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Department of Electrical Engineering

Doctoral Program in Electrical Energy Systems

DOCTORAL THESIS

Development of Optimal Energy Management and Sizing Strategies for Large-Scale Electrical Storage Systems supporting Renewable Energy Sources

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“The ultimate measure of a ***wo*man** is

not where ***s*he** stands in moments of comfort and convenience,

but where ***s*he** stands at times of challenge and controversy.”

Martin Luther King

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Abstract

The development and integration of Renewable Energy Sources (RES) will lead to a more sustainable energy future. However, several challenges rise for the power grid design and operation, related to the increase of uncertainties in energy forecast, the increase on the variability and intermittency of renewable generation, and the decrease of system inertia. These factors affect the energy balance of the system and thus, the grid stability and reliability could worsen, increasing the amount of required frequency ancillary services (also known as reserve services).

Meanwhile the contribution of renewable energies is increasing in the energy mix, RES plants should improve their participation and operation through electricity markets in a more controllable and reliable way. Additionally, current market design is being changing to allow an inclusive participation of RES plants and new flexible participants in well-rewarded flexibility markets (such as, reserve markets). In this context, Energy Storage Systems (ESS) are considered one of the key flexible technologies which can support RES operation (RES-oriented services) and grid services at the same time, such as: 1) RES capacity firming, 2) production predictability improvement, and 3) provision of ancillary services.

However, the ESS widespread deployment has been restricted by their high technology costs. Thus, this PhD thesis deals with the topic of the ***"Development of Optimal Energy Management and Sizing Strategies for Large-Scale Electrical Storage Systems supporting Renewable Energy Sources",*** with the objective of developing a methodology with a global perspective, in which an advanced energy management strategy (EMS) addresses the RES+ESS asset management for the long-term planning, and the optimal sizing and operation of electro-chemical ESS in the short term (at real-time), and ensures the proper framework to evaluate the cost-effectiveness of ESS integration on grid-connected applications.

Consequently, the main objectives of the proposed EMS are the following: i) optimize energy and reserve market scheduling and minimize market penalties and imbalances, regarding most recent forecast information, ii) re-schedule RES generation intra-daily to control forecast errors and manage ESSs, iii) operate at real-time operation to provide the grid set-points according to defined supervisory controls, iv) implement a closed-loop model predictive control, and v) evaluate and estimate properly the ESS lifetime through aging models.

The proposed EMS is validated by means of two case studies: Firstly, individual RES+ESS plants operate independently (considering a wind or solar plant with an energy storage system), and secondly, RES portfolio with distributed ESS is jointly scheduled and operated through several real-time supervisory controls.

Resumen

El desarrollo e integración de las fuentes de energía renovable (RES) conducirá a un futuro energético más sostenible. Sin embargo, surgen varios retos en el diseño y la operación del sistema eléctrico, relacionados con las incertidumbres en la predicción y el aumento de la variabilidad de la generación. Estos factores afectan el balance de energía del sistema y, por lo tanto, la estabilidad y seguridad de la del sistema eléctrico podrían verse afectadas negativamente, aumentando la cantidad de servicios auxiliares necesarios (de reserva o regulación de frecuencia).

Mientras que se produce un progresivo aumento de la contribución de las energías renovables en el mix energético, las plantas renovables deberán mejorar su participación y operación a través de los mercados de electricidad de una manera más controlada y segura. Además, el diseño actual del mercado está cambiando para permitir una participación inclusiva en mercados de flexibilidad, que son mejor remunerados (como la regulación secundaria). En este contexto, los sistemas de almacenamiento de energía (ESS) se consideran una de las tecnologías flexibles clave que pueden apoyar la operación de las energías renovables, mediante servicios como: 1) control de la potencia firme, 2) compensación de los errores de predicción, y 3) provisión de servicios auxiliares de regulación de frecuencia.

Sin embargo, el desarrollo del almacenamiento está siendo pausado por sus altos costes. Por lo tanto, esta tesis doctoral aborda el ***"Desarrollo de estrategias óptimas de gestión y dimensionamiento de los sistemas de almacenamiento eléctrico a gran escala como apoyo a fuentes de energía renovable",*** con el objetivo de desarrollar una metodología con una perspectiva global, que integra una estrategia de gestión de energía avanzada (EMS) abordando la gestión de activos (RES + ESS) a largo plazo, el cálculo del dimensionamiento y operación óptima del almacenamiento en los mercados eléctricos a corto plazo (en tiempo real), para asegurar un marco adecuado que permita evaluar la rentabilidad de la integración del almacenamiento en aplicaciones conectadas a la red.

En consecuencia, los objetivos principales de la EMS propuesta son: i) optimizar la programación de los mercados de energía y de reserva, ii) ajustar la programación de la generación horariamente para controlar los errores de previsión y gestionar la energía almacenada, iii) operar en tiempo real para asegurar las consignas de red, iv) implementar un control predictivo en lazo cerrado, y v) estimar adecuadamente la vida útil del ESS a través de modelos de degradación.

La estrategia de gestión de energía propuesta es validada a través de dos casos de estudio: en primer lugar, una planta renovable individual con almacenamiento operando de forma independiente (considerando una planta eólica o solar) y, en segundo lugar, un porfolio de generadores renovables con almacenamiento distribuido operando conjuntamente ante diferentes controles de supervisión.

Laburpena

Energia berriztagarri iturrien (RES) garapenak eta integrazioak energia alorrean jasangarriagoa den etorkizuna bideratuko dute. Hala ere, sistema elektrikoaren diseinuan eta operazioan hainbat erronka sortzen dira, aurreikuspenetan ematen diren ziurgabetasunarekin eta sorkuntzaren aldakortasunarekin erlazionatuta daudenak. Faktore hauek sistemaren energia balantzean eragina dute, sistema elektrikoaren egonkortasunean eta segurtasunean eragin negatiboa izanez, beharrezkoak diren frekuentziaren erregulazioko zerbitzu kopurua areagotuz.

Mix energetikoan energia berriztagarrien kontribuzioa handiagotze mailakatua gauzatzen den bitartean, instalazio berriztagarriek haien partaidetzan eta operazioan hobetu beharko lukete modu kontrolatuago eta seguruago batean elektrizitatearen merkatuaren bitartez. Horretaz gain, gaur egungo merkatuen diseinua aldatzen ari da malgutasunezko merkatuen inklusioa ahalbidetzeko, hobeto ordainduak daudenak (erreserbako merkatuak bezala). Testuinguru honetan, energia biltegiratze sistemak (ESS) energia berriztagarrien operazioak bermatu ditzaketen funtsezko teknologia malgu gisa kontsideratzen dira, hainbat zerbitzu emateko gaitasuna dutelako: 1) potentzia finkoaren kontrola, 2) aurreikuspen erroreen hobekuntza, eta 3) frekuentziaren erregulazioko zerbitzu osagarrien hornikuntza.

