition of minimum bid size is the first constraint.

$$Tot\_Agg\_P_{TR} = \begin{cases} Tot\_Agg\_P_{TR}, & Tot\_Agg\_P_{TR} \geq min_{bid\ size} \\ 0, & Tot\_Agg\_P_{TR} \leq min_{bid\ size} \end{cases} \tag{4.44}$$

After the constraint of the minimum bid, the prosumer still needs to check if it could bid something by comparing the prices. The model bid an only price for all the aggregated unit and follows the same explained on Section 4.3 for the accepted quantities.

For upward reserve, it is followed Eq. 4.21 and in the case of the downward reserve, Eq. 4.22.

After that, these constraints are verified, the model follows the same strategy to choose between the upward and downward reserve offered in the direction to avoid SoC saturation in the next 4 hours. Everything explained above is part of the controller of each prosumer.

Therefore, each prosumer will have their total power requested ($P_{req,TR}$) to their batteries. This total power is requested to the batteries and in the same way was done for the previous cases, it is found the $P_{real,AC}$ provided by the batteries. For discharge process the model follows Eq. 4.6, 4.8,4.10 and 4.11 whereas for charge process Eq. 4.7, 4.8, 4.9 and 4.11.

By knowing $P_{real,AC}$ for all the batteries of the prosumers, it is followed the same strategy as before in which priority is given to self-consumption and it is computed how much tertiary energy is available in each prosumer following the procedure of Section 4.3.

After the model has the total real tertiary energy bid by each prosumer, it is possible to compute the total energy real available in the aggregation.

$$Tot\_Agg\_P_{real,TR} = \sum_{i}^{n(users)} P_{real,TR,i} \tag{4.45}$$

Where: $Tot\_Agg\_P_{real,TR}$ is the total real aggregated power for tertiary reserve and $P_{real,TR,i}$ is the individual real tertiary of each prosumer.

Since the aggregator has the total real power aggregated for upward and downward services, then the aggregator checks again the constraint of the minimum bid size.

$$Tot\_Agg\_P_{real,TR} = \begin{cases} Tot\_Agg\_P_{real,TR} \geq min_{bid\ size} & ,awarded \\ Tot\_Agg\_P_{real,TR} \leq min_{bid\ size} & ,no\ awarded \end{cases} \tag{4.46}$$

This $Tot\_Agg\_P_{real,TR}$ is the one awarded on ASM, and the individual $P_{real,TR}$ per hour is the real tertiary $E_{real,TR}$ accepted by each prosumer that is used on the tertiary prediction model.

Loss of Regulation (%) is computed in the same way that was computed on the unconstrained case, and the share of the penalty is divided among the prosumers.

4.5 Economic Model

The economic evaluation is the fundamental tool that embodies economic procedures to analyze the effectiveness of the project and the feasibility of its investment. The duration of the investment is fixed to a defined period.

An economic analysis is carried out to assess the profitability of the battery purchase on different case studies. It is possible to divide the economic variables into two groups: one is related to investment costs: purchase and (eventually) the replacement of the battery; the second is related to the operation. The analysis is based on the tools for assessment of the Net Present Value (NPV).

The economic analysis is made for all the cases, and the cash flow is concerning the reference case.

The main elements of the investment analysis are:

- The initial investment, CAPEX that depends on the nominal energy and power of the battery.
- Operating costs related to the battery
- the yearly net cash flow is always Revenues-Costs, but depending on the study case, it could have more streams inside revenues and costs.
- For this type of system, there is a 50% tax exemption related to the battery investment

Net Present Value (NPV) is expressed as the following equation:

$$NPV = -I_O + \sum_{i=1}^{n} \frac{(R_i - C_i)}{(1+r)^i} + RV \tag{4.47}$$

Where:

- R is the present monetary value of the revenues projected at year i
- C is the present value of the operating costs related to the year i
- Io is the present value of the investment at year 0

- R is the discount rate or the cost of capital
- N is the useful life of the study
- RV is the residual value of the battery

The initial investment of BESS is as follows:

$$C_{inv}[k€] = k_e * E_n[MWh] + k_p * (P_n[MW] - E_n[MWh] * 1\ h) \tag{4.48}$$

Where:

- C_{inv} represents the CAPEX of the battery
- k_e represents the Energy-Related Cost
- E_n Nominal energy of the battery
- k_p represents the Power-Related Cost
- P_n Nominal power of the battery

This formula comes from the elaborations in the report [105] and represents a long-run cost approach for the batteries since prices will still be decreasing.

For the operating cost:

$$Op_{cost} = k_{op}\left[\frac{€}{MWh}\right] * E_n[MWh] \tag{4.49}$$

Where k_{op} represents a factor of the operating cost related to the battery

Analyses and comparisons between the different regulating strategies will be based on the NPV values break-even points. Different battery models will give different battery life estimation, and this will affect all the economic variables. A State of Health (SOH) model developed in Politecnico di Milano [106] is used to compute battery life as a function of average c-rate of operation.
In case the battery life finish before the study of profitability, the battery should be replaced, and this is an additional cost, thus reducing the profit of the prosumer.

Replacement costs at the end of battery life will be a fraction of the total investment cost since it should be only changed the batteries because the other elements of the BESS (i.e., connectors, inverter) usually have a longer life.

$$Rep_{cost} = k_{rep} * C\ inv \tag{4.50}$$

Where:

- Rep_{cost} is the replacement cost
- k_{rep} is the factor of replacement
- C_{inv} Initial investment cost of the battery

In the case in which the Horizon time of the study is lower than the battery life, there is an additional value of the battery investment. This value is known as the residual value of the battery, and it is calculated as it follows:

$$Residual_{life} = Batt_{life} - Horizon_{time} \tag{4.51}$$

By knowing the residual life, it is possible to compute the residual value (RV) to the NPV,

$$RV = \frac{C_{inv}}{Batt_{life} * Residual_{life}} \tag{4.52}$$

Behind-the-meter Case:

In general, for the cash flows, it is followed the simplified method of dedicated withdrawal to producers for the marketing of the electricity produced and fed into the grid, active from 1 January 2008 [107].

It consists in the transfer to the GSE of the electricity introduced into the network by the plants that can access it, at the request of the manufacturer, and as an alternative to the free market, according to principles of procedural simplicity and applying market economic conditions.

For this reason, the Dedicated Withdrawal configures a type of indirect sale, which allows the energy producer to rely on a certain buyer and clear and predetermined sales prices, without having to resort to direct contractual agreements with any third party buyers on the free market.

The economics streams for the behind the meter are:

The variation in energy injected will likely cause a negative impact with respect to reference case since with are decreasing it with relation to the case reference

$$Energy\ Injected\ revenue \left[\frac{€}{y}\right] = \Delta E_{inj} * P_z \tag{4.53}$$

Where:

- ΔE_{inj} is the change on injected energy with respect to the reference case
- P_z is the zonal price

Energy withdrawn should be a cost, but because in this case study, there is a decrease (because prosumers are self-consuming more), then there is a positive impact with respect to the case reference.

$$Energy\ withdrawn\ cost \left[\frac{€}{y}\right] = \Delta E_{with} * C_{bill} \tag{4.54}$$

Where:

- ΔE_{with} is the change in withdrawn energy with respect to the reference case
- C_{bill} is the cost of the bill

The tax relief will be reimbursed in 10 years 50% of the Capex,

$$Tax\ relief\ yearly\ [\frac{€}{y}] = C_{inv} * \frac{0.5}{10} \tag{4.55}$$

Market case: behind-the-meter and flexibility services provision

For the unconstrained case, it is followed the same streams that the behind the meter, but there are some additional revenues and cost related to the services sold in ASM.

The additional revenue is the total remunerated of the Upward energy, and since this price is paid as bid, it is not a constant value.

$$Up_{revenue}[€] = \sum_{j}^{n} Up_{energy,sold,j}[MWh] * Up_{price,j}[\frac{€}{MWh}] \tag{4.56}$$

Where:

- n is total hourly bids in one year.
- $Up_{price,j}$ is the hourly price paid.

The additional cost is the total of the downward energy

$$Dn_{cost}[€] = \sum_{j}^{n} Dn_{energy,sold,j}[MWh] * Dn_{price,j}[\frac{€}{MWh}] \tag{4.57}$$

Where:

- n is total hourly bids in one year.
- $Dn_{price,j}$ is the hourly price charged.

As already mentioned, if the percentage of LoR is greater than a threshold, there are penalties to pay. The economic penalty related to LoR is not constant because it depends on the Energy non provided of each simulation but in general, is:

$$Penalty\ [€] = k_{LoR\_T} * E_{non-provided} \tag{4.58}$$

Where:

- k_{LoR_T} is the economic penalty related to the energy non provided on tertiary [€/MWh]
- $E_{non-provided}$ is the energy loss in regulation as already explained in previous section [MWh]

Additional to this penalty, on the side of the prosumer it is also consider an imbalance for DAM, in the case there is a poor management of the battery and the batter is outside the limits of saturation of SoC.

$$Imbalances\ [€] = k_{LoR\_SC} * E_{imbalances} \tag{4.59}$$

Where:

- k_{LoR_SC} is the economic penalty related to the imbalances on self-consumption [€/MWh]
- $E_{imbalances}$ is the energy imbalance [MWh]

Aggregated case: the constraint of the minimum bid size

For the aggregated case, it is followed exactly the same concept of the market unconstrained, but with the difference that in this case there is an additional intermediate that is the aggregator, so how much profit will be earned or the cost associated will be first a share of the profit and then it will be divided into how many users are aggregated.

Chapter 5 Data Acquisition

Since the purpose of this study is to show recent and real behavior, data acquisition is of huge importance to the simulations. The development of the load and PV profiles used in this study are explained in the following paragraphs. All the assumptions elaborated for this data are explained in Section 5.1 and 5.2. Whereas section 5.3 describes a simplified machine learning method to forecast load and PV data. Since the model is not only focused on the technical but also on the economical part, it is important to consider the economic data, and Section 5.4 and 5.5 provide a description of the decisions taken for this.

5.1 Domestic Load Profiles

Data from the European *Micene project* (2002) [108] have been used to develop the load model. The project Micene represents the continuation of the actions undertaken with the Eureco project. Thanks to this project, the results of monitoring campaigns of electricity consumption of 400 households in Europe, 110 of which in Italy, were widely disseminated. The considered users in Italy were 110 families, resident in the regions Lombardy, Lazio, Piedmont, Puglia, Marche with an average number of members equal to 3.69 per household (two people in 9% of the families, three people in 34%, four people in 43% and five people in 14%). Since the *Micene project* considered only some household appliances, hence, to shape other household consumption sources, other data have been collected to develop a realistic load profile.

The model assigns to each unit a different number of components through a selection using random numbers and CDFs (Cumulative Distribution Functions). These components can vary between three and five (houses with one or two people are not considered to avoid excessively small loads). Then the model creates the fleet of appliances, which then produces the consumption profile of each user.

The idea was first to use the average power used by a given appliance in a particular quarter of an hour provided to determine the correspondent probability of using that appliance in the same quarter of an hour. Meanwhile, for those appliances that work with continuous cycles, the probability that the cycle starts in a precise timeframe was evaluated. The model associates each user the *probability of ownership* of a specific appliance and an *efficiency class* parameter. This was done for each appliance, and then the user fleet was created.

5.1.1 Appliances in the Project Micene

Since the functioning of each household appliance differs from the others, different methods and assumptions to compute the appliance consumption were considered.

The appliances considered in the Micene project were the following:

- Fridge & Freezer
- Washing machine
- Dishwasher
- Electric water heater
- Lighting installations
- Television & Personal Computer
- air conditioning

The ISTAT 2014 data [109] allowed to obtain possible *probabilities of ownership* for the most common household appliances, while for the appliances not treated in that document, a probability of ownership equal to one has been assigned, since they are appliances commonly owned by standard families.

The percentages probability of possession obtained from these data were the following:

- Fridge: 99.7% but in the model, it is approximated at 100%, assuming that any house has a fridge,
- Freezer: 24.3%,
- Washing machine: 96.4%,
- Dishwasher: 46.4%,
- Electric boiler 14.4%,
- For the air conditioning, a different approach has been used, since 2014, data do not reflect the current situation (air conditioner sales have significantly increased from 2014). An assumption was made, considering a percentage of 38.6% as the final probability of possession.

Since the project Micene data were out of date, *efficiency class* data were used to build a more realistic fleet of appliances. Considering an average life of household appliances around 7-8 years, the actual fleet of the model should be composed of appliances purchased in 2009-2010. Data about the efficiency class of appliances bought in Italy in 2009 were taken from available online documents about household appliances [110] (the devices whose class is not defined, are taken as class A).

Fridge and Freezer

Although there are some load variations during the day, the power requested by the fridge and freezer has been considered equal to the rated power and constant during the day. A fridge is always assigned to a unit, while for the freezer, the assignment depends on the probability of ownership. A reference consumption for the fridge was obtained from the European directives [111] , and then the power associated with each efficiency class has been computed. The power associated with the freezer was calculated by using a ratio between the freezer and fridge that was presented on the Micene project. No distinctions in consumption were applied for both refrigerator and freezer according to the numbers of users in the family.

Washing Machine

Starting from the data available in [111], it was possible to obtain the average power consumed per cycle by each efficiency class of the washing machine. This appliance consumption profile operates by cycles and not continuously, so it is important to evaluate a starting time per each day. It was assumed 220 washes per year, and the average duration of the washing cycle was assumed 90 min. The model evaluates the probability that the washing machine runs or not during the day considered, and then the starting time is chosen. No more than one cycle per day was considered, and the probability of having at least one cycle per day was related to the number of components of the house [109].

The probability of washing machine usage was determined, starting from the duration of the cycle and the average consumption of the Micene project sample. Summing the average power required in the quarters belonging to the timeslot corresponding to the cycle duration, a series of values for each quarter of an hour directly proportional to the probability of cycle start is obtained. These values are normalized, and through a CFD function and random numbers, the selection of the cycle per each day is done.

Dishwasher

The same approach applied to the washing machine was adopted for the dishwasher with the difference that the dishwasher took into account the dishwasher of only class A as a reference for consumption. As already seen for the washing machine, it was not enough to know the consumption related to the efficiency class of the appliance. Dishwashers operate in continuous cycles, which means that it was necessary to simulate, every day, the quarter-hour washing cycle starts, and to achieve this, Micene data was used.

Electric boiler, lighting, TV, and computers

The situation of these appliances is different from the one above. Appliances like electric boiler, lighting, TV, and computers have a discontinuous operation, and therefore there is not an identification of the time of a cycle.

For example, the model considers that the electric boiler, when used, works at its maximum power (1225 W), simulating a realistic behavior since the boilers usually have a power ranging from 1050 W to 1435 W. Moreover, its consumption profile is based on the power used by the water heaters equal to that used by the users in Micene. Regardless of the size of the family nucleus, there is only one electric boiler in the house.

In recent years, the energy demand required for lighting has changed, and this is due to modern technologies that allow reducing consumption. This aspect has been treated considering a scaling factor in where for each room, the probability of usage is obtained by just dividing the power profile in Micene by the assumed power used in the room. The probability of the light being switched on was calculated, and then the effective power used was computed.

TV and computer consumption profiles are considered discontinuous. The algorithm evaluates the starting time of the operating cycle with the same procedure applied for the washing machine. Moreover, the calculation of the probability of usage was obtained just as in other cases by dividing the power profile in Micene by the actual or assumed power used, for TV and PC, respectively.

Air Conditioning

For this appliance, a model was defined and considered the profile of appliance usage taken from Eureco project data and the amount of hour per day in which the air conditioning works. An algorithm capable of providing the quarterly air conditioning consumption of a single user was developed and was based on a profile of usage taken from Eureco. The number of devices assigned to each unit was related to the number of components: one for units with a number of components lower or equal to three, two for the others. The model assigns an air conditioning system of 1000 W to large rooms and one of 790 W to small rooms. The probability of usage was randomly selected, and the consumption was obtained.

5.1.2 Appliances not in Micene

Other appliances not treated in the Micene project have been modeled: traditional electric oven, cooker hood, microwave oven, tumble dryer, vacuum cleaner, iron, and hairdryer. As far as these appliances, there were no available real measures to extract the probability curves. Not to mention also, the small devices are not considered (i.e., mobile phone charger). However, since their consumption is very small and spread during long time frames, they were substituted by a constant low power request distributed throughout the day.

Regarding cooking appliances, the curve which describes the probability of a dishwasher to start its washing cycle was taken as a reference to assess the time in which cooking appliances are used. In particular, considering that Italians, on average, spend 35 minutes preparing lunch and dinner [112] and about 55 minutes to consume it, it was assumed an average time of 90 minutes before the dishwasher starting time.

For the electric oven, the average duration of a cycle was set to 30 min, and the power consumption was taken equal to 2.4 kW and 2 kW for A and B efficiency classes, respectively. The average consumption is defined with the usual method (CFD and random numbers) starting from the profile obtained by shifting the dishwasher, starting the probability curve, and considering the average consumption of the appliance and the number of household components. Considering the cooker hood, minor attention was given due to its low power consumption, whereas for the microwave consumption is related to the number of components, the average power is considered (416.67 W) as well as an average cycle duration equal to 5 minutes.

The tumble dryer is surely a high energy-consuming appliance, and it is notable to say that washing machine probabilities of usage were strictly related. The power consumption was related to the efficiency class: 0.98 kW for class A, 1.15 kW for class B, and 1.28 kW for class C devices. For the hairdryer, the same logic was applied, but in this case, a probability vector related to the electric boiler switching on is normalized and multiplied by the number of hair dryer daily uses, which depends on the number of components. Average power of 600 W was considered. As regards the vacuum cleaner and the iron, a probability distribution that considers the very low likelihood of using them during the night was generated. Also, in these cases, the average usage per week and cycle duration was considered.

5.1.3 Production of the Load Profile

Once the fleet of household appliances was created for each user by using all the assumptions aforementioned, the model sets a limit for the electricity meter. The *maximum power at the meter* for each unit was equal to 3 kW if at the user is associated with a number of maximum three components and to 4.5 kW in the case of four or more components. An "artificial intelligence" was also implemented not to exceed 110% of the power at the counter. It simply shifts the use of the appliances forward or backward in time to avoid overloading. With all the constraints mentioned, the Load profile was created for the number of 100 users.

5.2 PV Power Profile

Weather data (i.e., irradiation data) was procured from the website of ARPA (Regional Agency for the Protection of the Environment) of the Lombardy region, for both years 2016 and 2017 [113] to derive the PV profiles for each user. Fifty-six annual horizontal solar radiation profiles were collected from all the provinces of Lombardy, in .csv format, with 10 min intervals. The first step was the removal of defective samples communicated by the weather stations. These measures have been substituted with the previous one, if valid, or if some data were missed, they have been assigned using linear interpolation.

5.2.1 From Irradiation data to PV Power

Production from a real Photovoltaic model will have losses due to geometrical factors since it depends on factors such as tilt angle, the azimuth angle, the zenith angle, by material-dependent factors such as absorptivity and reflectivity, as well as by the distance between the nominal operating cell temperature, NOCT, and the standard conditions temperature. If the effect of temperature is neglected, it is possible to assume that the production of the PV panel is directly proportional to the horizontal radiation G_{hz}.