Hala eta guztiz ere, biltegiratzearen garapena motela da bere kostu altuengatik. Hortaz, doktorego tesi honen izenburua "***Iturri berriztagarrien sostengu den eskala handiko energia elektrikoaren biltegiratze sistemen kudeaketa estrategia optimoen garapena eta dimentsionamendua***" da, ikuspuntu globala duen metodologia garatzeko helburuarekin, non energiaren kudeaketa estrategia (EMS) aurreratu baten bidez epe luzean aktiboen (RES+ESS) kudeaketa gauzatzen den eta, bestalde, biltegiratzearen epe motzeko operazioa (denbora errealeko operazioa) eta dimentsionamenduaren kalkulua jorratzen den, biltegiratze sistemak duten aplikazioen errentagarritasunaren ebaluazio egokia ziurtatzeko.

Ondorioz, EMS-aren helburu nagusiak ondorengoak dira: i) energiaren merkatuaren eta erreserbaren programazioak optimizatu, ii) energia sorkuntzaren programazioa egunean zehar doitu aurreikuspen erroreak kontrolatzeko eta biltegiratze sistemak kudeatzeko, iii) denbora errealean operatu sarearen kontsignak bermatzeko, iv) begizta itxiko kontrol prediktiboa inplementatu, eta v) zaharkitze ereduen bidez ESS-aren bizitza era egokian estimatu.

Proposatutako energiaren kudeaketa estrategia balioztatuta dago bi azterketa-kasuren bidez: lehenik, biltegiratze sistema duen instalazio berriztagarri indibidual bat modu independentean operatzen (instalazio eoliko edo eguzki-instalazio bat kontsideratuz) eta bigarrenik, iturri berriztagarrien taldea biltegiratze sistemekin, non gainbegiratutako kontrol ezberdinekin batera operatzen duten.

Contents

Scientific contributions

Within this research thesis, several scientific contributions to the literature were published or are being peer-to-peer reviewed. These contributions are listed below.

JOURNAL ARTICLES:

a. Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Annual Optimized Bidding and Operation Strategy in Energy and Secondary Reserve Markets for Solar Plants with Storage Systems" *IEEE Transactions on Power Systems,* vol. 34, issue 6, pp. 5115-5124, November 2019. doi: **10.1109/TPWRS.2018.2869626**
b. Amaia González-Garrido, Andreas Thingvad, Haizea Gaztañaga, and Mattia Marinelli, "Full-scale electric vehicles penetration in the Danish Island of Bornholm—Optimal scheduling and battery degradation under driving constraints" Journal of Energy Storage, vol. 23, pp. 381-391, June 2019
doi: **10.1016/j.est.2019.03.025.**
c. Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Techno-Economic Impact of Energy Storage Sizing on Solar Plants in Continuous Intraday and Reserve Markets" *Elsevier Renewable Energy,* under review
d. Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Centralized Energy Management Strategy and Storage Sensitivity Analysis for Renewable Portfolio in Energy and Reserve Markets" *Elsevier Applied Energy,* under review

CONFERENCE ARTICLES:

e. Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Comparison of Market Operation Strategies for Photovoltaic Power Plants with Storage Systems Providing Frequency Ancillary Services" *2018 Thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER),* Monte-Carlo, April 2018
doi: **10.1109/EVER.2018.8362386**
f. Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Sensitivity Analysis of the Storage System Sizing for Solar Plants in Energy and Reserve Markets" *2018 15th International Conference on the European Energy Market (EEM)*, Lodz, June 2018
doi: **10.1109/EEM.2018.8469953**

g. Amaia González-Garrido, Igor Villarreal, Haizea Gaztañaga, Andoni Saez de Ibarra, and Pablo Eguia "Optimized Energy Management Strategy for Wind Plants with Storage in Energy and Reserve Markets" *Journal of Physics: Conference Series, vol. 1222 (2019), 012039.* Presented at *WindEurope Conference and Exhibition*, Bilbao, April 2019
doi: **10.1088/1742-6596/1222/1/012039**

h. Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Techno-Economic Assessment of Energy Management Strategies for a Renewable Portfolio with Storage Systems in Energy and Frequency Reserve Markets" *2019 16th International Conference on the European Energy Market (EEM)*, Ljubljana, Sept. 2019. **Best paper award**

ARTICLES IN COLLABORATION:

i. Victor Isaac Herrera, Aitor Milo, Haizea Gaztañaga, Amaia Gonzalez-Garrido, Haritza Camblong, and Andres Mauricio Sierra-Gonzalez "Experimental comparison of energy management strategies for a hybrid electric bus in a test-bench" *2018 Thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER),* Monte-Carlo, April 2018
doi: **10.1109/EVER.2018.8362389**

j. Victor Isaac Herrera, Aitor Milo, Haizea Gaztañaga, Amaia Gonzalez-Garrido, Haritza Camblong, and Andres Mauricio Sierra-Gonzalez "Design and Experimental Comparison of Energy Management Strategies for Hybrid Electric Buses Based on Test-Bench Simulation" *IEEE Transactions on Industry Applications*, vol. 55, no. 3, pp. 3066-3075, May-June 2019
doi: **10.1109/TIA.2018.2886774**

INTELLECTUAL PROPERTY REGISTRATION:

k. Amaia González, Andoni Saez de Ibarra, and Haizea Gaztañaga. "SS-1-19. Software para la gestión energética de una planta renovable con almacenamiento", *("Software for the energy management strategy for a renewable plant with an energy storage system")*, January 2019.

PATENT PENDING:

l. Amaia González, Andoni Saez de Ibarra, and Haizea Gaztañaga. "IKER017. Procedimiento e instalación para la gestión de energía eléctrica", *("Procedure and installation for energy management - centralized control")*, Sept. 2019.

Introduction

The development and integration of Renewable Energy Sources (RES) are enabling the reduction of greenhouse gas emissions and the dependence on fossil energy sources. However, several challenges rise for power grid design and operation, among others: the increase of uncertainties in energy forecast due to their high dependence on weather conditions, the increase on the variability and intermittency of power generation, and the decrease of the system inertia, since generators connected through power converters are increasing to a greater extent compared to synchronous generators. With the increasing integration of variable RES, these factors affect the energy balance of the system and thus, the grid stability and reliability could worsen, increasing the amount of energy required in the ancillary services.

Moreover, due to their power variability and their lower controllability, RES plants have more difficulties in participating and operating suitably under current electricity markets from a technical and economic point of view compared to conventional generators. Therefore, electricity markets and regulatory frameworks should be adapted to renewable sources in order to reduce market barriers, and to design effective and competitive electricity markets which encourage the inclusion and integration of new flexible participants such as energy storage devices.

In this context, Energy Storage Systems (ESS) are considered one of the key flexible technologies which will support high renewable penetrations in the electricity system, by enabling more flexibility and controllability to their market participation and operation. As a result, RES+ESS participate in a more reliable and profitable way in electricity markets. Consequently, RES+ESS maximize their economic profits.

ESS can deliver several utility services, such as: 1) RES capacity firming to smooth power variability and volatility, 2) production predictability and control to mitigate large forecast errors and reduce energy imbalances, and 3) provision of frequency ancillary services to maintain the energy balance between generation and load.

Thus, RES+ESS can also support the system stability and reliability, instead of being the source of these energy imbalances. At the same time, from a system operator point of view, the improvement of RES operation will lessen the frequency ancillary services required. As a result, the grid operation will be more reliable, being beneficial for all stakeholders.

However, the ESS widespread deployment has been restricted by their high technology costs, the difficulty to estimate their lifetime according to each particular application or service, the lack of deployment or commercial facilities, and several technical, economic and regulatory barriers caused by current electricity market design.

To become a cost-effective solution and recover the additional ESS investment, the joint operation of RES+ESS in multiple markets could increase their economic and technical value. In this way, the provision of frequency ancillary services, characterized of being high-value services and highly rewarded, will be another market opportunity for RES+ESS owners, achieving additional sources of revenues.

However, these ancillary services are characterized by a huge volatility and uncertainty in operation, which could hinder the RES operation. For this purpose, the adoption of advanced Energy Management Strategy (EMS) should be developed to achieve a controllable and reliable operation of RES+ESS which leads to a profitable exploitation.

Thus, the main problem found out in the current literature is the lack of a methodology for the proper sizing and operation of a renewable asset management in a realistic electricity market for the long-term planning and short-term operation assessment, giving a suitable and accurate framework to evaluate the cost-effectiveness of ESS integration for different RES technologies for grid-connected applications.

Besides the selection of a suitable ESS technology for the considered application and strategic objectives or services to be provided, the initial ESS sizing selection and its optimal operation are two crucial factors to assure a viable, profitable and efficient operation of RES+ESS asset.

Firstly, the selection of ESS capacity plays an important role in assuring a more reliable and profitable operation which leads to increase the market incomes. However, large ESS acquisition costs could result in a reduction of the overall asset profitability. In contrast, a smaller ESS capacity could not provide or operate successfully according to the technical requirements of the application, despite its acquisitional cost is reduced compared to an oversized ESS selection.

Furthermore, how the ESS is managed and controlled during their lifetime operation is essential for the ESS cost-effectiveness. During its lifetime, ESS degradation increases or decreases directly according to its more or less demanding operation defined to achieve the strategic objectives of the application. An optimal EMS shall optimize market scheduling, assess optimal ESS sizing, provide a controllable and reliable real-time operation, and after all, maximize portfolio or asset profitability.

According to the analyzed publications, currently it is still challenging to obtain significant profits from the integration of electrochemical ESS on grid-connected renewable applications due to several identified weaknesses from the literature and current market and economic restrictions.

Firstly, researches that are only limited to accommodate or smooth RES energy do not reflect the potential value of ESS. Thanks to the fast response of ESS, they can increase the asset revenues thanks to the participation in multiple electricity markets.

In order to control and manage suitably these energy resources, Virtual Power Plant (VPP) or Microgrid (MG) concepts emerge with the main objective of applying these energy managements strategies to operate and manage diverse distributed energy resources, mainly renewable plants and storage systems in a centralized way.

However, conventional and controllable plants (thermal power plants, microturbines or hydro units) are mostly taken into consideration in the literature, which reduce the unpredictable RES nature and soften the RES+ESS restrictive technical constraints.

Another important gap found along the literature review, after the optimization process for market scheduling, it is necessary to simulate and validate the proposed EMS on Real-Time (RT) operation as much realistic as possible, in which the influence of uncertain RT parameters (market prices, forecast errors, reserve market needs and ESS capacity fade) can be accurately validated in techno-economic terms.

Without a proper evaluation of the ESS operation, any technical evaluation would be less realistic or inaccurate. And thus, their suitability and profitability for any given application could be hardly assured and validated properly.

Regarding ESS features, its efficiency, acquisition and operating costs, technical constraints due to its limited capacity, aging model and capacity/power sizing analysis should be included in the methodology. Among all the literature analyzed in this field, the influence of ESS sizing, operation and degradation issues supporting renewable plants in multiple markets has not been yet assessed entirely. In particular, the ESS sizing has strong influence on the market schedule optimization, and consequently, on the reliability of the real-time operation.

That is, advanced EMS should be developed to improve and validate cost-effective ESS solutions to support utility-RES providing flexibility and controllability in multiple electricity markets and grid services, and ensuring adequacy, quality and security.

To deal with the identified challenges, the main aim of this PhD is the:

"Development of Optimal Energy Management and Sizing Strategies for Large-Scale Electrical Storage Systems supporting Renewable Energy Sources"

In addition to this main objective, other subsequent objectives are reached for the successful achievement of this PhD thesis:

- To develop the methodology for the optimal Energy Management Strategy (EMS) of large-scale ESS supporting RES in the energy and ancillary markets, with the objective of maximizing the portfolio profitability, by finding a trade-off between market revenues, overall storage costs and a reliable operation. The bidding optimization will calculate in the short-term the optimal daily bids for multiple markets according to the RES forecast profile and energy available in ESSs.
- To determine the optimal ESS sizing through a sensitivity analysis. ESS sizing has strong influence on the market schedule optimization, and consequently, on the reliability of the real-time operation. However, the optimal ESS capacity shall be defined after a long-term evaluation, not as a design parameter in the short-term optimization (daily market schedule) due to several uncertain parameters in the RT operation, such as, the reserve requirements and RES forecast errors.
- To evaluate the proposed methodology and validate the replicability of the proposed EMS methodology of this PhD thesis, two relevant case studies are selected. Firstly, individual RES+ESS plants operate independently, and secondly, renewable portfolio with distributed ESS is scheduled and operated through a centralized supervisory control. Moreover, a techno-economic analysis is conducted for one-year simulation period and validated under the Spanish market framework.

The dissertation document has been organized in five main chapters:

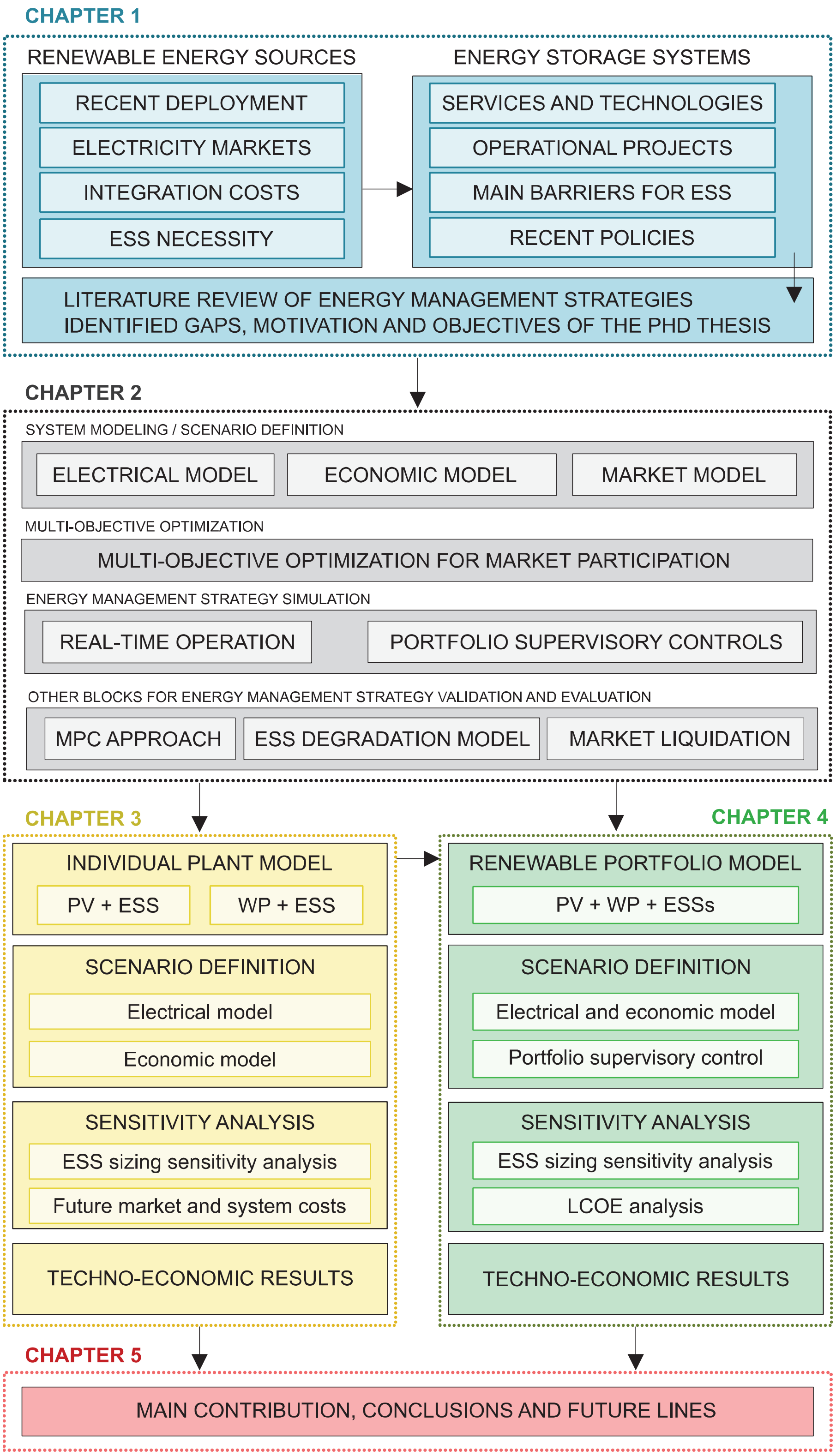
In chapter one, the recent deployment and main drawbacks of RES is contextualized. Then, the potential opportunities for ESS are described, as well as their main services, technologies and the most representative operational projects to date are exposed and analyzed. Furthermore, the global electricity markets and ancillary services are analyzed, and the main barriers for energy storage in electricity market are identified and listed. Then, recent changes in aforementioned markets are exposed and the most favorable market designs for ESS are discussed.

Finally, the main publication found in the literature are critically reviewed related to the optimal energy management strategy of renewable plants and energy storage systems. The main gaps identified from the literature are also reported, which served as a baseline to define the research objectives adopted in this dissertation.

In chapter two, the proposed EMS is explained and developed according to the identified gaps and potential market opportunities for ESS. The main objectives of the proposed EMS are the following: i) optimize all market scheduling regarding most recent forecast information considering ESS degradation and minimize expected energy imbalances and market penalties, ii) operate at real-time to follow energy schedule and requested reserve delivery, as well as smoothing RES variability and managing large RES forecast errors, according to the selected portfolio supervisory control, iii) re-schedule RES generation intra-daily to control forecast deviations and manage ESSs, and finally, iv) evaluate and validate this EMS under a realistic market framework in the short and long term.

In chapter three, the EMS methodology is validated by means of two case studies: solar and wind plants with a decentralized or individual operation. In chapter four, optimal centralized EMS for a renewable portfolio composed entirely by RES and ESS is evaluated. Therefore, the improvements from centralized EMS are to smooth RES intermittency, mitigate RES forecasts errors and reduce even more annual market penalties and imbalances, by taking advantage of RES complementarity and SOC equalization techniques, which increase the ESS lifetimes (reducing their operating and replacement costs). As a result, the profitability of the portfolio is maximized.

In chapter five, the main conclusions of the present work are collected. The main contribution of the PhD thesis in the field of the development of optimal sizing and energy management strategies for storage system to support renewable market participation are pointed out. Lastly, some future lines are commented.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Chapter 1 State of the art

In this chapter the recent deployment Renewable Energy Resources (RES) is contextualized. The worldwide short-term electricity markets and ancillary services are summarized, in which RES participate and operate nowadays or in the near future. Despite a gradual inclusion of RES generators in the electric network and their increasingly controllable participation in electricity markets, some intrinsic integration costs, impacts and drawbacks appear in the electric grid. The main current barriers are identified which reduce the RES business cases.

As solution, the potential opportunities for Energy Storage Systems (ESS) are described, as well as their main services, technologies and the most representative operational projects to date are exposed and analyzed. Later, several recommendations and guidelines are given in order to select the most suitable ESS technology according to the particular application and desired functionalities.

The main barriers for ESS related to the market design, economics and regulation are identified and listed, and the recent changes in aforementioned markets are exposed. Therefore, some conclusions and recommendations about the most favorable market designs or schemes for ESS are exposed and discussed.

Finally, the main publications found in the literature are critically reviewed related to the optimal energy management strategy of renewable plants and energy storage systems, and the main gaps identified from the literature are also reported, which serve as a baseline to define the research objectives adopted in this dissertation.

1.1 Renewable energy resources

The growing penetration of RES will contribute to achieve the targets toward a low carbon economy. Their global growth is mainly led by a noticeable reduction of investment and operating costs, resulting in less Levelized Costs of Energy (LCOE), which enable RES being increasingly more competitive than conventional power plants. Since renewable generation units are coupled to the grid by means of power converters instead of inert rotating masses of conventional generators, network stability and security is weakening. Furthermore, due to the variable nature of wind and solar generation and their geographical distributed resources, the power grid planning and real-time operation is being more challenging. For their suitable deployment, these renewable resources should be more controllable and predictable in their market participation and operation, as well as giving the same services and functionalities than conventional plants. Therefore, new cost-effective solutions should be developed to support RES integration in the electricity market.

1.1.1 Recent RES deployment

The First Industrial Revolution at the end of the 18th century brought about huge changes on the global economy, previously based on agricultural and craft sectors. New technological innovations encouraged an industry-based economy from that moment. Emerging energy resources, mainly the mineral coal, enabled the transformation of many productive processes through the creation and use of the steam engine. The textile-industry increased its productivity, the mineral coal replaced wood, water and wind as main source to produce energy, new steel making processes appeared and new forms of commerce emerged thanks to trains and ships. These technical developments also improved the quality of life of the society and increased the global population.

Even then, the first ecological and environmental concerns raised in response of the increasing levels of air pollution and the intensive consumption of coal.

Over the last century, the energy consumption per capita has increased unprecedented mostly based on fossil fuel resources, being a non-sustainable global economic growth [1]. This fossil-based dependence is constantly growing over last decades, despite more efforts are being increasingly made to promote Renewable Energy Sources (RES) and achieve the transition from a carbon-intensive to a low-carbon economy.