This horizontal radiation G_{hz} provided by the data has been transformed from kW to per-unit values, to favor their utilization in a Monte Carlo algorithm and to provide a realistic number of equivalent hours (h_{eq}) of operation it has been calculated:

$$h_{eq} = \sum_{h} \frac{G_{hz,h}}{\max{(G_{hz})}} \tag{5.1}$$

The available data were thus collected and imported into a timetable data-class, which was re-sampled into a time vector with $\Delta t = 15$ min for easier manipulation. The profiles were arranged in a structured data-class.

Next, all PV profiles were re-scaled to obtain a number of equivalent hours of operation within the range (1100 - 1300) hours. The result is a realistic PV plant profile.

After PV data was imported, a PV system was associated with each user of the aggregate. An annual load request obtained from the year 2016 was used as a reference [114]: the minimum power of the panel was determined as the power needed to cover this load, considering 1200 equivalent hours. Then the system was oversized, rounding up the minimum power by steps equal to 0.5 kW.

5.3 Simplified Machine Learning Method

Considering that the model needs predictions, as already was explained in Section 4, it was taken the original data for Load and PV profile of 2016, to provide a forecast for 2017. The forecasted values for Load profiles were an average of a set of users of the load data in 2016 that were having the same consumption. Instead, for the predicted PV Power, was used machine learning on *Spyder(Python 3.7)*, by training and testing a set of data related to the PV power with a standard linear regression from the scikit-learn library [115]. This dataset was composed of the PV power, the temperature, the consumption, and the radiation of the year 2016. With this data was created a model with high accuracy, and then these values were predicted for 2017 by using the radiation of 2017. Forecasted and Real data show similar numbers but no equal (Figure 5.1), which gives a good opportunity to use them as a prediction since not all that is expected, usually is true.

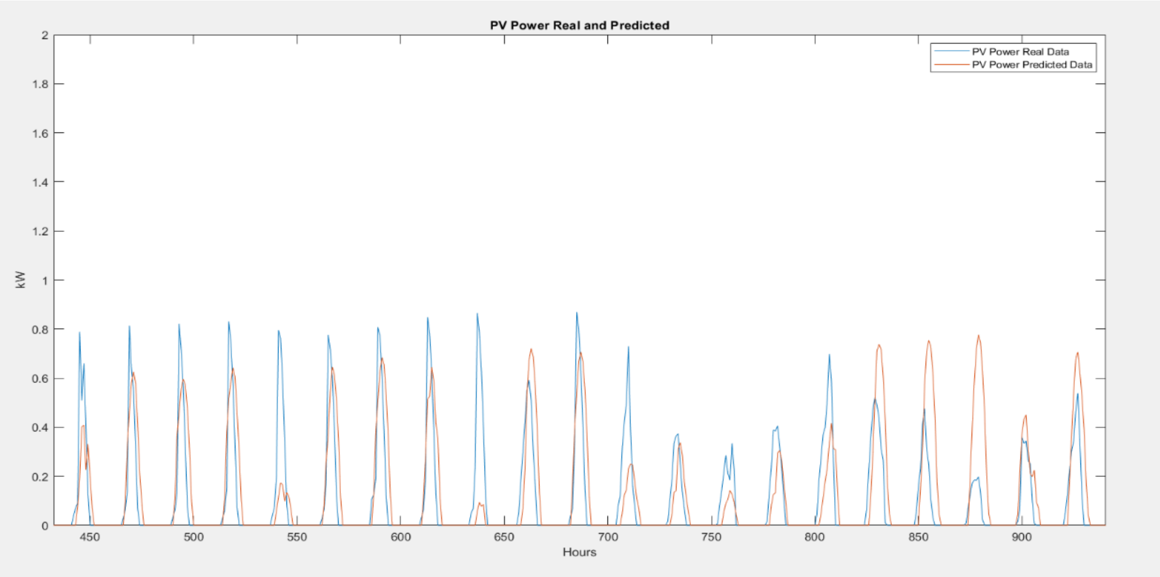

Figure 5.1 Example of correlation of Real and Forecasted PV Power

5.4 Input Data to the Controllers

The data used for the computation of the main energy flows are hourly PV data (Figure 5.2) and hourly load data (Figure 5.3) from typical users. The users have a Nominal Power of 2 kW, and the maximum consumption measured is nearly also 2 kW (in Italy, the contracted power for domestic users is usually 3 kW) [116] .

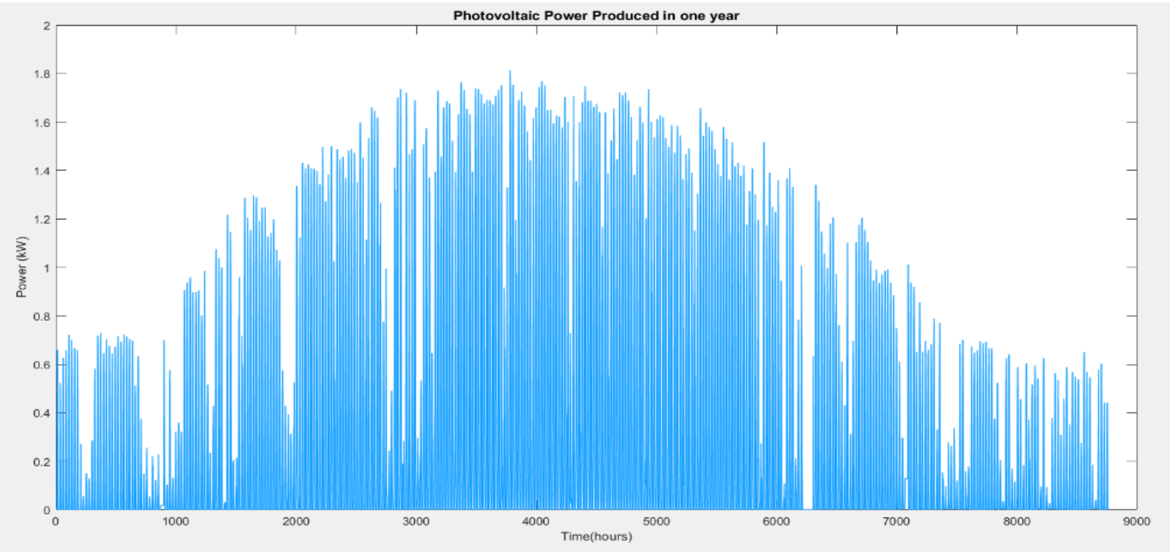

Figure 5.2 Example of PV Power produced in one year

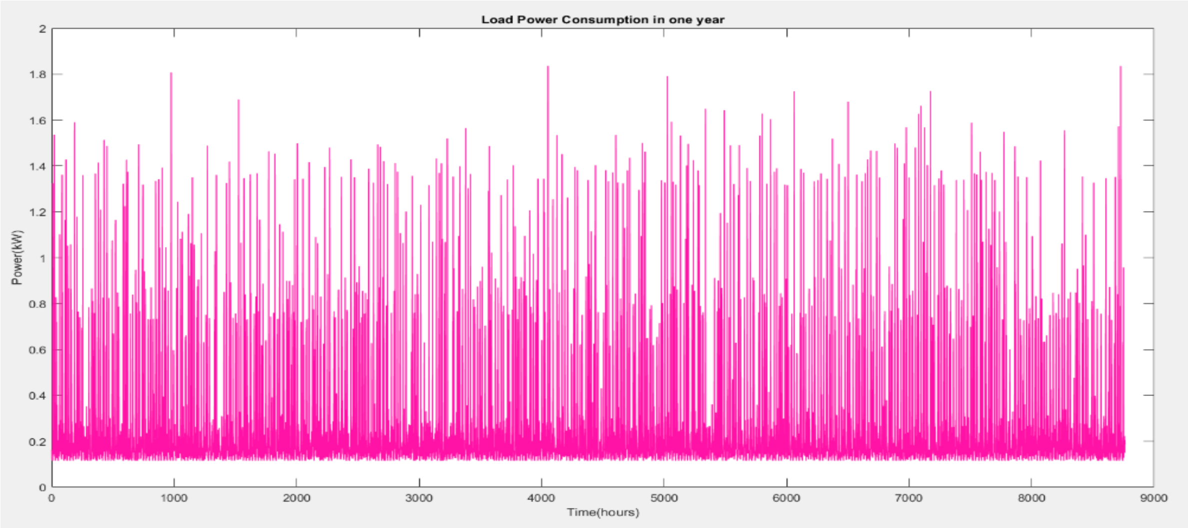

Figure 5.3 Example of Load Consumption in one year

On the controller of the behind-the-meter and the unconstrained case it is used load and PV data from section 5.1 and 5.2 of only one prosumer, instead for the forecasted data of the prediction for tertiary in the unconstrained, it is used the data developed in section 5.3.

For the aggregated case, the model adopted five users that have similar real profiles on PV (Figure 5.4) and Load Power (Figure 5.5). On the other hand, the forecast data is developed for the five users following section 5.3

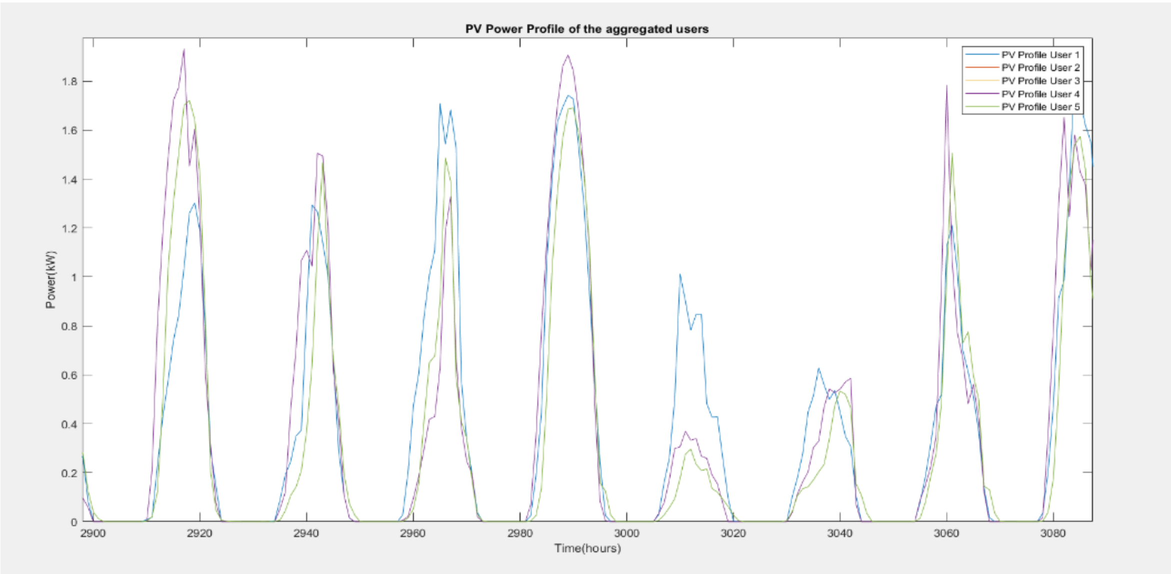

Figure 5.4 PV Power Profile of the aggregated users

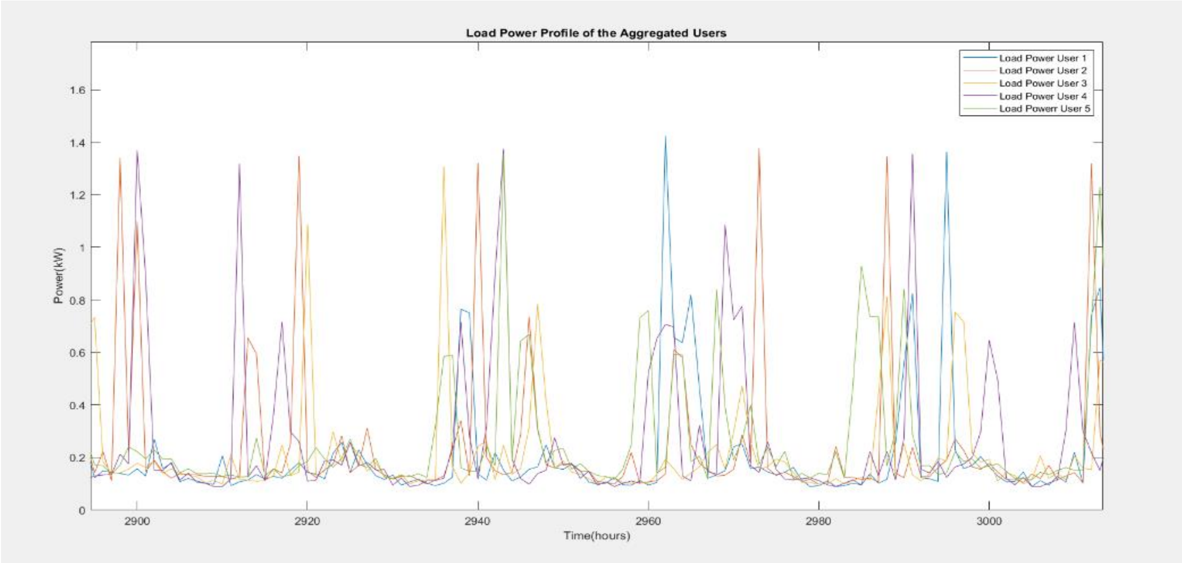

Figure 5.5 Load Power Profile of the Aggregated Users

5.5 Market Data

Considering that it is needed to simulate a market on the model, it has been used some prices to bid and other prices to simulate the Italian Market, which thresholds for acceptance of offers on ASM.

For the bid of the prosumer and aggregator, average prices from GME website for the year 2019 [117] have been adopted. Since prices bid on the market shows a repetitive behavior during the years, it has been assumed that this average price is the same for the bidding process. It could be noticed on Figure 5.6 and Figure 5.7, that the prices for upward are higher than the ones on downward reserve. Upward is a profit and since the prices for downward are not high, then the profit could have not significant decrease.

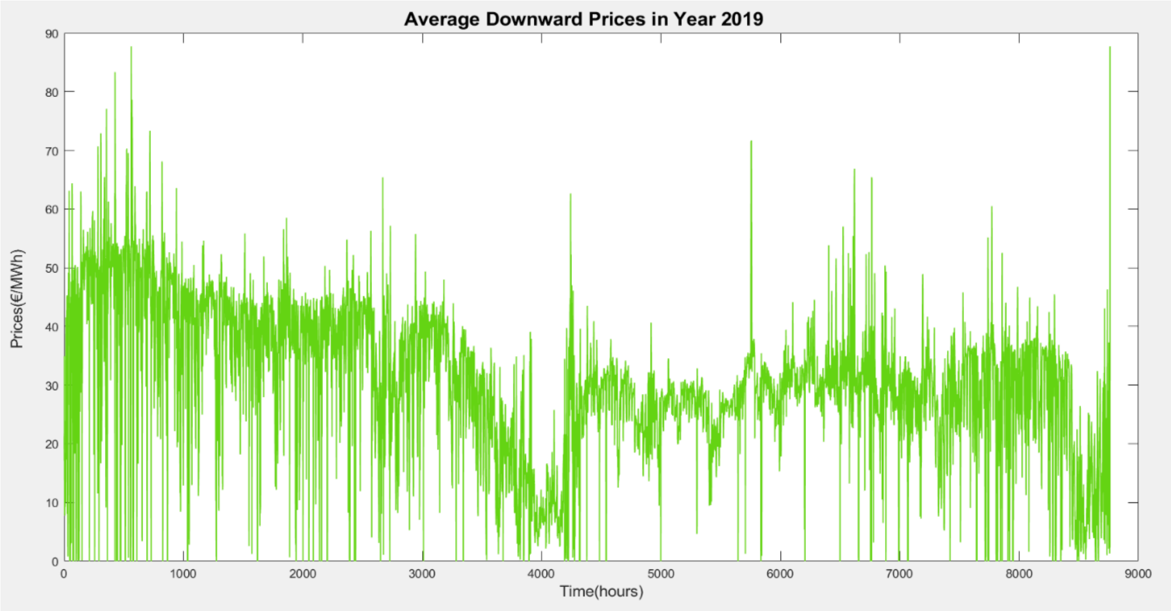

Figure 5.6 Average Downward Prices in 2019

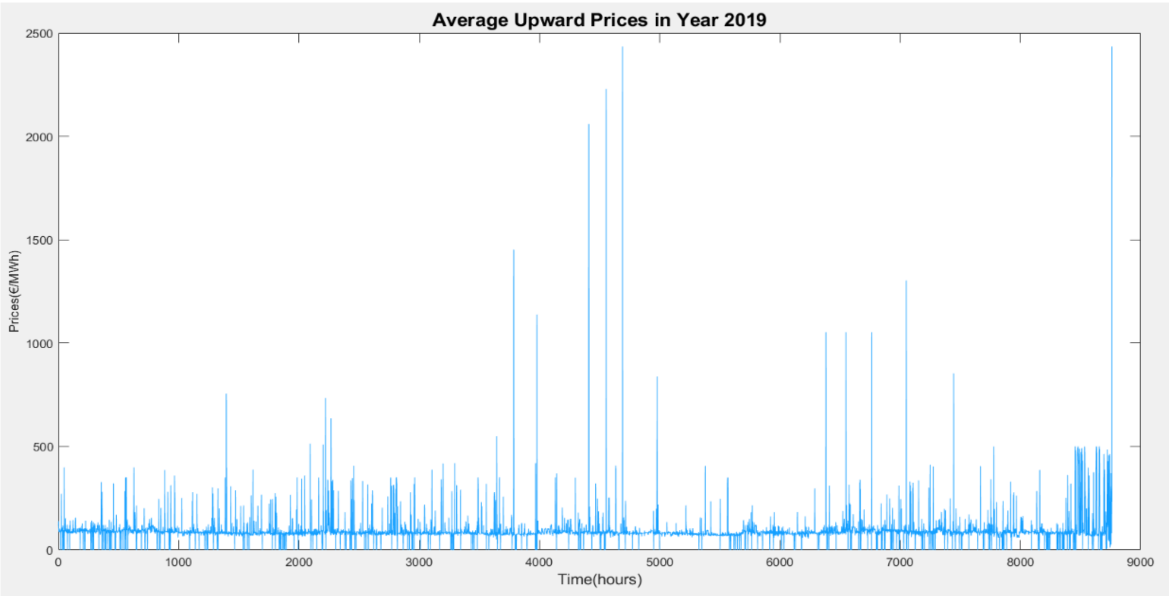

Figure 5.7 Average Upward Prices in 2019

For simulating the market model, it has been assumed a normal distribution by taking historical data of maximum hourly awarded prices for upward reserve and the minimum for downward reserve.

Due to several factors(i.e., market scenario, the quantity available for ASM) [118], ASM does not show repetitive behavior with the prices. Therefore, the prices for ASM were modeled by using excel to obtain random prices to provide a more realistic market.

It was used the following function on excel, which returns the price given a probability.

$$Random\ Price = NORMINV(probability, mean, standard_{dev}) \tag{5.2}$$

$mean$ is the arithmetic mean of the distribution and the location parameter and $standard_{dev}$ is the standard deviation of the distribution and the scale parameter.

For the probability, considering that ASM has many constraints, the prices will change randomly, and it has been assumed a random probability. The probability of Eq. 5.2, takes the following form:

$$Random\ Price = \ NORMINV(Rand(), mean, standard_{dev}) \tag{5.3}$$

Rand () will take values between 0 and 1.