"*Humanity's carbon footprint alone more than doubled since the early 1970s and remains the fastest growing component of the widening gap between the Ecological Footprint and the planet's biocapacity,*" stated Mathis Wackernagel, CEO of Global Footprint Network, "*To achieve the goals of the Paris Climate Accord (COP21), humanity would need to exit the fossil fuel economy before 2050.*"

Facing that situation, worldwide energy policies have intended to comply with the greenhouse gas (GHG) emission reduction commitments agreed in Kyoto Protocol in 1992 for the first time and in successive United Nations Climate Change Conferences (UNFCCC).

To reduce the dependence on fossil energy sources, decrease GHG emissions, and mitigate the climate change, renewable energy -mainly solar and wind- was increasingly deployed in the three main energy consumption sectors (electricity, heating/cooling and transport). Besides the increased integration of energy from renewable energy sources, the controlled energy consumption, together with energy savings and energy efficiency, should constitute other important and necessary measures to be promoted.

The development of energy from renewable sources should be carried out closely linked to the energy efficiency and digitalization. For this purpose, the energy sector needs to modernize the electric network to meet all the challenges of this new paradigm.

One of the first recent Green Papers "*A European strategy for sustainable, competitive and secure energy*" [2], published in 2006 by the European Commission, defined overall strategic objectives regarding sustainable energy use, competitiveness and security of supply, offering a clear European framework for national decisions on the energy mix. Several proposals were defined to achieve sustainable, competitive and secure energy.

Firstly, the "*sustainable, competitive and secure energy*" should be achieved through open and competitive energy markets based on low-carbon and renewable sources. In fact, a competitive single European electricity market would reduce prices, improve security of supply and boost competitiveness.

Secondly, additional electricity interconnections should be also developed to permit real competition between Member States as well as making a substantial investment over next decades to replace aging electricity generation capacity. For timely and sustainable investments, a properly functioning market is needed, giving the necessary price signals, incentives, regulatory stability and access to finance.

Thirdly, an effective legislative and transparent regulatory framework must be in place and be fully applied in practice. Thus, a close collaboration and exchange of information between transmission and distribution system operators will be enhanced. For this purpose, a European grid code will establish common rules and standards on issues that affect cross-border trade.

Finally, a long-term road-map for RES and energy efficiency goals should be adopted in order to deal with the challenges of climate change.

In this line, "*Renewable energy road map, renewable energies in the 21st century: building a more sustainable future*" [3], published in 2007, set out a long-term vision for renewable energy sources in the European Union (EU). It proposed that the EU should establish a target of 20% for the overall share of RES energy by 2020.

The Directive 2009/28/EC [4], two years later, established this mandatory target of 20% by 2020. Moreover, this directive stated that there was a need to support and promote energy from renewable sources into the transmission and distribution grid and the use of energy storage systems for integrating intermittent renewable sources into the grid.

Afterward, C This package proposed the target at the EU level of at least 27% for improving energy efficiency, for the share of renewable energy consumed and for total energy savings by 2030.

The share of RES energy in the EU Member States can be observed in Figure 1.1. The average target of European Members is 20% by 2020, although only eleven European countries have reached their own RES share objective before 2017.

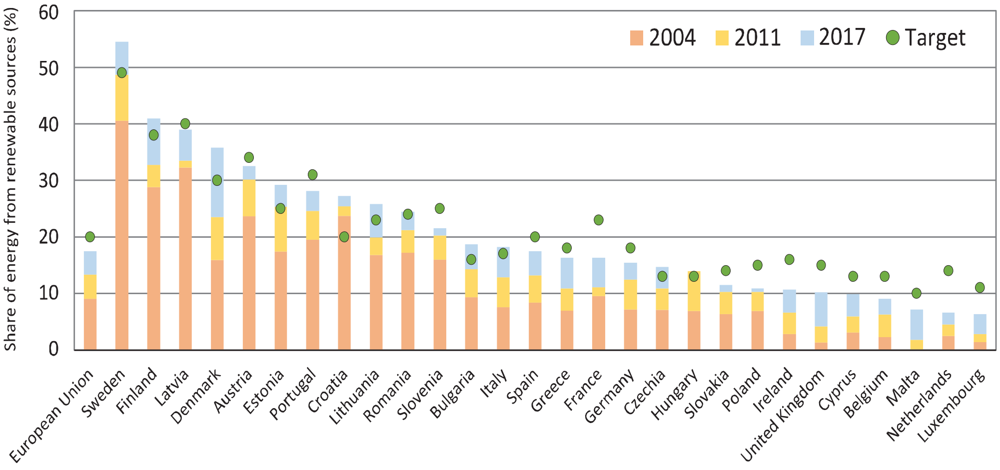


Figure 1.1 – Share of energy from renewable sources, 2017 (in % of gross final energy consumption). Data source from ec.europa.eu/Eurostat [5].

Not only the European Union is taking steps toward a sustainable energy [6]. Most countries have different strategies and policies to address the increasing RES share.

In the United States (US), the Environmental Protection Agency (EPA) in 2015 mandated reductions in pollution standards from new, existing and retrofitted fossil power plants and through stationary combustion turbines by the "*Clean Power Plan*" [7]. The Carbon Dioxide reduction objective was settled in 32% from 2005 levels by the year 2030. Regarding RES promotion, some US states have adopted Renewable Portfolio Standards (RPS) with the aim of increasing production of energy from RES. One of the most engaged state, California, established a RES target of 33% of the electricity by 2020, and 50% by 2030. The California Solar Initiative (CSI) [8] offered incentives for their investment and operating costs up to 2016. Moreover, the United States Department of Energy (DOE) encouraged the Wind Powering America (WPA) initiative to collaborate with all wind stakeholders, with the objective of achieving a 20% wind energy by 2030 scenario [9]. There is not a clear target at the US level. Thus, only 17% of the electricity comes nowadays from RES (6.6% wind, 1.6% solar and 8.8% hydroelectric) [10].

In 2014, the Turkish government approved its "*National Renewable Energy Action Plan*", targeting a 30% renewable energy share. Furthermore, "*China Strategic Energy Action Plan*", characterized by coal-based generation, proposed an objective of 15% of non-fossil fuels in primary energy consumption and a reduction of coal consumption less than 62%. These percentages mean an installed capacity of wind energy around 200 GW and solar about 100 GW in 2020.

Regarding different renewable energy resources, wind and solar energy have undergone an overwhelming worldwide development compared to other renewable technologies [11]–[14]. Overall, the global installed renewable power capacity by 2018 is 2378 GW (around 1000 by 2007) which could supply around 26.2% of global electricity production: 15.8%

of hydropower, 5.6% of wind and 2.4% of solar PV power. However, RES only reach 10.6% in terms of final energy consumption [14].

Onshore Wind Power (WP) is a proven and mature renewable technology that is being deployed globally on a mass scale. During the first half of 2000s, Germany, Spain and the United States are leaders in deployed capacity and wind generation. From 2005, a mass deployment of wind energy began also in China. From 2009, China deployed more wind capacity than any other country in the world. Around 49 GW of wind power capacity was added in 2018, bringing the global total wind installed capacity of WP to nearly 564 GW [14]: China (184 GW), the United States of America (94 GW), Germany (59 GW), India (35 GW) and Spain (23 GW). The European Union increased up to 179 GW in 2018 (32% of global WP) from 63 GW in 2008. Regarding off-shore wind energy, 18 GW was installed in the European Union by 2018.

Focusing on solar photovoltaic (PV) installed capacity, the cumulative installed capacity of PV reached roughly 100 GW at the end of 2012 (from 1.5 GW in 2000 and 40 GW at the end of 2009) [13]. While Europe was leader in the 2000s-decade, Asia's share started to grow rapidly in 2012 and this growth was confirmed in recent years. At the end of 2018, more than 480 GW of solar PV was installed [14]: China (175 GW), followed by Japan (55 GW), the United States of America (51 GW), Germany (46 GW), India (26 GW), and Italy (20 GW). The European Union represent 24% of the global PV cumulative installed capacity, with 125 GW at the end of 2018 [12].

The evolution of European renewable installed capacity for different scenarios are shown in Figure 1.2 for wind and Figure 1.3 for solar energy.

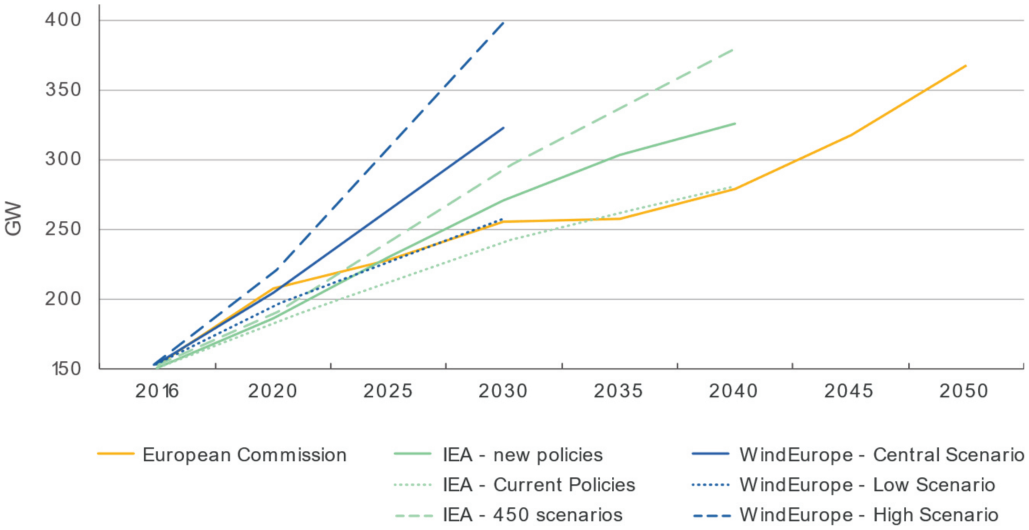


Figure 1.2 – European wind cumulative installed capacity. Source: [15].

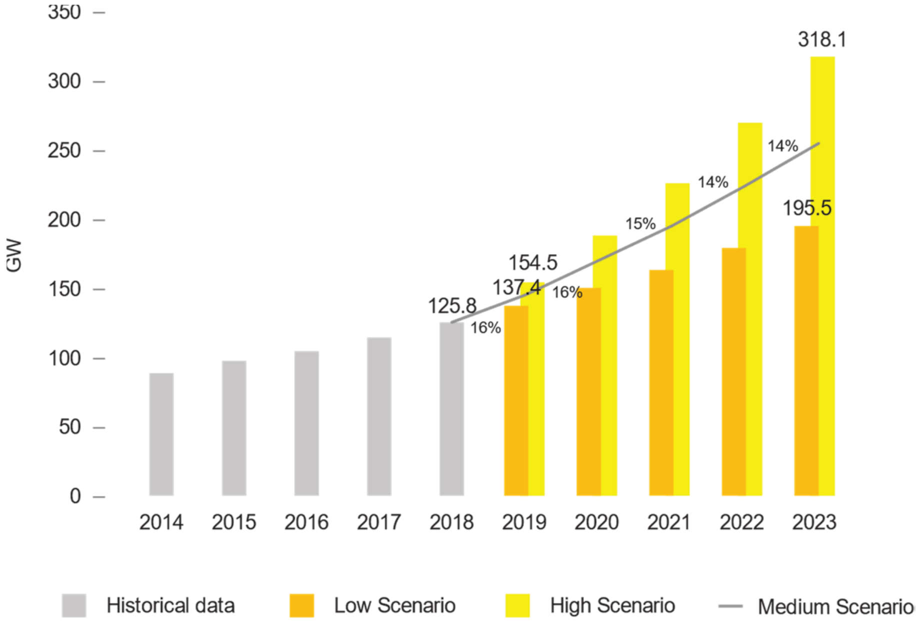


Figure 1.3 – European solar cumulative installed capacity. Source: [16].

As can be observed both renewable technologies have undergone an exponential growth in the RES installed capacity and their share in the mix generation. Therefore, they will increase significantly their presence in the electrical power system in next decades.

Therefore, their generation should be controlled and scheduled in the same way as conventional plants through the electricity markets. And consequently, they should be responsible of delivering the same amount of energy than expected. That is, the greater the participation of RES in the network is, the greater their responsibility to fulfil the demand curve and to meet the technical requirements as conventional plants shall be. Therefore, additional grid services and functionalities can be provided through new cost-effective innovative solutions.

1.1.2 Electricity market participation

In this section, the worldwide electricity market structure is described. Therefore, a clear classification and the main features of each market are conducted, including the distinctive features of each country. Generally, short-term electricity markets [17]–[22] are organized into Energy Markets (EM) and system adjustment services. Figure 1.4 shows the chronological representation of the main short-term electricity markets in which three stages are mainly defined: trading, delivery and billing. A description of short-term electricity markets is exposed below.

1.1.2.1 Energy markets and imbalance settlement

EM are classified in day-ahead market and intraday market.

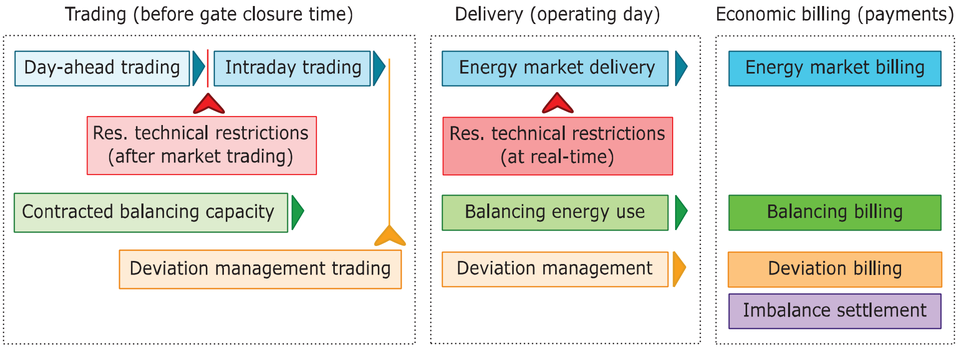


Figure 1.4 – Chronological representation of short-term electricity markets.

Firstly, the **Day-Ahead Market** (DM) is the main energy trading market to meet demand of the following day. Sellers of electricity present energy bids to the Market Operator (MO) for each of the production units they own. The MO collects purchase and sale bids, and calculates the price using a market-clearing pricing procedure.