For the mean and standard deviation, it has been used data from GME [117] specifically, the minimum price charged for Downward, and the maximum price paid for Upward. It is possible that the model could get negative numbers with Eq. 5.3, then for each service, it has been set some constraints in terms of maximum or minimum thresholds for the prices.

In the case of downward service,

$$\begin{gathered} if\ Random\ Price < 0; the\ random\ price = 0 \\ if\ Random\ Price > 50; the\ random\ price = 50 \\ if\ 0 < Random\ Price < 50; random\ price = random\ prce \end{gathered} \tag{5.4}$$

Min downward price is 0, and the Max downward price is set to 50, to be around the Day-ahead Market.

For the Upward service then,

$$\begin{gathered} if\ Random\ Price < 50; the\ random\ price = 0 \\ if\ Random\ Price > 200; the\ random\ price = 200 \\ if\ 0 < Random\ Price < 200; random\ price = random\ price \end{gathered} \tag{5.5}$$

Where:
Min upward max price is 50
Max's upward max price is 200.

In case the price is 0, it means that no upward regulation was sold for that hour in that zone. Therefore, where the simulated upward price is below 50 €/MWh, then it is set equal to 0 €/MWh, meaning that no upward regulation can be sold in that hour.

5.6 Economic Data

For the investment cost, the values are on the report [105] for currency on dollars. If a conversion is performed, the values for energy and power-related cost are the following: k_e is approximately 400 k€/MWh and k_p is 150 k€/MW. The operating cost factor k_{op} =10€/kWh/y, and for the replacement factor of the battery, it is assumed a k_{rep} =50%. The Cost of Capital assumed is k=2% [119], a typical value for the residential systems.

The economic penalty related to LoR (*pLoR*) is not constant since it depends on the quantity of energy no provided. As a reference, the initial value is based on the constants given by Italian TSO for both upward and downward reserve penalty [120], which is 140 €/MWh, and for the penalty of the imbalances on DAM, it is considered 100 €/MWh.

For the price of injected energy, it was taken the annual average for the Year 2019, and for the study on the North Region of Italy, the value is approximated to 51.25 €/MWh(Figure 5.5) and was published in the annual report of 2019 by GME (Gestore Mercati Energetici) [117].

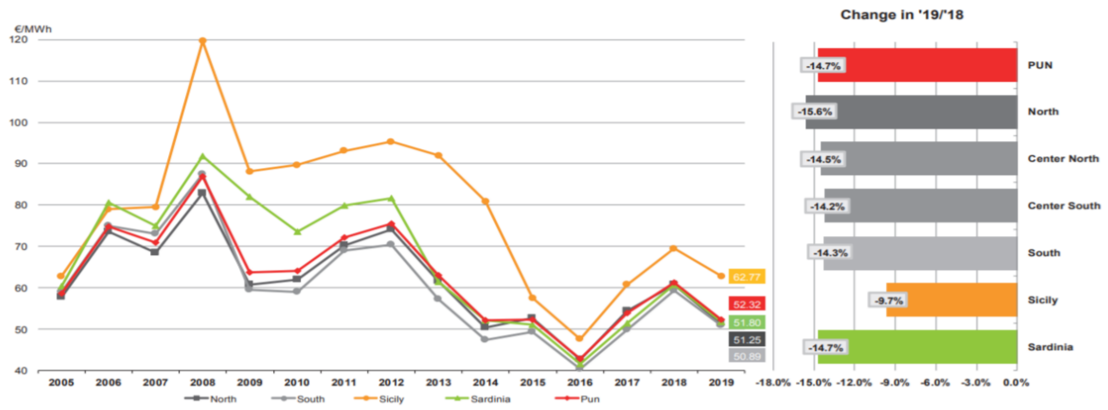

Figure 5.8 Average annual zonal prices in the DAM market [127]

For means of this study, it has been assumed that the withdrawn price is the cost of the bill that is applied to the users. The final price for electricity prices for domestic consumers for 2018 was an average of 20.2 €/MWh [117].

The prices for upward and downward were already explained in Section 4.5

Parameters	**Value**
Horizon time	10 Years
Cost of Capital	2%
Electricity Cost	202 €/MWh
Zonal Price	51.25 €/MWh
Penalty for LoR	140 €/MWh
Penalty for imbalances	100 €/MWh
OPEX Factor	10 €/kWh/y

Table 5.1. Economic Parameters used in the simulations

Chapter 6 Numerical simulations and Results

Since the primary goal of the study is to show that a prosumer at the domestic level can provide benefit to itself (by maximizing the self-consumption and earning money on the market) and to the system (by providing flexibility and reducing the exchange energy with the grid) conjointly with a logic of aggregation, it has been developed models already explained on Chapter 4. The behavior of the model is shown on the results of the simulation for each case in Section 6.1. With these models, a thorough sensitivity analysis was performed, and the parameters studied by each case are explained in section 6.2.
Section 6.2.1 shows the case where the prosumer only has storage and only performs self-consumption. Additionally, in this chapter, it has been developed three other study cases where the focus is on the energy exchanged corresponding to the total sum of tertiary regulation (downward and upward) exchanged to the market and also the energy self-consumed. In section 6.2.2, there is the unconstrained case that proposes self-consumption and participation on the market of a single prosumer. This case where there is not a minimum bid size required acts as relaxation concerning the realistic regulatory framework represented in section 6.2.3, introducing the minimum bid size commonly adopted in the ASM. Thus, the prosumer can only access the market through an aggregator. There is an overview of what happens if the aggregator changes the number of aggregated units. Since the study is to exploit the best for the aggregation, a sensitivity analysis has been proposed on the minimum bid size. Whereas in section 6.2.4, it is provided a comparison of the cases to show the techno-economical outcomes and improvements clearly.

6.1 Results

In the next section, a detailed description of the behavior of the BESS in each of the cases is given. The BESS is sized as follows: 1.5 kW, 4.5 kWh. Instead, the prosumer selected has a contracted power of 3 kW and a rooftop PV plant of 2 kW. The power flows are generally expressed in per unit with respect to BESS nominal power. After the description of the battery behavior, section 6.2 and the following ones will be devoted to the sensitivity analysis. This analysis aims to give technical and economic feedbacks regarding the effectiveness of different sizing and different operations on the market.

6.1.1 Behind-the-Meter Case

In this case, the prosumer has battery storage and only bid on DAM. This means that the battery is only used for doing self-consumption.

From Eq. 4.1, it is known that by having the difference of power, it is possible to see the behavior of the powers on the side of the prosumers. From Figure 6.1 representing the end of February and beginning of March, it could be seen that whenever the prosumer has more Load Power than PV power, then the difference has a positive value: BESS is requested to discharge for that specific time (pink dotted line above zero). In case the prosumer has more PV Power than the consumption of the prosumer, the diagram shows a pink dotted line with negative values. This means that the battery could be charged.

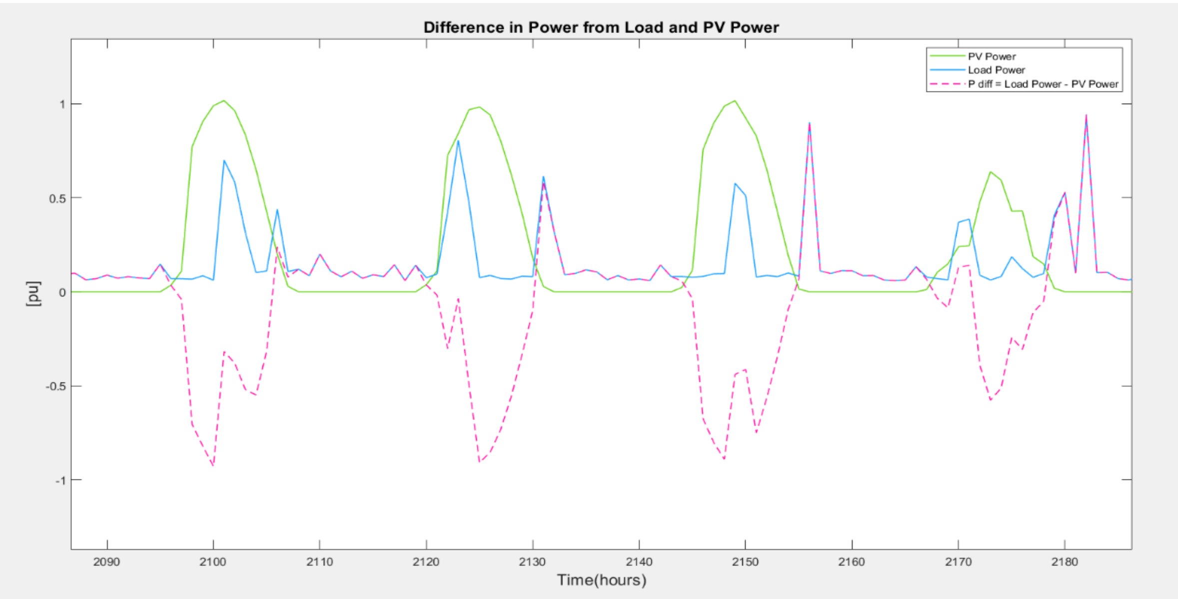

Figure 6.1 Difference in Power between Load and PV Power in the ends of February and beginning of March

From section 4.2.1, in the BESS model, it is not only considered the difference in the power coming from the data of the users but also the auxiliaries' power as pointed out Eq. 4.5. Then the required power sums up the self-consumption needs and the auxiliary contribution. The contribution of the auxiliary is usually a small fraction of what is needed for SC, and it is always positive (it discharges the battery).

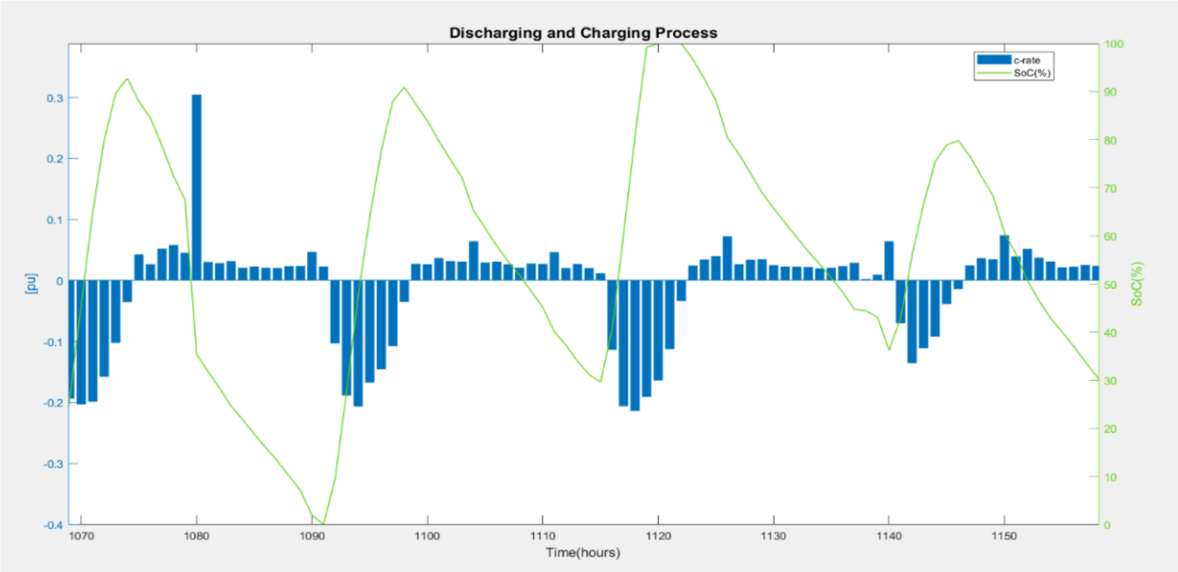

Figure 6.2 Discharge and Charge Process in the middle of February for Behind the Meter Case

From Figure 6.2, it could also be seen how the State of Charge of the battery changes whenever we are requesting to the battery. Around hour 1080, it could be seen that there are many points where there are positive values. This means that the prosumer is continuing to discharge the battery; on the other side, around hour 1120, it could be seen many points with a negative contribution to the battery that charges the battery completely. One very important thing here is that if the prosumer continues having a negative contribution, meaning that has more PV power but reaches 100% of SoC, then there is not enough space to store the energy, so the prosumer injects to the grid, and this is considered as an Imbalance. On the other side, if the prosumer has more positive values meaning that is consuming and continue to consume without having more generation of the PV Power, then the prosumer reach a point where there will not be more energy to use as consumption and then will withdraw from the grid and in the same way as injection this is also considered as an imbalance.

6.1.2 Unconstrained Case

In this case, market participation is introduced along with self-consumption. The prosumer bids everything available to the tertiary reserve without the restriction of the minimum bid. The first thing to do is to forecast how much it is available for tertiary reserve, and for doing this, it follows the self-consumption logic, as explained in section 4.3.2.

To know the total available for tertiary reserve, the model considers the actual SoC, and it could be seen that at higher SoC, the model estimate that there is more available power for upward than downward, and in the case the battery is almost discharged, then the model estimate that there is more available downward than upward as it could be seen on Figure 6.3.

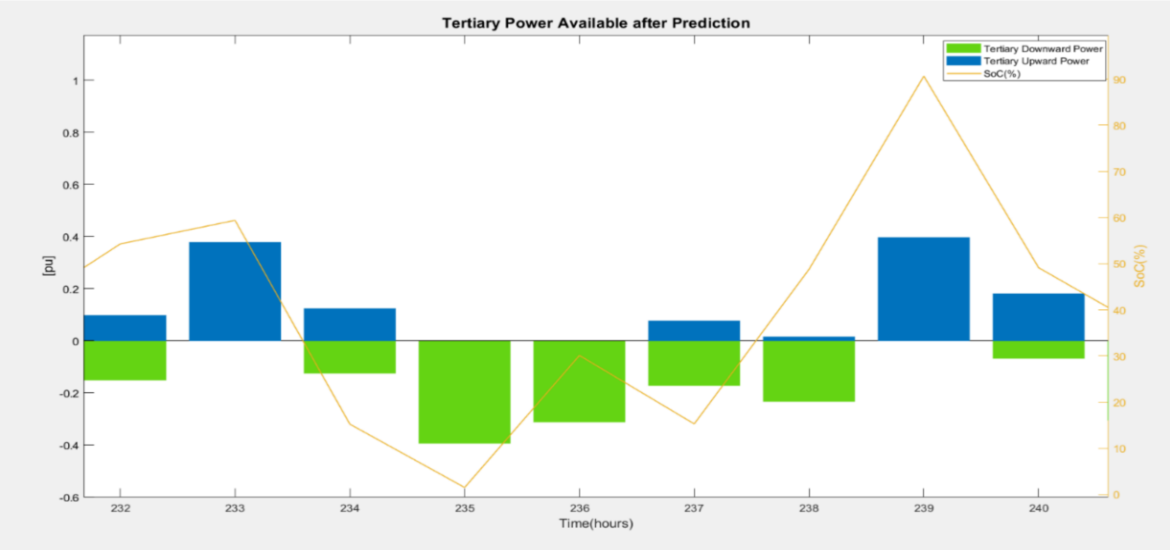

Figure 6.3 Tertiary Power Available after Prediction

In this case, the model considers that there is no restriction on the minimum bid size so that the prosumer can bid all its energy available, but in theory, this is not completely true because, according to the price on the market, the bid could be rejected or accepted. If the prosumer wants to provide an Upward reserve to the market, by following Eq. 4.21, it should be remembered that this available power is only accepted in case the price that the prosumer bid is lower than the one on the market. As could be seen in Figure 6.4, whenever the pink line (the market price) is above the yellow one, as could be seen in around hour 1082, the energy available is accepted, and then it is possible that the prosumer could bid this energy to the Market. It is also possible that the market price is lower than the one the prosumer bid, and in this case, as it could be seen around hours 1071 and 1074, it is not possible to bid.

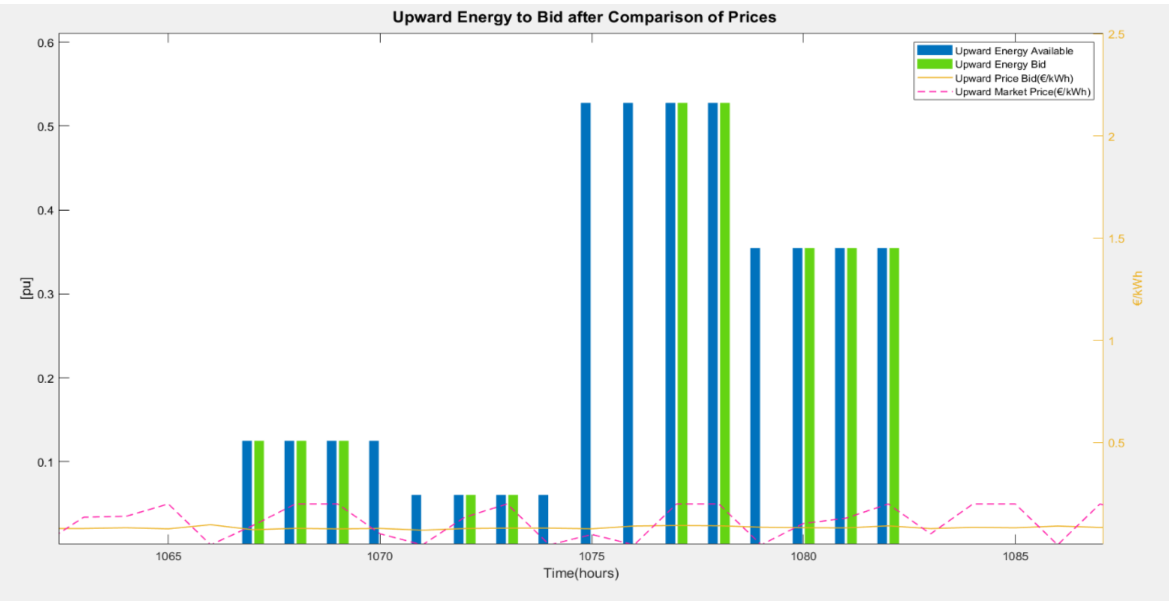

Figure 6.4 Upward Energy to bid After Comparing the Prices

In the case where there is enough available capacity in the battery because it is almost or completely discharged, then it is possible that the prosumer bid for downward reserve, where the prosumer will have energy that is coming from the grid, but this is a cost, and in this case, for the market, it is more convenient to pay less. Different from the Upward reserve and following Eq. 4.22, it could be seen on Figure 6.5 that prosumer is awarded whenever the price offered is higher than the one on the market as it could be seen for hour 92 to 95 where whenever the light line is above the dotted pink one, is always awarded.

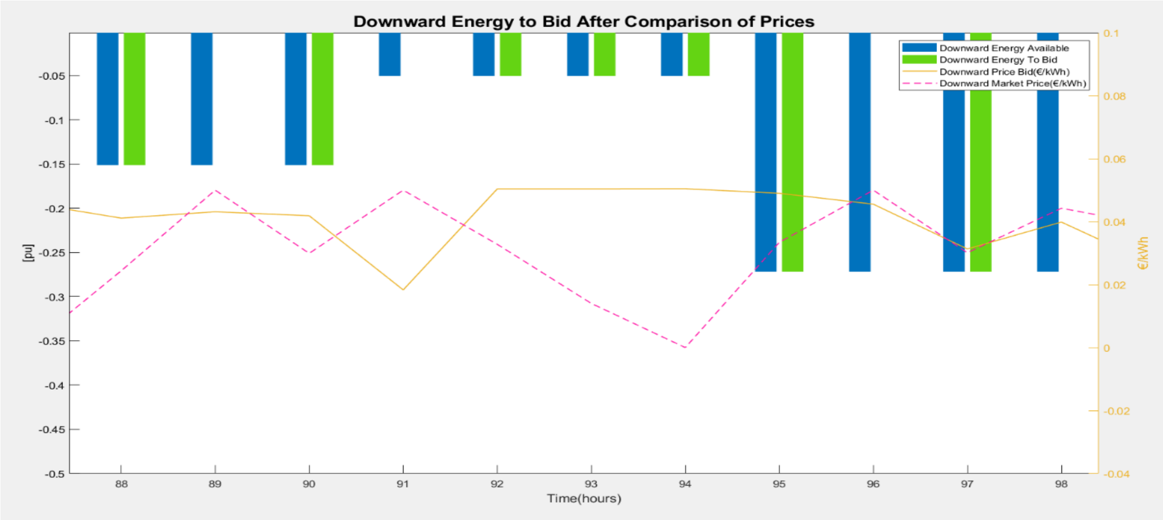

Figure 6.5 Downward Energy to Bid after comparing the prices

All these accepted energies that comply with Eq. 4.21 and Eq. 4.22 could bid on the market. For selecting between upward and downward, it has been developed a strategy already explained on methodology where the purpose is to bid on the market by allowing the battery to keep the SoC far from saturation. Whenever the battery is close to 54%, the prosumer provides upward, and then if the battery is below this value, the model selects for downward reserve, as it could be seen in Figure 6.6.

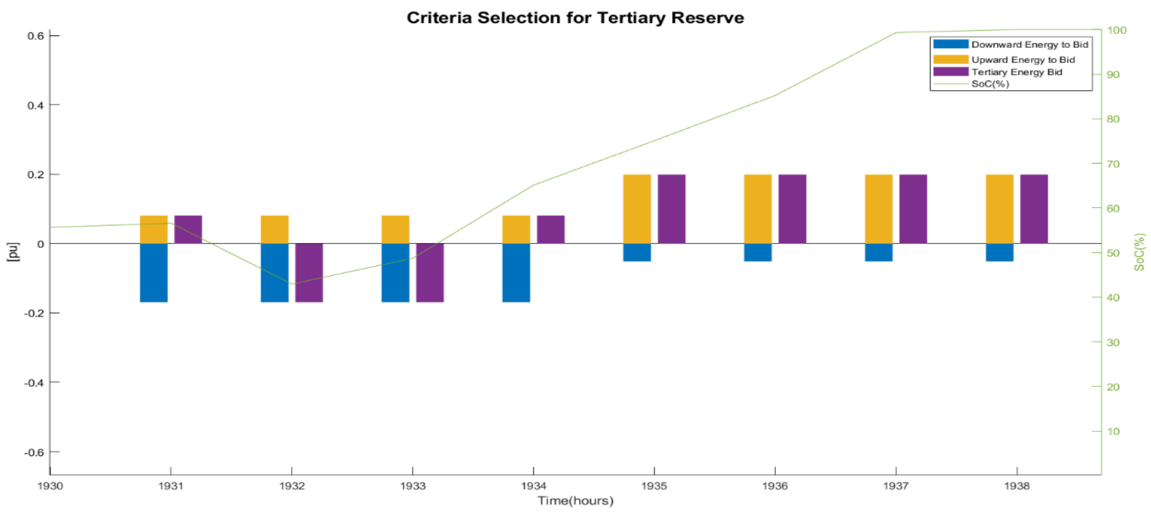

Figure 6.6 Criteria Selection for Tertiary Reserve in Unconstrained Case

$P_{req,TR}$, together with power requested for self-consumption (P_{diff}) give the total power required. Sometimes these two services have different signs, and the SoC is effectively managed, as it could be seen in Figure 6.7. It could be seen around hour 1683 that even if for self-consumption is a positive contribution, the downward tertiary requested is larger than SC, and then instead of the SoC being discharging, it shows the opposite. This behavior also could be seen around hour 1692, where there is more contribution of the PV power than the service of upward, and then the battery gets fully charged.

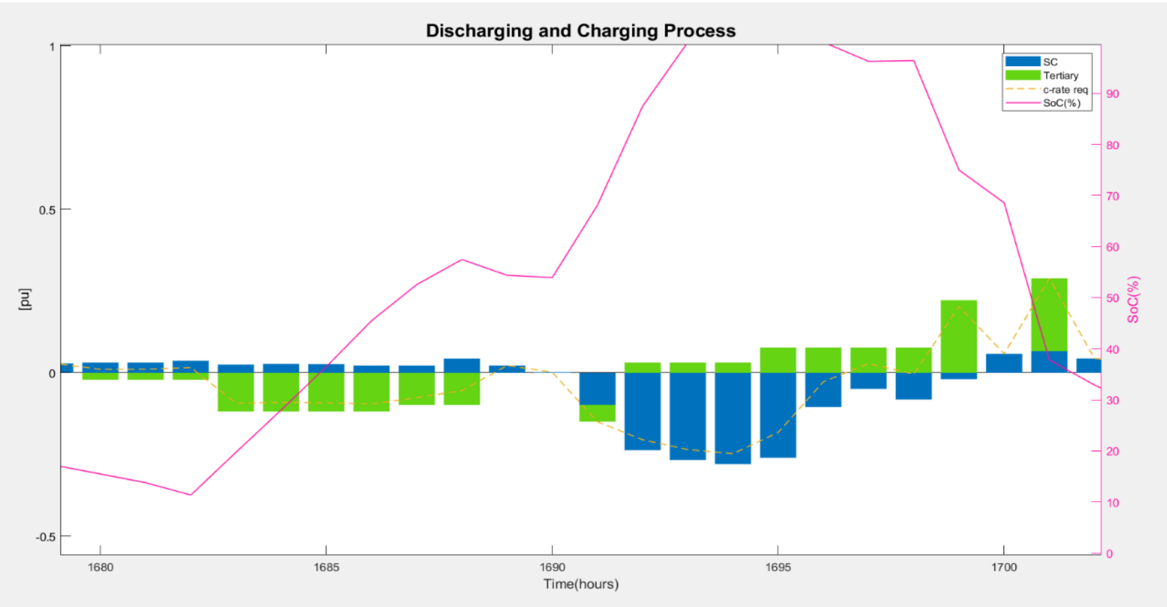

Figure 6.7 Discharge and Charge Process of Unconstrained Case

6.1.3 Aggregated Case

The aggregated case introduces in the market the constraint of the minimum bid size. The single prosumer is inserted in an aggregated unit enabled to ASM via the aggregator. Therefore, it can provide services on the market only if the available power by the aggregated unit is greater or equal to the minimum bid. Then this available energy will have two constraints different from the previous, the minimum bid size and the prices on the market.

The following diagrams (Figure 6.8 and Figure 6.9) show the average available power of a user (green line), and the other side, how much the aggregator does after all the houses aggregated, its available predicted energy as for upward and downward reserve respectively.

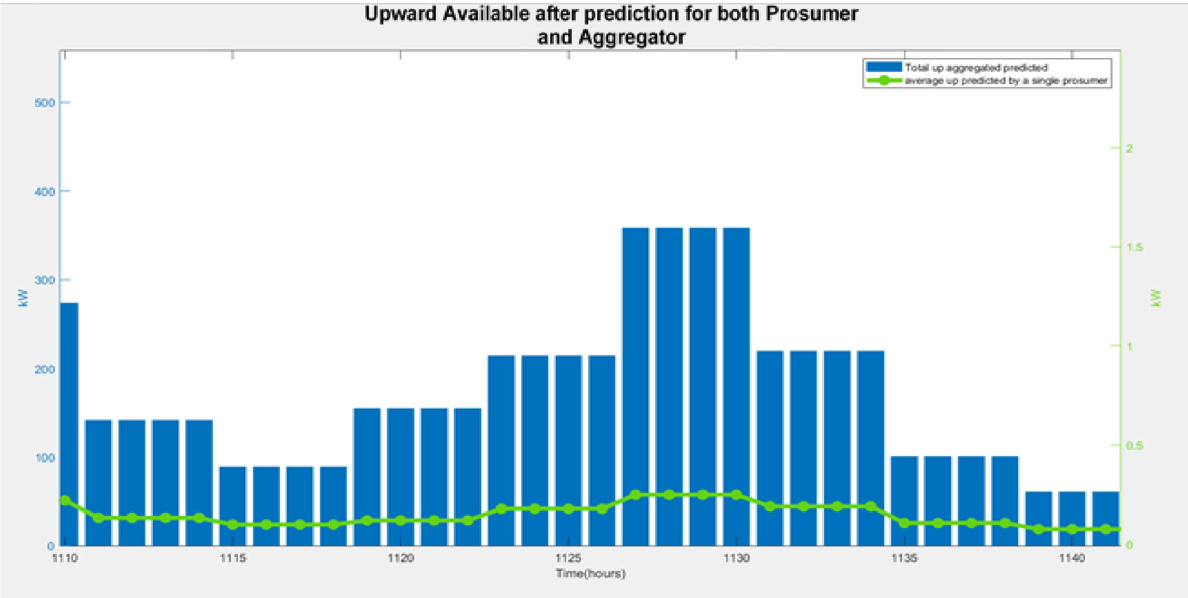

Figure 6.8 Upward Available for prosumer and aggregator

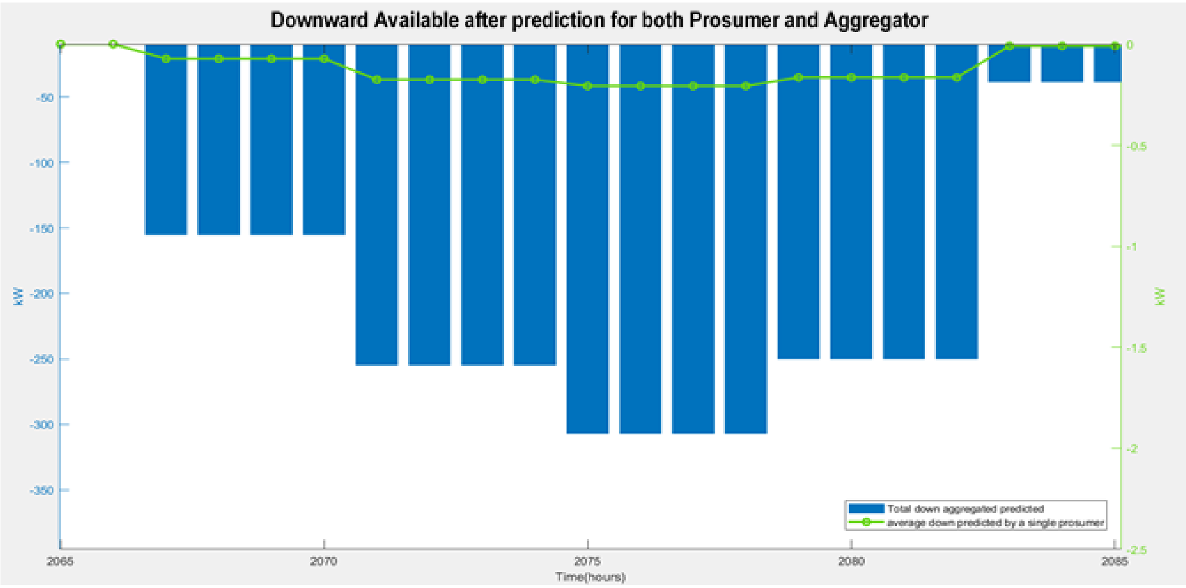

Figure 6.9 Downward Available for prosumer and aggregator

This power is the one that is computed by knowing the actual energy on the battery. Part of these values will not be accepted since they should respect first the minimum bid size, and secondly, the price bid should respect the market conditions.

The aggregator will manage and aggregate all the total power available of each user, and then it will bid this total power with a price on the market. Upward reserve to the market is only accepted if greater than 200 kW, and in the case, the price they bid is lower than the one on the market, as shown in Figure 6.10

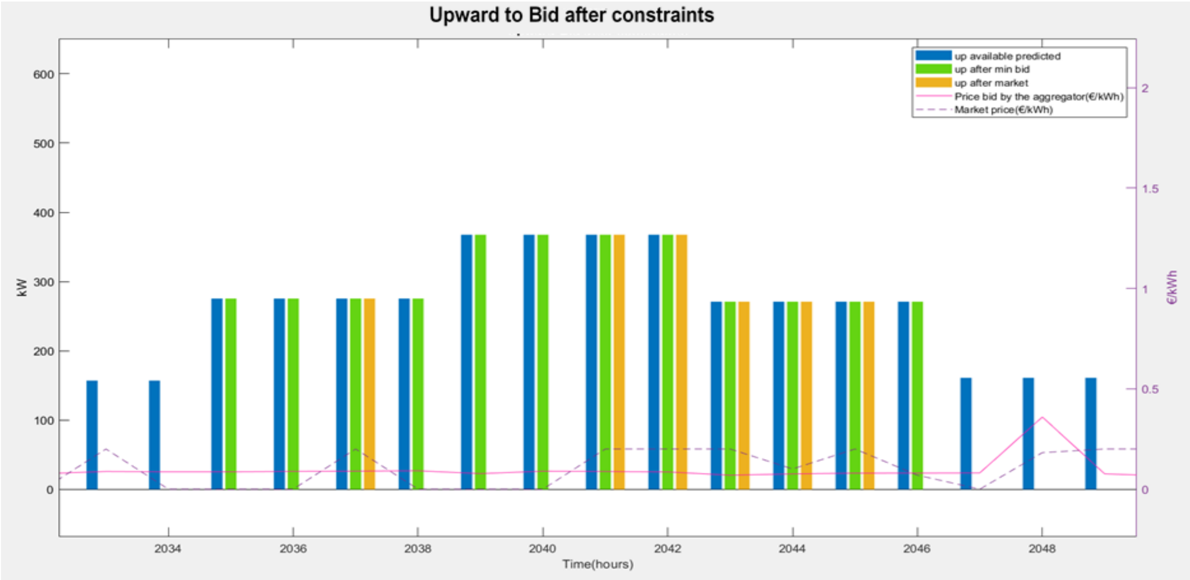

Figure 6.10 Upward Available to Bid after constraints

Downward reserve to the market is only accepted if greater than an absolute power 200 kW, and in the case, the price they bid is higher than the one on the market, as in Figure 6.11.

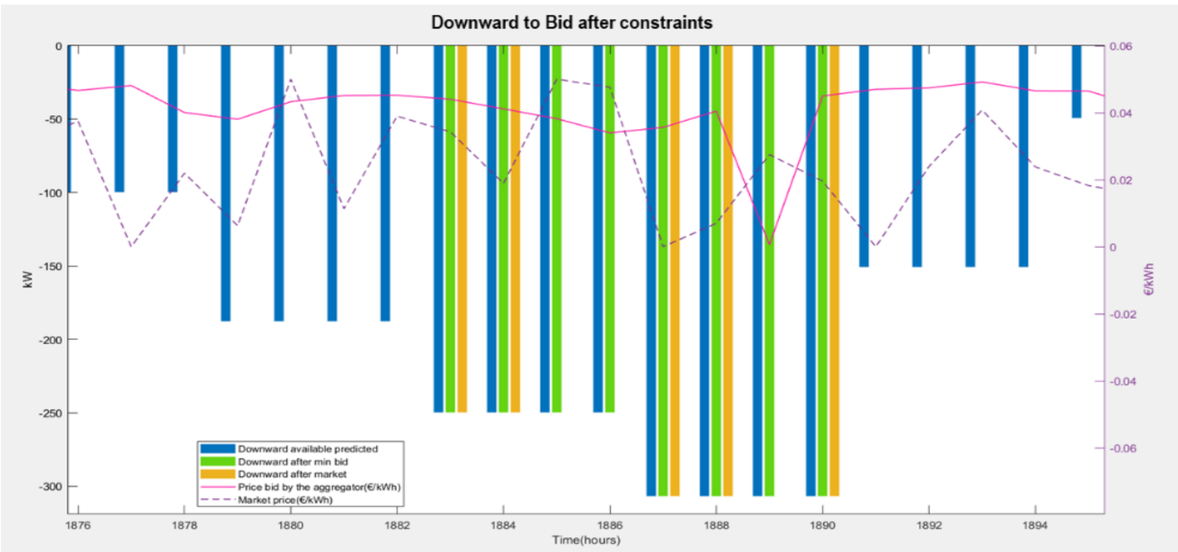

Figure 6.11 Downward Available to bid after constraints

It is followed the same criteria as before, and then this tertiary contribution is requested to the battery(Figure 6.12), but it is expected that it is required less for tertiary than before because of the additional constraint on the minimum bid.

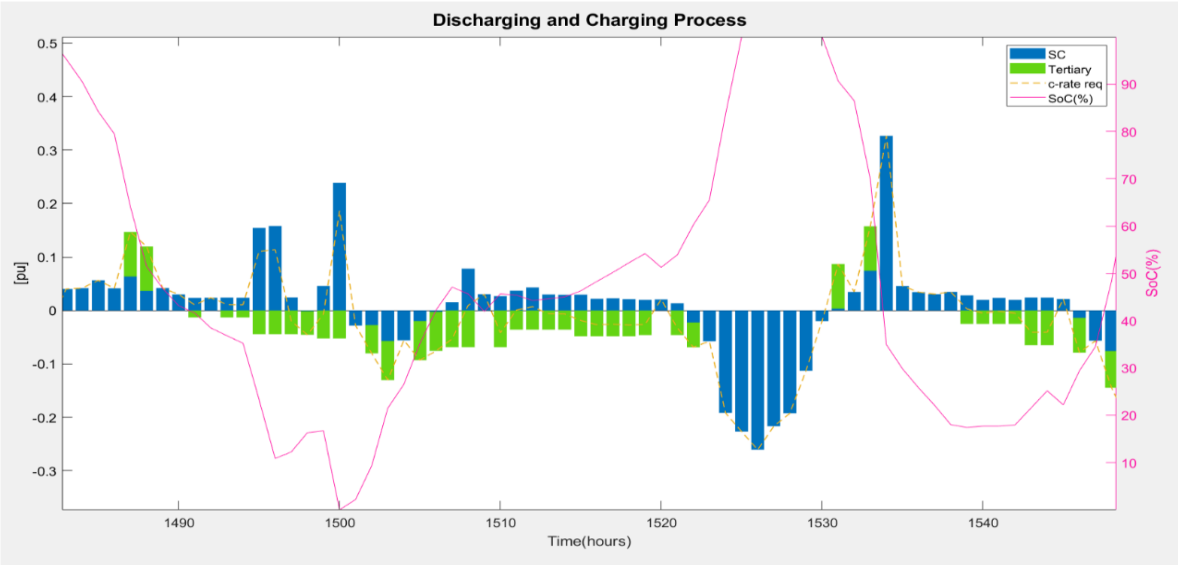

Figure 6.12 Discharge and Charge Process in Constrained Case

Since the tertiary reserve is something that was predicted, it is possible that this prediction could go wrong so in this case, after knowing the real power of the batteries, the aggregator could see that is possible that some of these power is not complying with the minimum bid size and therefore there are not awarded as in Figure 6.13 as shown around hour 1231-1234.