Energy products are mainly auctioned at hourly marginal price (€/MWh), whereas time resolution varies in Europe (1h, 30 min or 15 min). The DM traded energy in Spain was 76% of the consumption in 2017 [23] where most RESs take part. In contrast, bilateral contracts are widely used in Germany, France or United Kingdom [24]–[26].

The **Intraday Markets** (IM) (IM do not exist in USA markets) are similar to the day-ahead market but cleared closer to power delivery and may cover a shorter trading horizon. These trading mechanisms, closer in time to the power delivery, allow a higher accuracy on generation forecasts by intermittent sources. Therefore, non-dispatchable producers can make adjustments to their DM schedules. IM improves greatly forecast accuracy and reduces energy deviations and reserve needs [27]. In that way, the balancing services could be reduced.

Moreover, in most countries this IM is delivered in a 15 min-basis in central Europe and 30 min-basis in France, while in Spain or Italy are on hour-basis. IM energy trading is based on discrete auctions (at marginal price) or Continuous Intraday Market (CIM) (based on pay-as-bid price). CIM has low liquidity in Nord-pool [28]–[30], whereas in Spain CIM was launched in June 2018 together with discrete auctions. IM has high liquidity and market participants (around 10% of total traded energy).

Imbalance settlement (IB) means a financial settlement mechanism aiming at charging or paying Balance Responsible Parties (BRPs) for their energy imbalances (deviations between generation, consumption and commercial transactions). According the balance responsibility definition defined in regulation EU-2019/943 [31], "*all market participants shall be* *responsible for the imbalances they cause in the system. To that end, market participants shall either be balance responsible parties or shall contractually delegate their responsibility to a BRP of their choice. Each BRP shall be financially responsible for its imbalances and shall strive to be balanced or shall help the electricity system to be balanced.*”

However, this balancing responsibility can be derogated for some demonstration projects or particular renewable plants. In some countries, like Spain or Denmark, RES plants are financially responsible for their own energy imbalances like other generators. CIM will be taken into advantage to minimize greatly their own energy imbalances. In contrast, wind plants do not bear their extra balancing costs in France or they are only partially responsible in Germany [32]. In addition to the Feed-in-Tariff (FIT) support, this issue could be the reason why RES plants do not participate usually in European CIM [33][26]. Including more RES responsibility could reduce the illiquidity in CIM.

IB settlement billing can be established as one or two-price system as in Table 1.1. In the one-price system, the purchase and sales prices of imbalance power are identical. In the two-price system, separate prices are calculated for the purchase and sales of imbalance power, depending on the direction of each BRP's energy imbalances (negative or positive) and the system needs (upward or downward). The IB is settled on two-price system in Spain, Italy or France, and one-price in Germany [33].

Table 1.1 – IM settlement billing for one and two-price system.
Market prices: λ^{DM} (day-ahead), $\lambda^{imb^+}, \lambda^{imb^-}$ (imbalances), $\lambda^{up}, \lambda^{dw}$ (balancing).

IB settlement	BRP imbalance	System needs		
		Upward (+)	In balance	Downward (-)
One-price	Positive (+)	λ^{imb^-} ($\approx \lambda^{up}$)	λ^{DM}	λ^{imb^+} ($\approx \lambda^{dw}$)
	Negative (-)	λ^{imb^-} ($\approx \lambda^{up}$)	λ^{DM}	λ^{imb^+} ($\approx \lambda^{dw}$)
Two-price	Positive (+)	λ^{DM}	λ^{DM}	λ^{imb^+} ($\approx \lambda^{dw}$)
	Negative (-)	λ^{imb^-} ($\approx \lambda^{up}$)	λ^{DM}	λ^{DM}

1.1.2.2 System adjustment services

The system adjustment services include all those services required to ensure the system's operation, including the resolution of technical restrictions, Ancillary Services (AS) and deviation management.

Focusing on AS, they are procured by the Transmission System Operator (TSO) or by the Distribution System Operator (DSO) to maintain system stability and security, divided into: frequency ancillary services (or balancing services), and non-frequency ancillary services (voltage support and black-start capability).

The objective of frequency ancillary services (or balancing services) [34]–[36],[37] is to maintain the system frequency within predefined stability limits and achieve instantaneous physical balance between generation and demand, in order to maintain a satisfactory level of operational security and with a satisfactory quality of supply.

Frequency ancillary services terminology and characteristics vary considerably between countries [17]–[20], [38]–[40] but their objective is alike. Frequency ancillary services guarantee energy balance and stabilize, maintain and recover the system frequency. They allow the short-term covering of dispatched power due to equipment failures, sudden loss of a generation or a transmission line, intermittent nature of renewable resources, large load deviations or transmission constraints [21].

In some countries these services have their own markets whereas they are compulsory in other regions. Moreover, the gate closing times, minimum bid size, or the activation times are also different among countries which make difficult to assess or compare techno-economically the potential of ESS for all markets as a whole. These frequency ancillary markets, summarized in Figure 1.5, are organized as follows according to the European Network of Transmission System Operators (ENTSO-E) in the EU and Federal Energy Regulatory Commission (FERC) in the USA.

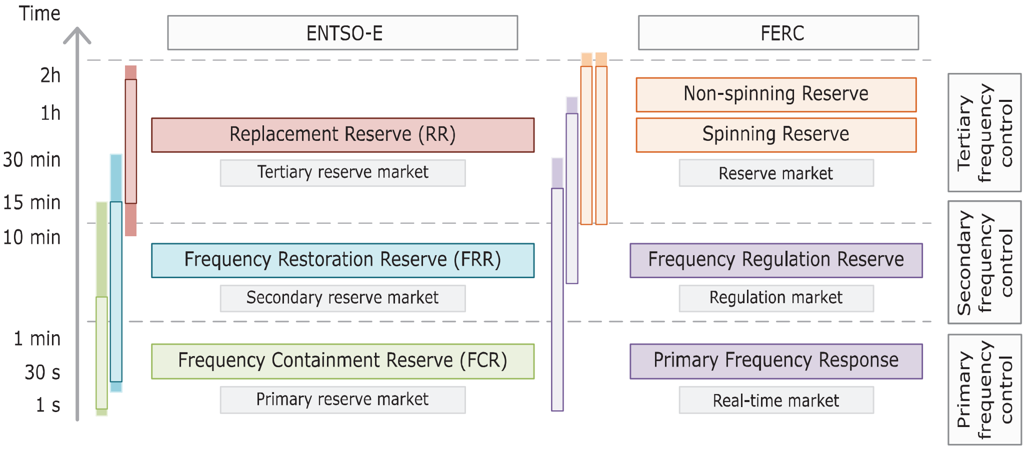


Figure 1.5 – Frequency ancillary services and time-frame horizons in the EU and the USA.

The **primary reserve markets** (similar to real-time market in USA) provides the primary frequency control services (also known as Frequency Containment Reserve (FCR) by the UCTE or Primary Frequency Response by the FERC). This market provides energy to cover both generation excess or deficit and constitutes the last market prior to power delivery to balance production and consumption, which reacts to system needs in even shorter time periods of seconds to maintain instantaneously the power balance in the whole synchronously interconnected system.