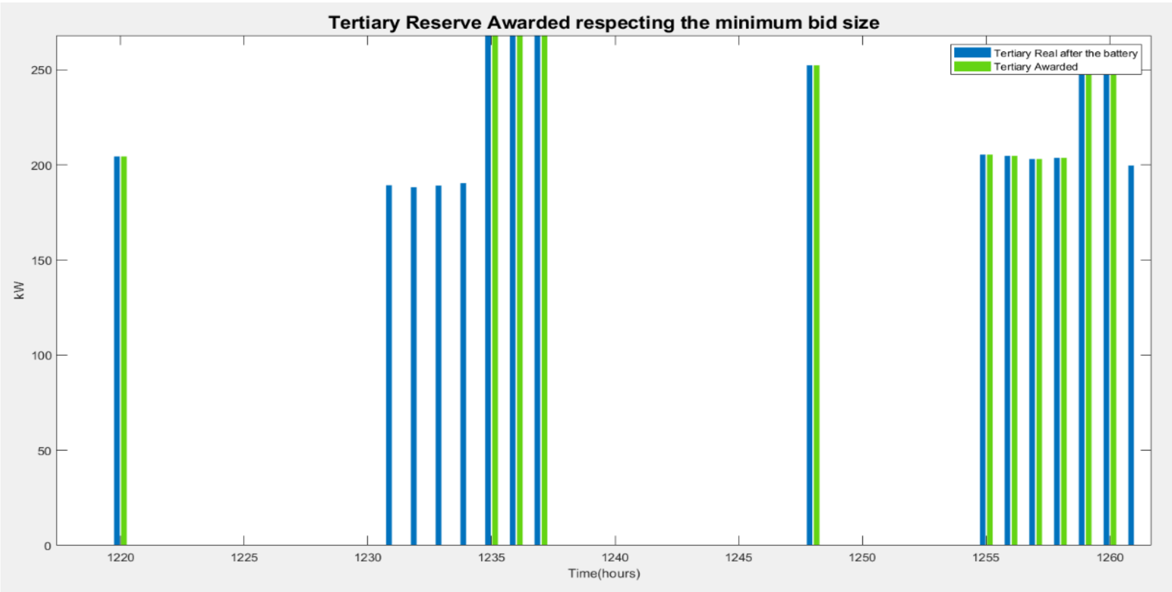

Figure 6.13 Tertiary Reserve Awarded after respecting the minimum bid

6.2 Simulation Layout for Sensitivity Analysis

For each of the cases, it was tested the battery sizing and other parameters to have a large sensitivity analysis. Only focusing on the battery sizing it was studied EPR= 2.5 h, 3 h, 3.5 h, 4 h, and for the Nominal Power of the battery, it was considered P_n= 1.5 kW, 2 kW, 2.5 kW, 3 kW.

It was proposed for only self-consumption to give a sensitivity analysis to study the battery sizing, to identify which is the most advisable sizing to storage.

	EPR(h)			
	2.5 h	**3 h**	**3.5 h**	**4 h**
1.5 kW				
2 kW				
2.5 kW				
3 kW				

Table 6.1. Parameters studies on sensitivity analysis for SC

For the unconstrained case, it is possible to bid all the band available for tertiary reserve. Continues by doing a sensitivity analysis on the battery sizing, but additionally, this case introduced a safety factor as a constant on the study. The values of the safety factor are: 0.25, 0.5, 0.75,1.

	K=0.25			
	2.5 h	**3 h**	**3.5 h**	**4 h**
1.5 kW				
2 kW				
2.5 kW				
3 kW				

Table 6.2. Parameters studies on sensitivity analysis
for unconstrained case

Considering that in the unconstrained case, it is added the constraint of the minimum bid, the analysis is kept with a safety factor of 1. This means that everything available was a potential bid on the market to create an opportunity to have better profits. By focusing on the number of houses, it was examined the quantity that could be of interest of the prosumer, by also changing P_n of the battery and keeping constant EPR.

	EPR(h)=2.5			
	400 houses	600 houses	800 houses	1000 houses
1.5 kW				
2 kW				
2.5 kW				
3 kW				

Table 6.3. Parameters studied on number of houses aggregated

Considering that by having lower houses aggregated, it is possible not to have enough band available for tertiary reserve, since for small prosumers could be a problem to reach the minimum bid size of 200 kW. Therefore, it was done a sensitivity analysis by changing the regulatory framework and analyzing how is affected by keeping EPR and varying the minimum bid with P_n of the battery.

	EPR(h)=2.5			
	50 kW	100 kW	150 kW	200 kW
1.5 kW				
2 kW				
2.5 kW				
3 kW				

Table 6.4. Parameters studied on the minimum bid for aggregation

6.2.1 Behind-the-Meter Case

In this case, the prosumer has the battery storage and bids only on DAM. Still, there are some imbalances to consider in the simulations.

Figure 6.14 shows a perfect distribution of the energy injected. It could be seen that the highest injection to the grid is exploited on the smallest battery with a value of 775.08 kWh. As EPR increases, the injection is decreasing a little, but the most significant change is when Nominal Power increases. A larger battery allows to cope with the PV power during summer for more hours, a saturation of SoC is reached less often than with smaller batteries, and they can significantly increase the self-consumption of a prosumer.

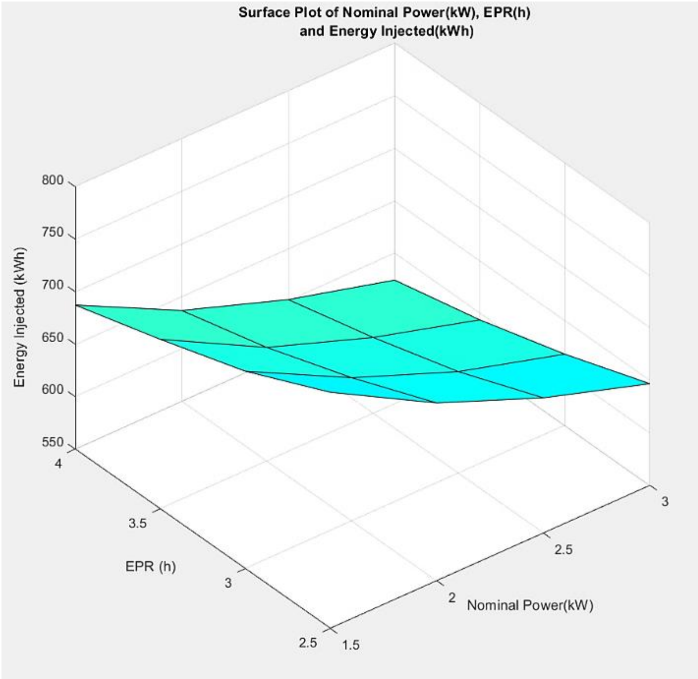

Figure 6.14 Surface Plot of Nominal Power, EPR and Energy injected

In Figure 6.15, it could be seen that the behavior for withdrawn energy is different from the injected one. Figure 6.15 shows some peaks in two completely opposites points. On the P_n =1.5 kW, EPR=2.5 h with withdrawn energy equal to 455.17 kWh, and the other point is when P_n = 3kW, EPR= 4 h with 441.98 kWh. Remarkably, a further increase in the size of the battery storage system does not result in a further increase in self-consumption. The behavior of the battery shows that at the beginning, there start as high numbers of withdrawn energy, then there is a minimum point of the withdrawn energy and is around 2-2.5 kW and EPR=3-3.5 h, given the highest self-consumption on this battery sizing and after that starts increasing again with higher EPR and P_n .

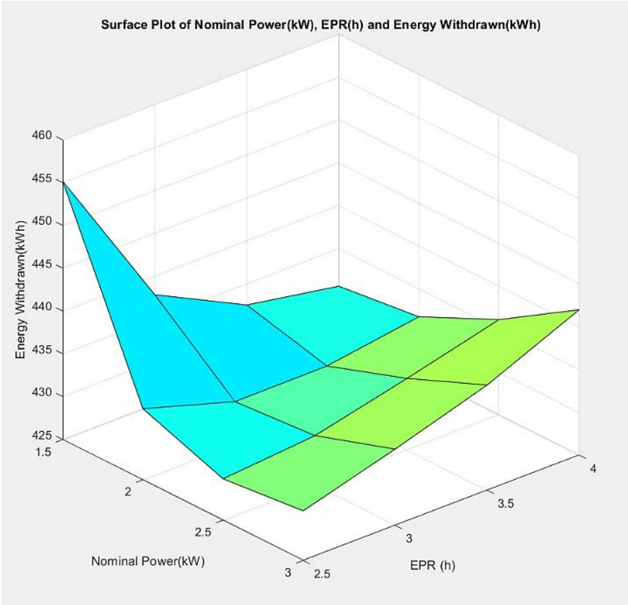

Figure 6.15 Surface Plot of Nominal Power, EPR and Energy Withdrawn

This behavior on the withdrawn could affect the distribution of the NPV, but still, it should be remembered that for this case, it is not only considered the remuneration for injected energy as a revenue. There are also some costs connected to the bill for withdrawn, the CAPEX, and OPEX of the battery, plus the imbalances that are paid in case the battery reaches the limits of saturation, and it does not comply with the baseline proposed. All these factors affect the NPV, not only the streams of the energy exchanged with the grid. Figure 6.16 shows that the highest EPR and Nominal Power show the lowest NPV, mainly because of CAPEX. whereas the highest is for the smallest battery with a total remuneration of 426.47 €

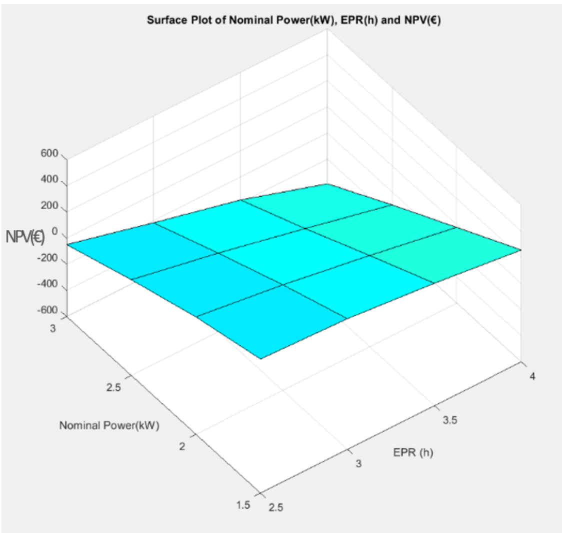

Figure 6.16 Surface Plot of Nominal Power, EPR and NPV in Behind the Meter Case

Figure 6.16 also shows that the larger battery storage systems are not financially advantageous because as EPR increases for larger P_n, there is no return on the investment. This is in part due to the reduced injection as nominal power increases but is mainly because of the CAPEX of the battery, as already said. The improvement in selling is not as significant as the actual cash flow per year due to the high cost of the battery for larger batteries (Figure 6.17)

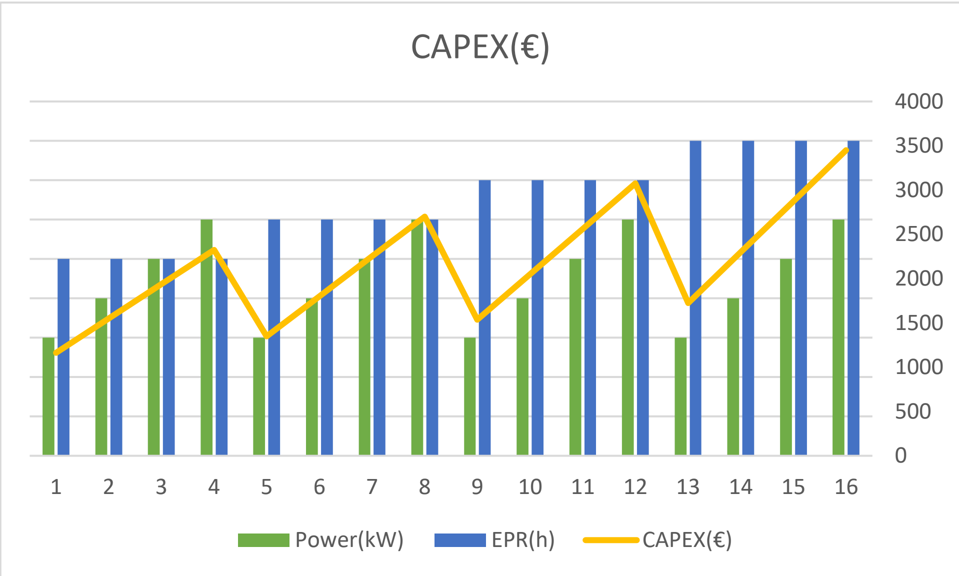

Figure 6.17 Capex of the batteries considering EPR and Power

Adding storage to the PV system of a prosumer increases the self-consumption. However, the benefits of storing are limited since it is only obtained good values of NPV for small batteries, which is something positive, but it is not the case for larger batteries. Battery storage could be applied for a second function to improve the profitability of the energy storage system for the prosumer. Prosumer could increase the exploitation of the battery by providing multiple services.

6.2.2 Unconstrained Case

In this case, it is introduced market participation along with self-consumption. It is assumed a regulatory framework in which the prosumer could access on his own to the market. The prosumer bids everything available to the tertiary reserve without restriction. For this analysis, it has been considered one user with its battery, and for the available tertiary, it has been applied a safety factor, as explained in section 6.2. This factor is an opportunity to risk or to be conservative in the bidding, and the main purpose of this case is to understand the performance on the energy exchanged, self-consumption, and NPV by changing the battery sizing and keeping the K_s constant. In figure 6.18, it could be seen that mostly in all the cases increasing power, self-consumption increases when there is a safety factor from 0.5-1. On the side of K=0.25, it could be seen that the behavior is a little different from the other threes where it could be appreciated a little increase on EPR=2.5 h.

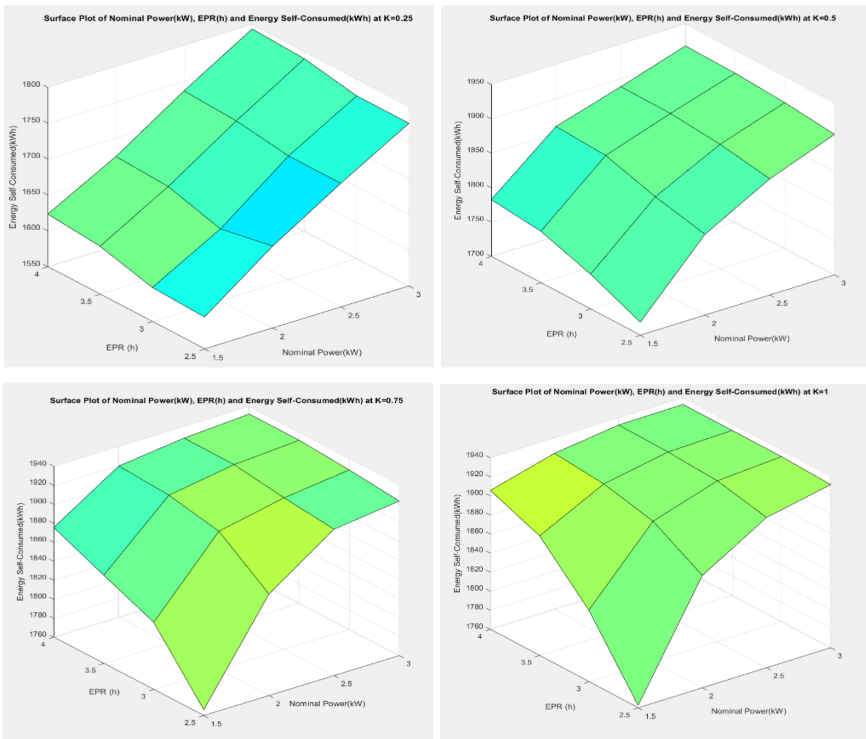

Figure 6.18 Plot of Energy Self-consumed, Nominal Power and EPR with constant K_s

As in the previous case, the energy that is withdrawn does not follow the same pattern as it is observed for a safety factor equal to 0.25, but it is more uniform than before. Through the introduction of the market, the energy self-consumed increase. As K_s increases (giving more importance to the market by bidding all the available) and by having larger bigger batteries, it shows that almost everything that was required for consumption was met. There was almost none withdrawn energy on these conditions (Figure 6.19). Introducing the market has an increasing benefit on the self-consumption, and this type of multiple show synergies in the system.

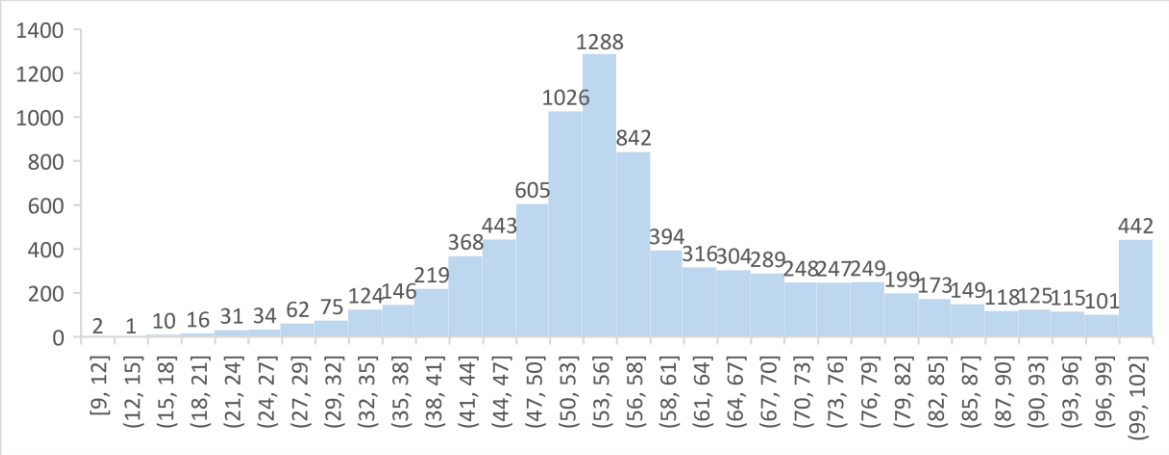

Figure 6.19 Frequency of the State of Charge in Unconstrained Case

It could be observed from the previous Figure that the battery mostly gets not discharged, and this is thanks to the introduction of the tertiary provision which avoid the most to be in the limits of saturation. It could be appreciated that there are many points where the battery is getting full, so it is possible to provide upward on the ASM, which gives the prosumer higher revenues than injected energy.

It can be appreciated in Figure 6.20 that as the nominal power of the battery and EPR increase, it is exchanged more energy in the market, but this could not guarantee that it could have the best economic return. From what could be seen in the Figure below, it seems that for small powers and EPR, it is not advantageous to bid on the ancillary markets.

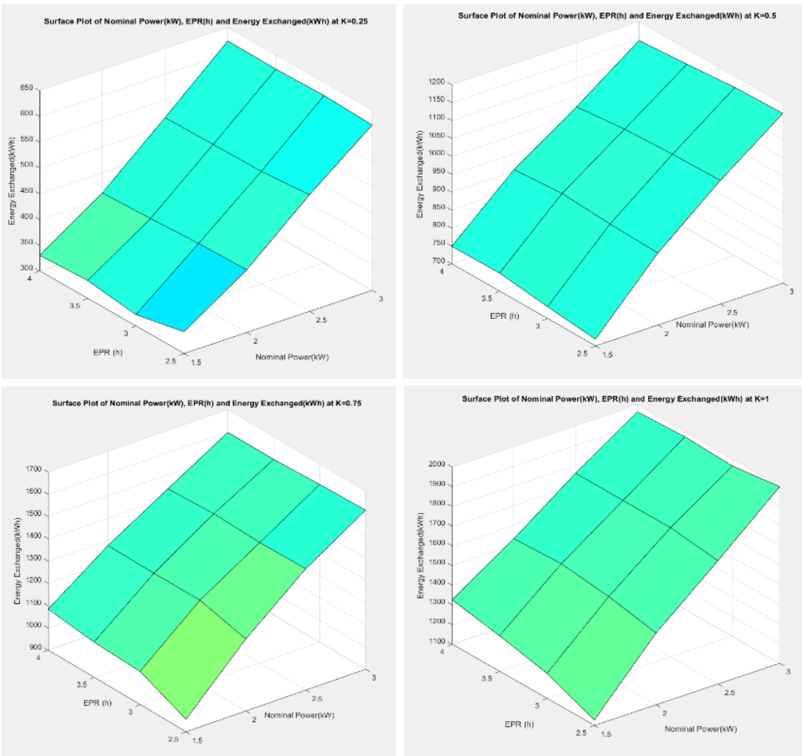

Figure 6.20 Plot of Energy Exchanged, Nominal Power and EPR with constant K_s

From Figure 6.20, it could also be observed that the change in energy exchanged is more significant as the safety factor is changed. This means that if the prosumer or aggregator risk and bid everything on the market, could exchange more energy and therefore, it is possible to have higher incomes, but it also shows that if EPR increases, also it is increased the energy that is not be provided (Figure 6.21) and this is a penalty.

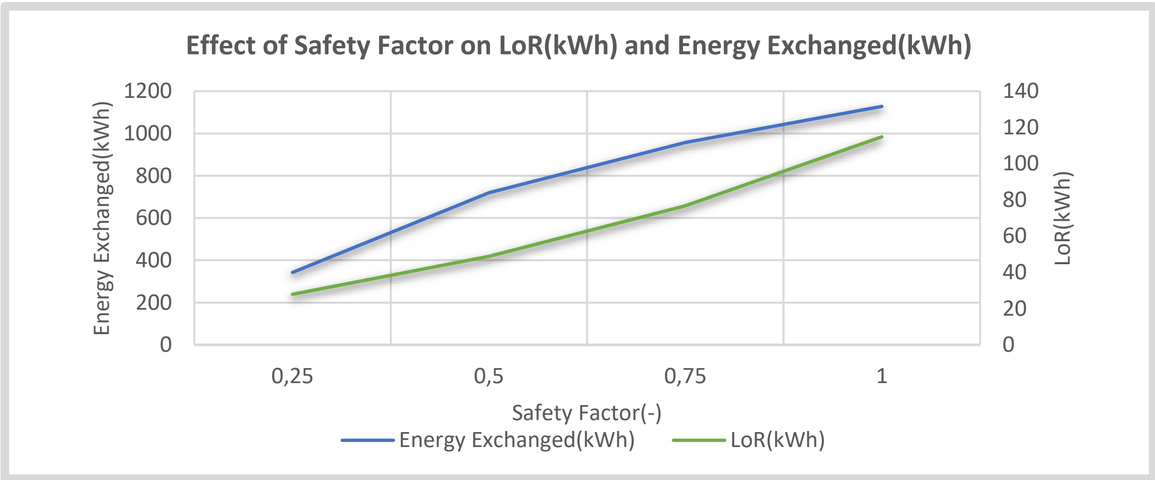

Figure 6.21 Effect of Safety Factor on LoR and Energy Exchanged

The penalty associated with LoR affects the NPV. Anyway, the NPV is most impacted by the higher CAPEX sustained for larger batteries as in the behind-the-meter case (see Figure 6.17)

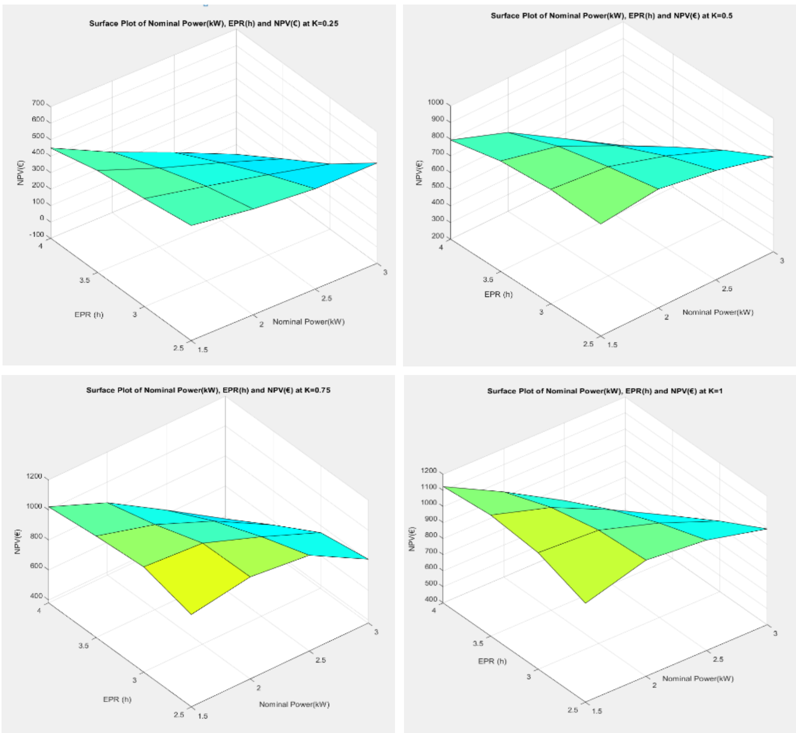

Figure 6.22 Plot of NPV, Nominal Power and EPR with constant K_s

NPV generally increases, but still, the increasing CAPEX lets smaller batteries be more attractive from an economic point of view. It can be seen that a larger K_s increases CAPEX and moves the attractiveness toward larger batteries (EPR= 3 h and P_n=2 kW instead of EPR=2.5h and P_n =1.5 kW shows the highest NPV in case of K_s = 1). However, as the power approaches 3 kW and with EPR greater than 3.5 h, it shows a decrease in the NPV. This is because the revenues are not so high to cover the costs of the battery.

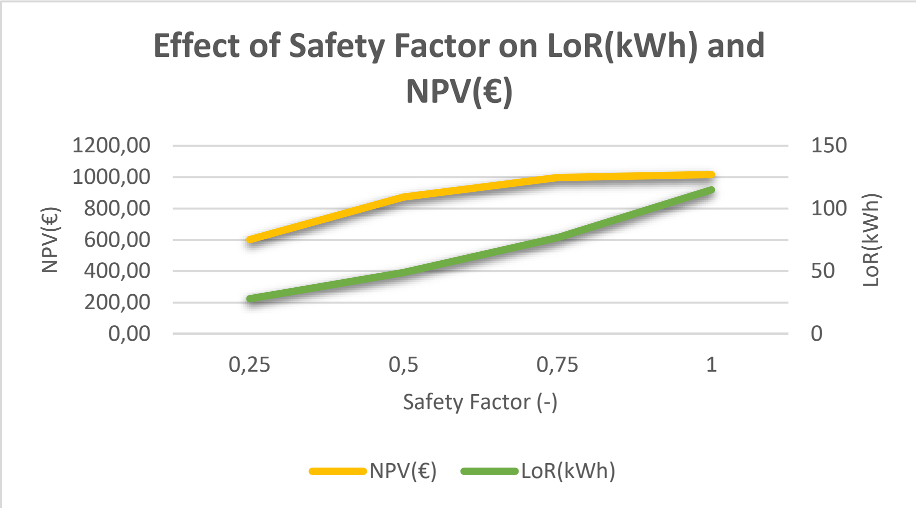

Figure 6.23 Effect of Safety Factor on LoR and NPV

NPV is more attractive in case of higher K_s, but Figure above shows that the increase in revenues concerning lower K_s, is decreasing. This means that the reliability of how much the prosumer bid on the market is decreasing, and the main factor is that LoR is increasing; therefore, the penalty decreases the profit.

As said before, the regulatory framework of most of ASM does not allow prosumers and DERs, in general, to access the market on their own. One of the regulatory barriers present in ASM is the minimum bid size that is accepted on the market. Since a single prosumer cannot cope with the amount of kW requested to bid, it accesses the market as an aggregated unit. To do this, an entity called aggregator and acting as BSP on behalf of the DERs is necessary.

6.2.3 Aggregated Case

Since, in this case, it should be considered the role of the aggregator, then not all the revenues and costs may be applied to the users. Considering that this prosumer is part of aggregated prosumers, the revenue and costs are shared among them. In addition to this, there is the role of the aggregator, and this means that also this figure has its profit. It has been decided a profit-sharing with the aggregator, and the users will receive and paid 25% of the tertiary provision. In contrast, the aggregator will get the 75% since it will be the one in charge of many functions such as gathers and manages the groups of prosumer and develop optimization strategies to reinforce the benefit of bidding on the market [121].

Houses

The minimum bid size for the aggregation in Italy is 200 kW, as was already explained. This study assumes an aggregated unit composed of domestic prosumers only, and a sensitivity analysis is proposed taking into account of different sizes of the aggregator. This is simplified by proposing a set of simulations with different quantities of houses aggregated (Figure 6.24).

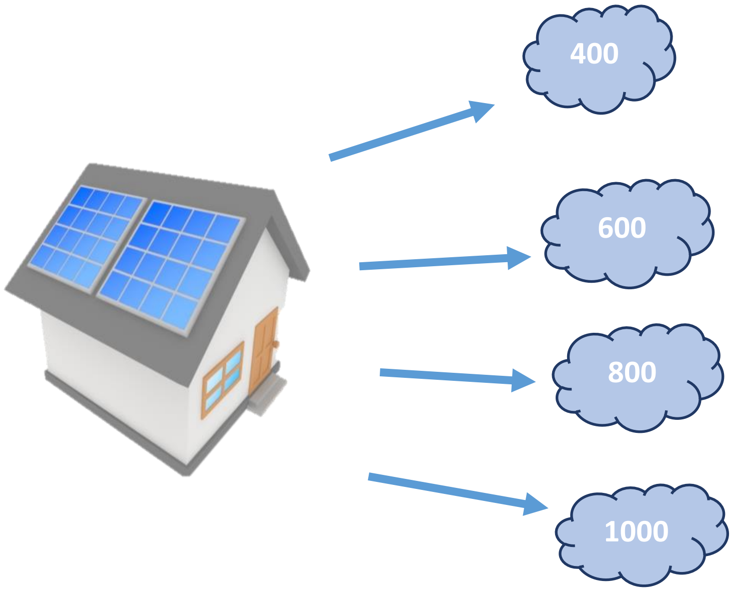

Figure 6.24 Number of Houses studied for aggregation

As in the previous cases, it is studied the perspective of a single prosumer. The differences are on the share of profit, as said before. Also, it is considered that the penalty for LoR in tertiary reserve is share as the 25%. EPR is kept constant, but instead of analyzing the risk of bidding on the market, it has been set $K_s = 1$. In Figure 6.25, it could be appreciated that for all the EPR, the distribution of the energy exchanged (upward and downward energy) is practically the same with the highest energy exchange in larger batteries, being the highest value of energy exchanged of 1274.56 kWh on the EPR=3 h.

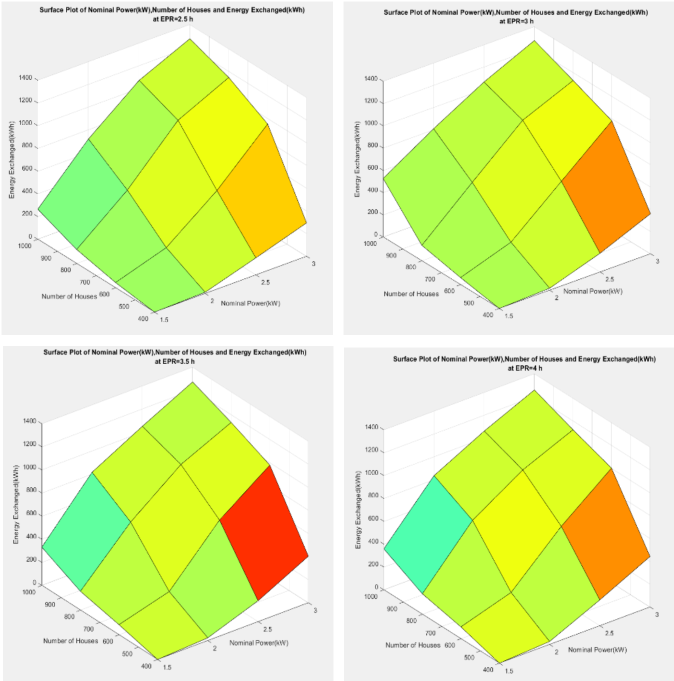

Figure 6.25 Plot of Energy Exchanged, Nominal Power and Houses with constant EPR

If in figure 6.25, it is focused on the highest points of each plot, one thing that could be appreciate is that for all EPRs when Nominal Power = 1.5 kW and 400 houses aggregated, there is no exchange of energy on ASM. With too small batteries and low houses, prosumers cannot reach the minimum bid size. Instead, by increasing P_n and houses, the energy exchanged increases more and more, different from EPR, that still increase but less. As said before, the smallest battery does not exchange energy with the ASM, but as it seems in Figure 6.26, NPV is still better if there are more houses aggregated for a nominal power of 1.5 kW. On the other hand, it could be observed that the biggest NPVs are observed when there are 1000 houses aggregated and specifically on the power of 2kW.

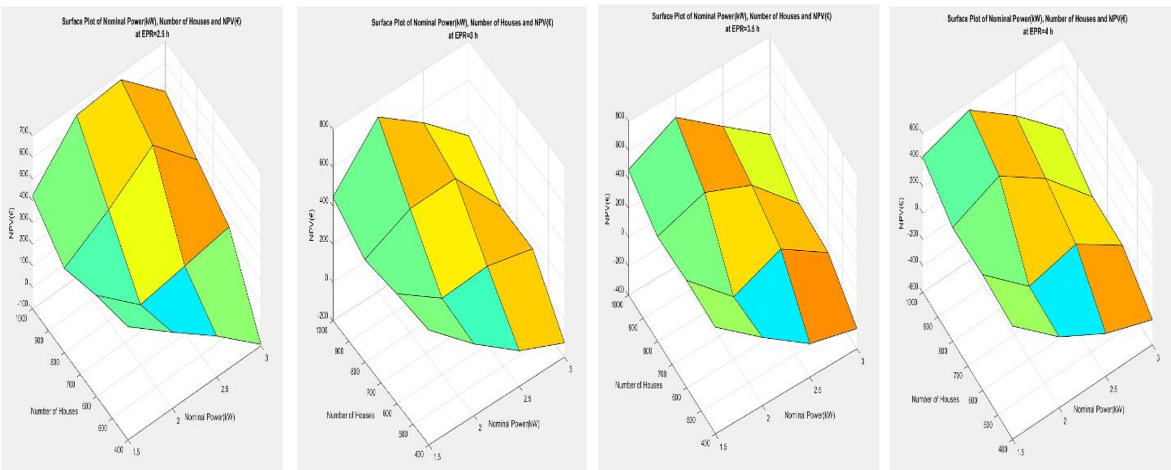

Figure 6.26 Plot of NPV, Nominal Power and Houses with constant EPR

Another interesting thing that it could be observed from Figure 6.26 is that there are many points where there is negative NPV making not suitable for the use of these batteries. This is mainly on the most significant powers of the battery where again, it could be seen that if the revenues are not good enough to cover the costs, then there is not beneficial for the prosumer different from the unconstrained case where it is obtained higher NPV since there is no limitation on the bid.

Regulatory Framework

As it was observed from above, by having small batteries, it could be seen that it is not of a big benefit to the prosumer to bid on ASM if the houses aggregated are smaller. One of the significant evolutions of ASM includes the decrease in minimum bid size. The adopted case already has low value of minimum bid size: 200 kW. In this section, a small sizing for the battery is adopted, and a sensitivity analysis is performed on the minimum bid size to show how this modifies the participation of DERs. It has been considered the actual bid size of 200 kW, and then it was decreased by a step of 50 kW. Thus, the tested minimum bid sizes are 50 kW, 100 kW, and 150 kW. To compare with previous results, the energy exchanged, and NPV are shown to investigate if this change on the minimum bid size could be favorable. It does not exhibit a bit different in the energy exchanged concerning the EPR, but it could be noticed that by reducing the minimum bid size, it is possible to bid more tertiary energy on the market.

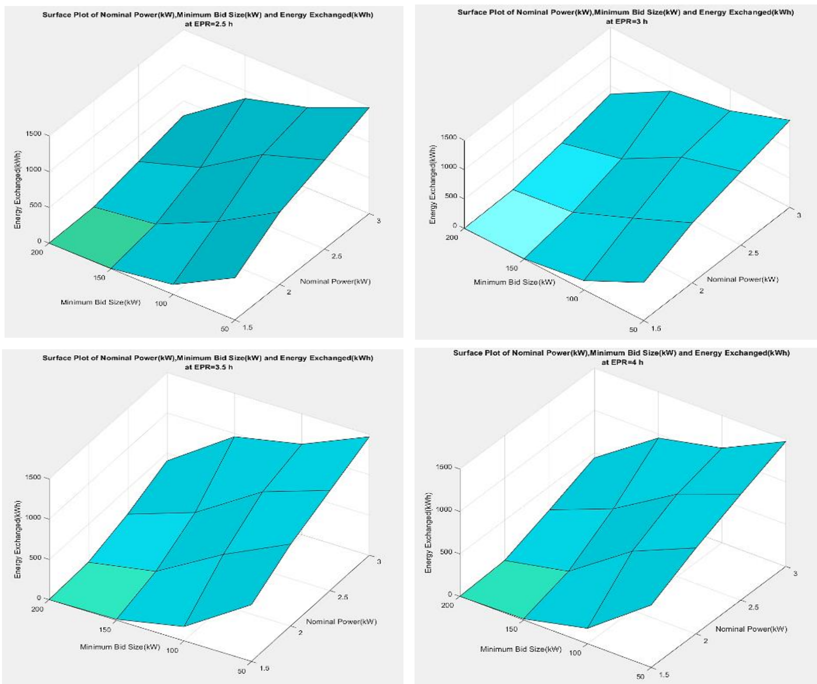

Figure 6.27 Plot of Energy Exchanged, Nominal Power and Minimum bid with constant EPR

It can be seen that a large increase of the provided energy for tertiary regulation is present from 200 kW to 150 kW of minimum bid and nominal power of 3 kW. Then, the increment is lower for smaller bid sizes. This increase in energy exchanged reflects higher NPV with respect to the other bid sizes.

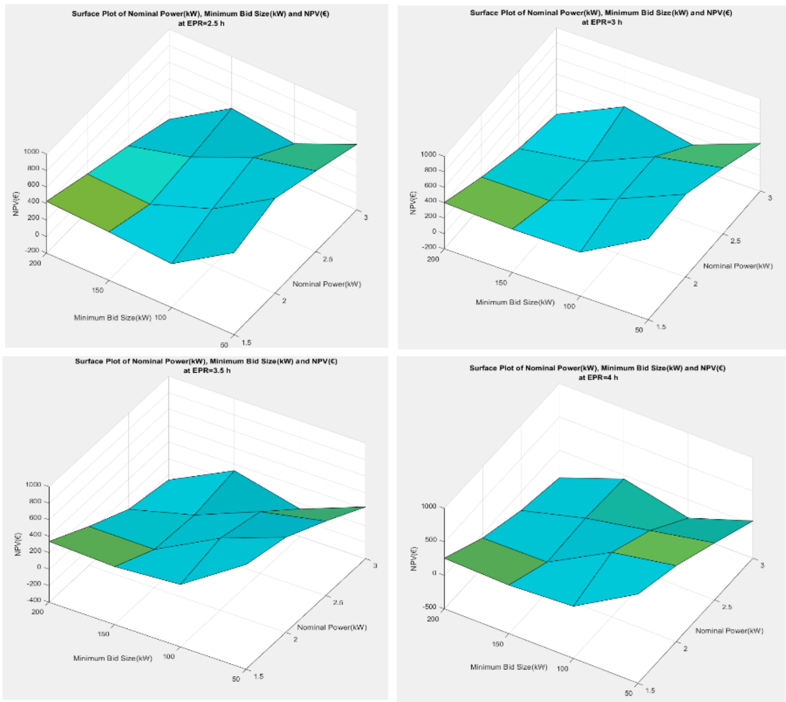

Figure 6.28 Plot of NPV, Nominal Power and Minimum bid with constant EPR

Still, some negative NPVs are present. In another view, it could be seen that the highest the EPR, the lowest are the incomes to the user. With a nominal power of battery of 2 kW, usually, there is a middle point in NPV, and this because even if the streams of revenues are not as big as higher nominal powers, the initial investment is also in the middle for them.

6.2.4 Comparison of the study cases

As a matter of comparison to see which one of the cases it is better on the domestic side. It has been selected as a nominal power for the battery of 1.5 kW and EPR=3 h. This choice has been decided since smaller batteries have lower CAPEX, and prosumers could see this as a conservative investment, plus EPR=3 is when they start having a band for tertiary reserve, and part of this study is also to provide flexibility.

BESS life as a critical parameter has been compared, together with NPV as a representative of the return on the investment. The other parameter compared is the self-consumption that is one of the main benefits for the prosumers in having a PV panel in their houses.

BESS life shows in Figure 6.29 to be around 13 years, and the lowest BESS life is observed in the unconstrained case because the battery is stressed with more cycles.

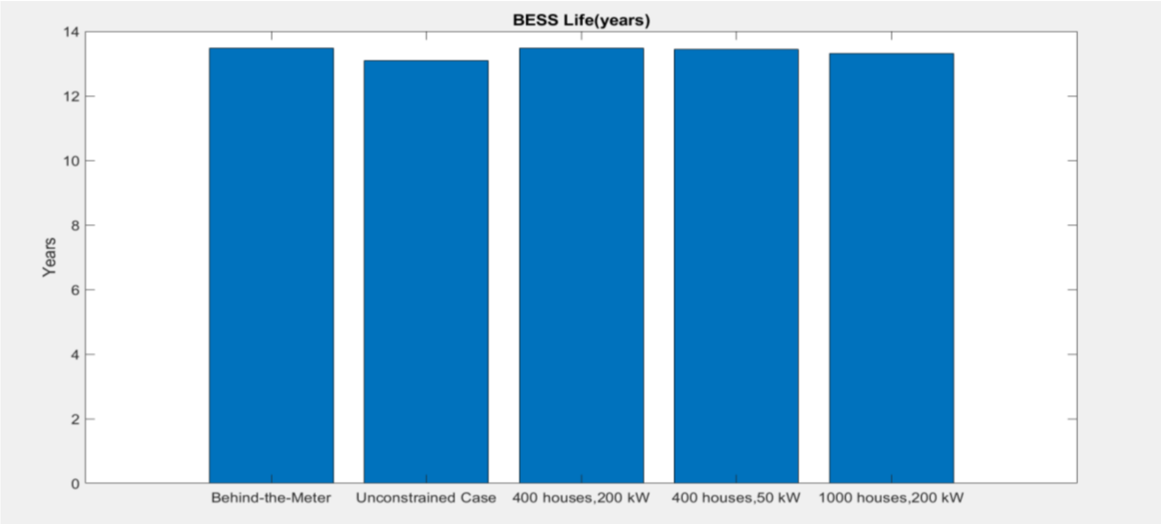

Figure 6.29 BESS life of the different cases

Even if the unconstrained case has the lowest battery life, in the Figure 6.30, it could be seen that energy self-consumed is high, and by reducing the amount of energy that is withdrawn from the grid, it could be possible that they exploit the best revenues of all the cases. Additional, considering that is not the minimum bid size, they have all the plenty possibility to bid all the available energy.

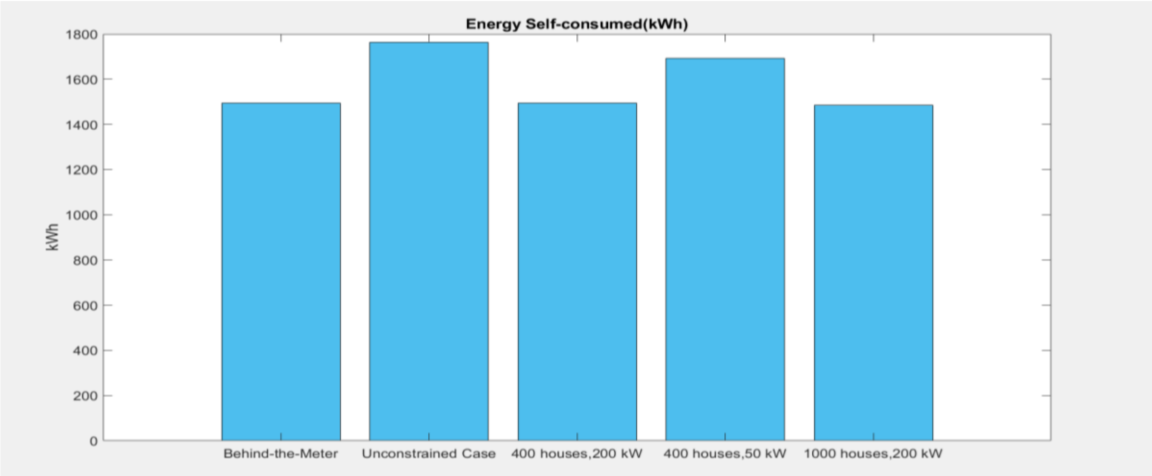

Figure 6.30 Energy Self-consumed of all the cases

As said before, the unconstrained case has the most significant self-consumed energy of all the cases, but if it is focused in the only SC and 400 houses aggregated with the actual minimum bid size, it could be seen that prosumers exploits the same quantity of energy and it may seem as not convenient to participate on the ASM since by having the role of aggregator, the prosumers should cover some costs to pay for aggregate their energy. In this study, it was not considered how much it is paid to the aggregator, but even if the prosumers are not guaranteeing energy, the management of the aggregator to the prosumers is a cost.

As it was stated before, aggregating more houses in the battery with lower nominal powers no help significantly to the profit, as shown in Figure 6.31. Therefore, it is better to keep the same quantity of houses and then to decrease the minimum bid size as shown the figure where for 400 houses and 200 kW, it was found 400.43€, on the other hand, with a minimum bid of 50 kW, it showed a NPV of 850.95€.

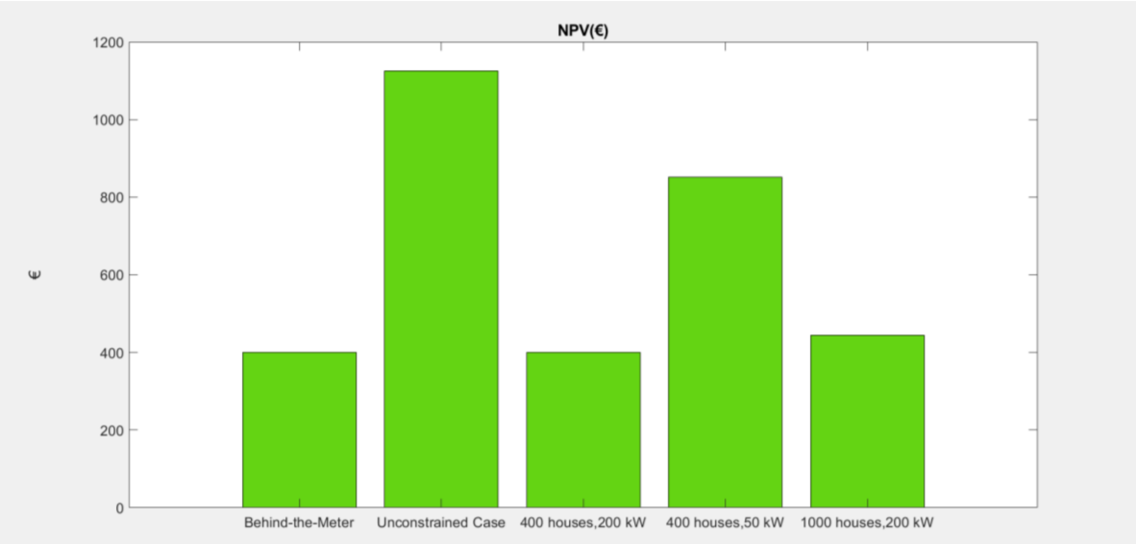

Figure 6.31 NPV comparing all the cases

Chapter 7 Conclusions

The scope of this work was to discover the effective management of aggregated energy storage systems at the domestic level by evaluating the performance of the Battery Energy Storage System (BESS) in providing grid services, from both technical and economic points of view, to show that a prosumer can provide benefit to itself by maximizing the self-consumption and to the system by providing flexibility.
The study was performed by simulating one year of different strategies developed through study cases. Storage was used in the PV system of the user to increase the amount of time that the PV system could use to power a load by storing energy.

As a first case, it was only considered self-consumption, but since it was possible to exploit more, the function of the battery was also developed in a study where the prosumer created a more flexible and reliable grid system through the participation in ASM. It was simulated tertiary control provision with regulating bands available after following self-consumption logic. The strategy developed was to provide passive SoC restoration via the provision of multiple services, and since the prosumer must respect the program proposed by the BRP, SC was always the priority.

Since the regulatory framework of most of ASM does not allow prosumers and DERs, in general, to access the market on their own, the participation of the prosumer to the ASM was studied by including it in an aggregated unit, with an aggregator acting as BSP as an interface with the market. The role of all the involved parties, such as the Balance Responsible Party (BRP) and Balancing Services Provider (BSP), were economically modeled. Considering that the market requirements are not always satisfied by the aggregate, some of the rules of the market were neglected and were considered an "unconstrained" case in which it was possible by a single prosumer to bid on its own on the market, without having a minimum bid limit.

The outcome of this study shows that battery storage could improve the profitability of the energy storage system for the prosumer. Participation in the ASM allows prosumers to increase self-consumption. The analysis also shows in Figure 6.31 that participation in the ASM allows prosumers to increase revenues where the unconstrained case showed revenue of 1124.98 € compared with a 400.43€ of behind the meter. Thus, the BESS investment interest in the case of multiple services provisions arises.

NPV was more attractive in case of higher safety factors, meaning that as a prosumer, it is better to provide all or almost all the band of tertiary power available. On the other hand, higher safety factors cause a higher rate of energy non-provided on the total energy requested (referred to as Loss of Regulation in the study). This decreases the reliability of the aggregated unit in providing flexibility to the system operator.

With smaller batteries, the energy exchanged on the market is small. On the other hand, larger batteries exchange more energy with ASM. Nevertheless, the larger investment costs are predominant (BESS barely show scale economy), and the NPVs are generally larger for small batteries.

The best NPVs are shown for the unconstrained case study, featuring self-consumption and participation to market with no minimum bid size. The unconstrained case even shows the lowest battery life of all the cases. In any case, it was evident to see that energy self-consumed was higher than for the other cases, and by reducing the amount of energy that was withdrawn from the grid, this case presented the highest revenues among all the cases.

Considering the presence of minimum bid size, no energy is exchanged on the market for aggregated units featuring less than 400 houses. Therefore, since the aggregator will face some management cost even in case of no energy traded on the market, it is not convenient to have aggregated units smaller than 400-600 houses. In this study, it was not considered the economic treatment reserved by the aggregator to the prosumers, only focusing on the prosumer revenue and cost streams. In any case, the management of the aggregator will be a cost, and the aggregator would probably propose a profit-sharing mechanism.

Future studies could focus on the impact of the payment and profit-sharing between the aggregator and the prosumer. Furthermore, the imbalance impact on revenues is relevant. Thus, a topic to be considered could be developing a strategy aimed to lower to zero the imbalances. Other improvements could be increasing the number of batteries simulated by the model in the aggregated case, to show the impact on the aggregation of much different power and load profiles.

Acronyms

AC	Alternate Current
ASM	Ancillary Services Market (Mercato del Servizio di Dispacciamento)
BESS	Battery Energy Storage System
BMS	Battery Management System
BOL	Beginning-of-Life
BRP	Balance Responsible Party
BSP	Balancing Service Provider
BtM	Behind the Meter
CAES	Compressed-Air Energy Storage
CCV	Close Circuit Voltage
CDF	Cumulative Distribution Functions
CE	Coulombic Efficiency
CEER	Council of European Energy Regulators
CSP	Concentrated Solar Power
DAM	Day-Ahead Market
DC	Direct Current
DCO	Publication of consultation documents
DER	Distributed Energy Resources
DG	Distribution Grid
DOD	Depth of Discharge
DR	Demand Response
DSO	Distribution System Operator
EOL	End-of-Life
EPR	Energy to Power Ratio
ESS	Energy Storage System
EU	European Union
EUAA	End Users Association of Australia
EV	Electric Vehicles
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
GME	Gestori di Mercati Energetici
GSE	Gestori dei Servizi Energetici
HVAC	Heating Ventilation Air conditioning
ICT	Information and Communication Technology
IPEX	Italian Power Exchange

IRR	Internal Rate of Return
JCR	Joint Research Centre
LoR	Loss of Regulation
MB	Balancing Market
mFRR	Manual Frequency Restoration Reserve
MI	Intra-Day Market
NEBE	Notification d'Échange de Blocs d'Effacement
NECP	National Energy and Climate Plan
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
O&M	Operation and Maintenance
OCV	Open Circuit Voltage
P2D	Pseudo Two-dimensional
PCS	Power Conversion System
PHES	Pumped Hydro Energy Storage
PNIEC	Piano Nazionale Integrato Energia Clima
PUN	Single National Price (Prezzo Unico Nazionale)
PV	Photovoltaic
RES	Renewable Energy Sources
RR	Replacement Reverse
SC	Self-Consumption
SEI	Solid Electrolyte Interface
SGT	Smart Grid Technology
SoC	State of Charge
SoE	State of Energy
SoH	State of Health
SP	Single-particle
TIDE	Testo Integrato del Dispacciamento Elettrico
TR	Tertiary Reserve
TSO	Transmission System Operator
UPR	Relevant Production Units
UVA	Unitá Virtuali Abilitate
UVAC	Unitá Virtuali Abilitate di Consumo
UVAM	Unitá Virtuali Abilitate Miste
UVAN	Unitá Virtuali Abilitate Nodali
UVAP	Unitá Virtuali Abilitate di Produzione
V2G	Vehicle to Grid
VPP	Virtual Power Plant
VRE	Variable Renewable Energy

Bibliography

[1] European Environment Agency, «European Environment Agency,» 16 December 2019. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/renewable-gross-final-energy-consumption-4/assessment-4. [Consultato il giorno 29 August 2020].

[2] T. D. Corsatea, S. Giaccaria, C. F. Covrig, N. Zaccarelli e M. Ardelean, «RES diffusion and R&D investments in the flexibilisation of the European electricity networks,» *Renewable and Sustainable Energy Reviews,* vol. 55, pp. 1069-1082, 2016.

[3] J.-M. Glachant, J. Vasconcelos e V. Rious, «A conceptual framework for the evolution of the operation and regulation of electricity transmission system towards a decarbonised and increasingly integrated electricity system in the EU,» 2015.

[4] ieso, 15 January 2020. [Online]. Available: http://www.ieso.ca/en/Learn/Ontario-Power-System/A-Smarter-Grid/Distributed-Energy-Resources. [Consultato il giorno 18 August 2020].

[5] J. do Prado, W. Qiao, L. Qu e J. Agüero, «The Next-Generation Retail Electricity Market in the Context of Distributed Energy Resources: Vision and Integrating Framework.,» *Energies,* vol. 12, n. 491, 2019.

[6] «Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU,» *Official Journal of the European Unition,* pp. 125-199, 14 June 2019.

[7] Y. Miao, A. Von Jouanne e A. Yokochi, «Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements,» *Energies,* 2019.

[8] ARERA, «Delibera 05 maggio 2017 300/2017/R/eel,» 2017.

[9] G. Rancilio, A. Lucas, E. Kotsakis, G. Fulli, M. Merlo, M. Delfanti e M. Masera, «Modeling a large-scale battery energy storage system for power grid application analysis,» *Energies,* vol. 12, n. 17, p. 3312, 2019.

[10] H. E. Murdock, «Renewables 2019 global status report,» 2019.

[11] S. Europe, «Global Market Outlook For Solar Power 2019-2023,» Tech. Rep, 2019.

[12] REN21, «Renewables 2019 Global Status Report,» REN21 Secretariat, Paris, 2019.

[13] G. d. S. E. S. Rapporto, «Statistico Solare Fotovoltaico 2018,» 2019.

[14] G. Lettner, H. Auer, A. Fleischhacker, D. Schwabeneder, B. Dallinger e F. Moisl, «Existing and future PV prosumer concepts,» Technische Universitaet Wien, Fundacion Tecnalia Research & Innovation, with the Collaboration of PVP4Grid Consortium, Vienna, 2018.

[15] M. d. S. Economico, «Italy's National Energy Strategy,» 2017.

[16] E. Comission, «Battery Storage to drive the power system transition,» 2018.

[17] W. E. Council, «Energy Storage Monitor, Latest trends in energy storage,» 2019.

[18] IRENA, «Electricity Storage and Renewables: Costs and Markets to 2030,» International Renewable Energy Agency, Abu Dhabi, 2017.

[19] A. D. Bank, «Handbook on Battery Energy Storage System,» 2018.

[20] I. ESMAP, «Energy Storage Trends and Opportunities in Emerging Markets,» ESMAP, 2017.

[21] L. Goldie-Scot, BloomberNEF, 5 March 2019. [Online]. Available: https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/. [Consultato il giorno 3 August 2020].

[22] Eurobat, «Eurobat,» 2016. [Online]. Available: https://www.eurobat.org/images/news/publications/eurobat_batteryenergystorage_web.pdf. [Consultato il giorno 11 August 2020].

[23] C. Liu, Z. G. Neale e G. Cao, «Understanding electrochemical potentials of cathode materials in rechargeable batteries,» *Materials Today,* vol. 19, pp. 109-123, 2016.

[24] H. D. Yoo, E. Markevich, G. Salitra, D. Sharon e D. Aurbach, «On the challenge of developing advanced technologies for electrochemical energy storage and conversion,» *Materials Today,* vol. 17, pp. 110-121, 2014.

[25] K. Ozawa, «Lithium-ion rechargeable batteries with LiCoO2 and carbon electrodes: the LiCoO2/C system.,» *Solid State Ionics,* vol. 69, pp. 212-221, 1994.

[26] C. M. Park, J. H. Kim, H. Kim e H. J. Sohn, «Li-alloy based anode materials for Li secondary batteries,» *Chemical Society Reviews,* vol. 39, pp. 3115-3141, 2010.

[27] P. Poizot, S. Laruelle e S. Grugeon, «Nano-sized transition-metal oxides as negative-electrode materials for lithium-ion batteries,» *Nature,* vol. 407, p. 496–499, 2000.

[28] M. Noel e V. Suryanarayanan, «Role of carbon host lattices in Li-ion intercalation/de-intercalation processes,» *Journal of Power Sources,* vol. 111, pp. 193-209, 2002.

[29] J. Wang e X. Sun, «Olivine LiFePO 4: the remaining challenges for future energy storage,» *Energy & Environmental Science,* vol. 8, pp. 1110-1138, 2015.

[30] O. M. A. A. Mansour, «Determining the Power and Energy Capacity of a Battery Energy Storage System Utilizing a Smoothing Feeder Profile to Accommodate High Photovoltaic Penetration on a Distribution Feeder,» 2016.

[31] B. Chen, H. Ma, H. Fang, H. Fan, K. Luo e B. Fan, «An approach for state of charge estimation of Li-ion battery based on Thevenin equivalent circuit model,» *IEEE,* pp. 647-652, 2014.

[32] H. He, R. Xiong, X. Zhang, F. Sun e J. Fan, «State-of-charge estimation of the lithium-ion battery using an adaptive extended Kalman filter based on an improved Thevenin model,» *IEEE Transactions on vehicular technology,* vol. 60, pp. 1461-1469, 2011.

[33] A. Attanayaka, J. P. Karunadasa e K. Hemapala, «Estimation of state of charge for lithium-ion batteries-A Review,» *AIMS Energy,* vol. 7, p. 186, 2019.

[34] W. Chang, «The state of charge estimating methods for battery: A review,» *International Scholarly Research Notices,* 2013.

[35] A. Barai, W. D. Widanage, J. Marco, A. McGordon e P. Jennings, «A study of the open circuit voltage characterization technique and hysteresis assessment of lithium-ion cells,» *Journal of Power Sources,* vol. 295, pp. 99-107, 2015.

[36] H. Ren, Y. Zhao, S. Chen e T. Wang, «Design and implementation of a battery management system with active charge balance based on the SOC and SOH online estimation,» *Energy,* vol. 166, pp. 908-917, 2019.

[37] A. Anvari-Moghaddam, J. Dulout, C. Alonso, B. Jammes e J. Guerrero, « Optimal Design and Operation Management of Battery-Based Energy Storage Systems (BESS) in Microgrids,» *InTechOpen,* 2017.

[38] «Battery University,» 20 Febraury 2018. [Online]. Available: https://batteryuniversity.com/learn/article/discharge_characteristics_li. [Consultato il giorno 28 August 2020].

[39] H. Hemi, N. K. M'Sirdi, A. Naamane e B. Ikken, «Open Circuit Voltage of a Lithium ion Battery Model adjusted by data fitting,» in *2018 6th International Renewable and Sustainable Energy Conference (IRSEC),* 2018.

[40] A. Jacobs. [Online]. Available: https://quadquestions.com/blog/2014/12/27/qav250-c-rating-explained/#:~:text=The%20C%20rating%20is%20inversely,right%20battery%20for%20the%20job.. [Consultato il giorno 26 August 2020].

[41] Battery University, 25 October 2017. [Online]. Available: https://batteryuniversity.com/learn/article/bu_808c_coulombic_and_energy_efficiency_with_the_battery#:~:text=Coulombic%20efficiency%20(CE)%2C%20also,battery%20over%20a%20full%20cycle.. [Consultato il giorno 28 August 2020].

[42] D. o. E.-. U. S. o. America, «USA PNGV Battery Test Manual,» DOE/ID-10597, 2011.

[43] K. Li e K. J. Tseng, «Energy efficiency of lithium-ion battery used as energy storage devices in micro-grid,» in *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society,* 2015.

[44] J. Y. Kang, Z. P. F. e C. Du, «A novel way to calculate energy efficiency for rechargeable batteries,» *Journal of Power Sources,* vol. 206, pp. 310-314.

[45] Apple, [Online]. Available: https://www.apple.com/batteries/why-lithium-ion/. [Consultato il giorno 30 August 2020].

[46] G. Rancilio, «Battery energy storage systems for ancillary services provision,» 2018.

[47] C. R. Birkl, M. R. Roberts, E. McTurk, P. G. Bruce e Howey, «Degradation diagnostics for lithium ion cells,» *Journal of Power Sources,* vol. 341, pp. 373-386, 2017.

[48] O.-G. EUROPE. [Online]. Available: https://www.off-grid-europe.com/info/battery-lifespan/. [Consultato il giorno 30 August 2020].

[49] F. Yang, D. Wang, F. Xu, Z. Huang e K. L. Tsui, «Lifespan prediction of lithium-ion batteries based on various extracted features and gradient boosting regression tree model,» *Journal of Power Sources,* vol. 476.

[50] X. Han, L. Lu, Y. Zheng, X. Feng, Z. Li, J. Li e M. Ouyang, « A review on the key issues of the lithium ion battery degradation among the whole life cycle,» *ETransportation,* vol. 1, 2019.

[51] J. Vetter, P. Novák, M. R. Wagner, C. Veit, K. C. Möller, J. O. Besenhard e A. Hammouche, « Ageing mechanisms in lithium-ion batteries,» *Journal of power sources,* vol. 147, pp. 269-281, 2005.

[52] A. Xiao, «Power fade in lithium ion batteries: Effect of advanced electrolyte,» *University of Rhode Island,* 2008.

[53] B. Xu, A. Oudalov, A. Ulbig, G. Andersson e D. S. Kirschen, «Modeling of lithium-ion battery degradation for cell life assessment,» *IEEE Transactions on Smart Grid,* vol. 9, pp. 1131-1140, 2016.

[54] Z. Cao e A. Roc, «Life Prediction Model for GridConnected Li-ion Battery,» NREL: National Renewable Energy Laboratory, Seatttle, Washington, 2017.

[55] «Electropaedia,» 2005. [Online]. Available: https://www.mpoweruk.com/life.htm#:~:text=An%20alternative%20measure%20of%20cycle,its%20initial%20value%20when%20new.. [Consultato il giorno 30 August 2020].

[56] AMDC Energy Limited, [Online]. Available: http://www.amdcenergy.com/battery-energy-storage-system.html. [Consultato il giorno 25 July 2020].

[57] M. Galvenonis, «ENERGY TOOLBASE,» 6 April 2020. [Online]. Available: https://www.energytoolbase.com/newsroom/blog/the-primary-components-of-an-energy-storage-system-that-you-need-to-know. [Consultato il giorno 28 July 2020].

[58] C. Brivio, «Battery Energy Storage Systems:Modelling, Applications and Design Criteria,» Politecnico di Milano, 2017.

[59] C. Di Profio e M. Alborghetti, «BESS energy management strategies for multiple ancillary services provision,» 2019.

[60] M. R. Jongerden e B. R. Haverkort, «Which battery model to use?,» *IET software,* vol. 3, pp. 445-457, 2009.

[61] D. W. Dees, V. S. Battaglia e A. Bélanger, «Electrochemical modeling of lithium polymer batteries,» *Journal of power sources,* pp. 310-320, 2002.

[62] M. Doyle, T. F. Fuller e J. Newman, «Modeling of galvanostatic charge and discharge of the lithium/polymer/insertion cell,» *Journal of the Electrochemical society,* vol. 140, 1993.

[63] J. Newman, 2014. [Online]. Available: URL http://www. cchem. berkeley. edu/jsngrp..

[64] V. Ramadesigan, P. W. Northrop, S. De, S. Santhanagopalan, R. D. Braatz e V. R. Subramanian, «Modeling and simulation of lithium-ion batteries from a systems engineering perspective,» *Journal of the electrochemical society,* vol. 159.

[65] D. Zhang, B. N. Popov e R. E. White, «Modeling lithium intercalation of a single spinel particle under potentiodynamic control,» *Journal of the Electrochemical Society,* vol. 147, 2000.

[66] G. A. Rincón Mora, «An accurate electrical battery model capable of predicting lifetime and IV performance motivation,» *IEEE Transactions on Energy Conversion,* vol. 21, pp. 1-8, 2005.

[67] L. Beltramin, «State-of-the-Art of the Flywheel/Li-ion Battery Hybrid Storage System for Stationary Applications,» 2018.

[68] A. Michael, «Energy Liberalisation and EC Competition Law,» in *Fordham 28th Annual Conference*, 2001.

[69] M. Polo e C. Scarpa, «The liberalization of energy markets in Europe and Italy,» 2003.

[70] «Terna,» [Online]. Available: https://www.terna.it/en/electric-system/electricity-market. [Consultato il giorno 29 May 2020].

[71] G. Telarico, M. Cigno e A. S. Scimè, «The Law Reviews,» July 2020. [Online]. Available: https://thelawreviews.co.uk/edition/the-energy-regulation-and-markets-review-edition-9/1228298/italy. [Consultato il giorno 3 August 2020].

[72] B. Bosco, L. Parisio e M. Pelagatti, «Deregulated Wholesale Electricity Prices in Italy,» *SSRN,* vol. 888736, 2006.

[73] A. Gianfreda e L. Grossi, «Zonal price analysis of the Italian wholesale electricity market,» *IEEE*, pp. 1-6, 2009.

[74] «AleaSoft Energy Forecastinng,» [Online]. Available: https://aleasoft.com/european-electricity-markets-panorama-italy/. [Consultato il giorno 2 August 2020].

[75] GME, «Annual Report 2018,» Gestore Mercati Energetici, 2018.

[76] G. Oggioni e C. Lanfranconi, «Empirics of Intraday and Real-time Markets in Europe: Italy,» DIW - Deutsches Institut für Wirtschaftsforschung, Berlin, 2015.

[77] a2a, «Italian Energy Market Overview, 2015&2016 Market Analysis & Price Forescasting,» 2017.

[78] M. Caprabianca, M. C. Falvo, L. Papi, L. Promutico, V. Rossetti e F. Quaglia, «Replacement Reserve for the Italian Power System and Electricity Market,» *Energies,* vol. 13, p. 2916, 2020.

[79] U. O. Handbook, «Appendix 1: Load-frequency-control and performance,» UCTE Brussels, Belgium, 2004.

[80] L. Marchisio, F. Genoese e F. Raffo, «Distributed Resources in the Italian Ancillary Services Market: taking stock after two years».

[81] E. Bellini, «Italy opens ancillary services market to pilot renewable energy and storage projects,» *pv magazine,* 9 May 2017.

[82] «Testo integrato del dispacciamento elettrico (TIDE) - Orientamenti complessivi,» 2019.

[83] E. Bellini, «Aros Solar Technology,» 9 May 2017. [Online]. Available: http://www.aros-solar.com/en/bollettino/bulletin/italy-opens-ancillary-services-market-to-pilot-renewable-energy-and-storage-projects. [Consultato il giorno 2 August 2020].

[84] RSE e P. d. Milano, «Analisi dello stato attuale e delle possibili evoluzioni dei mercati elettrici in Italia,» 2019.

[85] K. Oureilidis, K.-N. Malamaki, K. Gallos, A. Tsitsimelis, C. Dikaiakos, S. Gkavanoudis, M. Cvetkovic, J. Mauricio, J. Maza Ortega, J. Ramos, G. Papaioannou e C. Demoulias, «Ancillary Services Market Design in Distribution Networks: Review and Identification of Barriers,» *Energies,* vol. 13, n. 917, 2020.

[86] H. Gerard, E. Rivero e D. Six, «Basic schemes for TSO-DSO coordination and ancillay services provision,» SmartNet, 2016.

[87] R. Verzijlbergh, L. De Vries, G. Dijkema e P. Herder, «Institutional challenges caused by the integration of renewable energy sources in the European electricity sector,» *CrossRef,* vol. 75, n. 660-667, 2017.

[88] Eurobat, «Battery Energy Storage in the EU- Barriers, Opportunities, Services and Benefits,» Eurobat, 2016.

[89] J. Juffermans, *Aggregators and flexibility in the Dutch electricity system,* 2018.

[90] J. Ikaheimo, C. Evens e S. Karkkainen, «DER Aggregator Business: the Finnish Case,» VTT, 2010.

[91] «Stem,» 2019. [Online]. Available: https://www.stem.com/. [Consultato il giorno 3 August 2020].

[92] Deloitte Center for Energy Solution, «Deloitte,» 2018. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-

and-Resources/gx-er-challenges-opportunities-global-battery-storage-markets.pdf. [Consultato il giorno March 2020].

[93] EUAA, «Demand Side Response in the National Electricity Market Case Studies-End Use Customer Awareness Program,» 2005.

[94] EUAA, «Trial of a Demand Side Response Facility for the National Electricity Market: Independent Consultants'Report,» 2004.

[95] IRENA, «Innovation landscape brief: Aggregators,» International Renewable Energy Agency, Abu Dhabi, 2019.

[96] Frontier Economics, « South Australia’s Virtual Power Plant,» Frontier Economics, Mlebourne, 2018.

[97] European Parliament, «Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency,» *Official Journal of the European Union,* pp. 1-56, 2012.

[98] P. Bertoldi, P. Zancanella e B. Boza-Kiss, «Demand Response status in EU Member States,» JRC Science for Policy Report, 2016.

[99] A. Bader, «Stakraft,» 2018. [Online]. Available: https://www.statkraft.com/newsroom/news-and-stories/archive/2018/virtual-power-plant-europes-biggest-power-plant-is-100-renewable/. [Consultato il giorno 19 August 2020].

[100] V. Chiesa, D. Chiaroni, S. Franzò e F. Frattini, «Electricity Market Report L'apertura del MSD oltre i progetti pilota:quali ricadure per il sistema paese?,» 2019.

[101] ARERA, «Orientamenti relativi alla Partecipazione del veicoli elettrici al mercato per il servizio di dispacciamiento, per il tramite delle infrastrutture di ricarica dotate di tecnologia: Vehicle to Grid,» 2020.

[102] CEER, «Flexibility Use at Distribution Level,» A CEER Conclusions Paper, Brussels, 2018.

[103] G. Rancilio, M. Merlo, A. Lucas, E. Kotsakis e M. Delfanti, «BESS modeling: investigating the role of auxiliary system consumption in efficiency derating. In 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM),» *IEEE,* pp. 189-194, 2020.

[104] M. Moncecchi, A. Borselli, D. Falabretti and L. a. M. M. Corghi, " Numerical and Experimental Efficiency Estimation in Household Battery Energy Storage Equipment," *Energies,* vol. 13, p. 2719, 2020.

[105] S. Schoenung e J. Eyer, «Benefit/cost framework for evaluating modular energy storage.,» *Sandia,* 2008.

[106] C. Brivio, S. Mandelli e M. Merlo, «Battery energy storage system for primary control reserve and energy arbitrage,» *Sustainable Energy, Grids and Networks,* vol. 6, pp. 152-165, 2016.

[107] G. S. Energetici, «GSE,» [Online]. Available: https://www.gse.it/servizi-per-te/fotovoltaico/ritiro-dedicato. [Consultato il giorno 07 17 2020].

[108] F. Di Andrea e A. Danese, «MICENE MIsure dei Consumi di ENergia Elettrica in 110 abitazioni Italiane-Curve di carico dei principali elettrodomestici e degliapparecchi di illuminazione (italian),» *eERG, end-use Efficiency Research Group, Tech. Rep.*, 2004.

[109] P. Ungaro, «L'indagine Istat sui consumi energetici delle famiglie: principali risultati,» 2014.

[110] M. Presutto, M. G. Villani, D. Scarano e S. Fumagalli, «Il mercato degli elettrodomestici e la sua evoluzione temporale,» 2010.

[111] E. Commission, «Direttiva 2003/66/CE della Commissione, del 3 luglio 2003, che modifica la direttiva 94/2/CE che stabilisce modalità d'applicazione della direttiva 92/75/CEE del Consiglio per quanto riguarda l'etichettatura indicante il consumo d'energia dei frigoriferi,» 2003.

[112] «Coldiretti,» 18 January 2019. [Online]. Available: https://www.coldiretti.it/archivio/consumi-per-i-single-un-60-di-spesa-rispetto-alla-famiglia-media-18-01-2009. [Consultato il giorno 2020 September 2020].

[113] «ARPA Lombardia,» [Online]. Available: https://www.arpalombardia.it/Pages/ARPA_Home_Page.aspx.

[114] C. Tononi, «Multi-service participation to the ancillary services market: an approach based on aggregated residential users equipped with PV and energy storage systems,» 2019.

[115] N. Singh, «towards data science,» 25 February 2019. [Online]. Available: https://towardsdatascience.com/a-beginners-guide-to-linear-regression-in-python-with-scikit-learn-83a8f7ae2b4f. [Consultato il giorno 28 August 2020].

[116] ARERA, «Relazione Annuale Stato dei Servizi Volume 1,» 2019.

[117] GME, «Gestore Mercati Energetici,» [Online]. Available: https://www.mercatoelettrico.org/It/Tools/Accessodati.aspx?ReturnUrl=%2fIt%2fdownload%2fDownloadDati.aspx%3fval%3dMB_PTotali&val=MB_PTotali. [Consultato il giorno 3 April 2020].

[118] V. Canazza, «Il mercato dei servizi di dispacciamento in Italia: analisi e approcci di simulazione,» Padova, 2016.

[119] G. Litjens e E. V. S. W. Worrel, «Economic benefits of combining self-consumption enhancement with frequency restoration reserves provision by photovoltaic-battery systems,» *Applied energy,* vol. 223, pp. 172-187, 2018.

[120] Terna, «Rapporto mensile sul Sistema Elettrico-Dicembre 2017,» Terna, Rome, 2018.

[121] U. Montanari e A. T. Siwe, «Prosumers as aggregators in the dezent context of regenerative power production.,» *IEEE,* pp. 167-174, 2014.

[122] M. Gianni, "GSE," 25-29 September 2017. [Online]. Available: https://www.gse.it/documenti_site/Documenti%20GSE/Studi%20e%20scenari/PV%20market,%20business%20and%20price%20developments%20in%20Italy.PDF. [Accessed 15 April 2020].

[123] F. Tilli e G. Maugeri, «National Survey Report of PV Power Applications in Italy,» 2018.
[124] 7 September 2018. [Online]. Available: https://powerhouse.net/en/scenario/unlocking-flexibility/. [Consultato il giorno 29 July 2020].
[125] Terna, «Fast Reserve Seminario illustrativo del progetto pilota,» Roma, 2020.
[126] D. Cascone, «Participation of RES and ESS to the Italian Ancillay Services Market: A Collaborative approach based on domestic users aggregation,» 2018.
[127] GSE, «Annual Report,» 2019.
[128] L. Meeus e T. Schittekatte, «The EU electricity network codes.,» 2018.
[129] C. Tribbia, «Solving the Italian Electricity Power Exchange,» 2015.