The primary reserve market is cleared just minutes before the actual power delivery (in some USA market regions -PJM and ISO-, Finland or Sweden), the day before in Denmark, Germany or Norway, the week before in France and Belgium, the year before in United Kingdom or be a mandatory service in Spain and Italy.

The **secondary reserve markets** (known as regulation market in USA) provide the secondary frequency control through the available active power reserves (also known as Frequency Restoration Reserve (FRR) by the UCTE or Frequency Regulation by the FERC). This market deals with greater imbalances to restore power balance and system frequency to the nominal value in several minutes.

The regulation market is typically cleared once a day on an hourly basis and assigns to production units the power bands to be used in real-time operation for load following. FRR service consists of an auction-price for capacity reservation (€/MW) and a price for energy product in real-time operation (€/MWh). FRR are active power reserves available to restore system frequency to its nominal value. The minimum size offers, auction times and clearing process are diverse in European markets [20],[40].

Moreover, FRR market auctions are cleared in most European countries, while in France it is a mandatory service. Regarding the capability auction, it is typically cleared on an hourly basis on daily auctions (in some USA market regions, Spain, Portugal and France), weekly auctions (in Germany and Belgium), or monthly auctions (in the Netherlands).

Concerning minimum bid size, the minimum hourly capacity reservation in Spain is 10 MW. Across central and north Europe, the minimum bid offer is established between 1-5 MW, and less than 1 MW in France. With the increasing RES penetration and distributed generation, it is expected to be reduced to 1 MW in the short-term [20],[40].

The pricing rule is marginal in Spain and Norway, pay-as-bid price in most Europe, or regulated price in France and Poland. All this information about ancillary markets can be consulted in the annual survey [40] carried out by ENTSO-E.

Later, these power capabilities (upward and downward bands) are required in real-time operation. The time-frame for this FRR activation is also different in each country. The Automatic Generation Control (AGC) provides up and down real-time load-following capability to enforce continuously the balance between production and consumption. Generation units that provide regulation service must be able to respond to AGC signals from the system operator and change their output accordingly on very short time scales. It could generalize that its start-up time shall not be delayed for more than 30 seconds and must be capable of being maintained for a period of 15 minutes until being replaced by Replacement Reserves.

Regarding the involved BRPs, the provision of balancing services by wind and/or solar generators is allowed, for example, in Spain (since 2016 [41]), Denmark and the Netherlands [32]. ESS can only participate in FRR in the Netherlands, Switzerland and UK [40].

The **tertiary reserve markets** (known as reserve market in USA) provide tertiary frequency control by standby power reserves (known as Replacement Reserve (RR) by the UCTE or reserve capacities by the FERC) whose objective is to restore or support the required level of Frequency Restoration Reserve (FRR) and to be prepared for additional larger system imbalances, such as failure of facilities or equipment in operation (production units or transmission lines), sudden demand changes or large fluctuations of production from intermittent and non-dispatchable sources. In case of USA markets, it can be classified as spinning and non-spinning reserve capacity.

1.1.3 Renewable integration costs

Despite a gradual deployment of RES generators in the electric network and their controllable participation in electricity markets, some intrinsic impacts will be produced to the extent that their inclusion is increased in the next decades.

With the increasing penetration of renewable resources in the electricity markets, their variable and intermittent production will increase the need of ancillary services or will affect future electricity prices. The controllable operation of RES will therefore play an active role on future secure networks, instead of being the source of these imbalances.

Anyway, to accommodate high RES while enforcing high standards for security of supply, integration costs are incurred in other parts of the system [27], [33], [42]–[44]: i) grid costs for network reinforcement and constraint issues, ii) profile costs result from the temporal profile mismatch, and iii) balancing costs as a result of RES forecast errors, which may require that additional reserve plants are held in readiness.

It is difficult to determine integration costs, because they cannot be measured or calculated directly, they should be estimated. Based on several studies, the integration costs can widely range from 10-30 €/MWh for wind and 25-50 €/MWh for solar at 10%-30% penetration levels [42], [45]. Focusing on the balancing costs, most analyses conclude that they could vary depending on the RES technology and the flexibility of the system [27]: from 12 €/MWh up to almost 50 €/MWh with a 50% penetration level. The impact of RES market value on average electricity price is represented in Figure 1.6.

Consequently, it is expected an increment of market prices due to these RES integration costs. That is, future market prices will increase according to the European Commission [46] in order to cover investment and operating costs of new installed capacity according to their Levelized Cost of Energy (LCOE) and the integration costs.

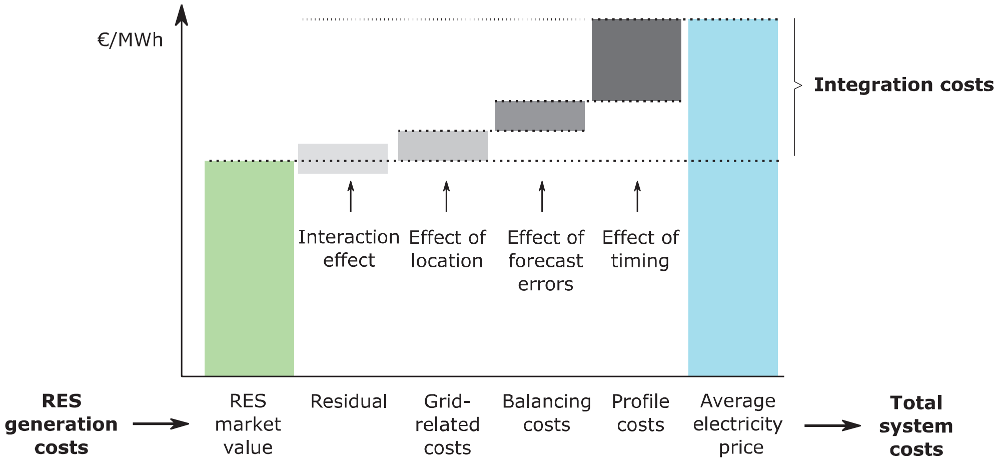


Figure 1.6 – Integration costs: profile, balancing, grid costs. Adapted from: [42].

An analogy of the RES integration costs can be made from the load perspective (see Figure 1.7). Profile costs are related to generation forecast profile which should be daily scheduled, in the same way system load should be predicted and scheduled. Balancing costs are required for load following and short-time regulation, in the same way as smoothing intra-hourly RES generation variability and instantaneous power intermittency.

As can be observed in Figure 1.8, there are different barriers regarding the market design or policies which increase the integration costs or discourage RES integration.

For example, early gate closures in energy markets (DM and IM) worsen the renewable predictability, and consequently their forecast errors increase. A reduction of time resolution for these markets (for example, intra-hour bids) could also improve market schedule according to their generation forecast profiles. Early gate closures for capacity or reserve markets also increase the uncertainty of reserve compliance, which reduce the feasibility of the business cases for RES participation.

Moreover, market design (gate closure times, minimum offers' size, or price clearing methods) has a direct impact on integration costs, as can be seen in Figure 1.8. Reasonable clearing market prices procedures (i.e. marginal prices or pay-as-bid prices) are also important for defining feasible business cases.

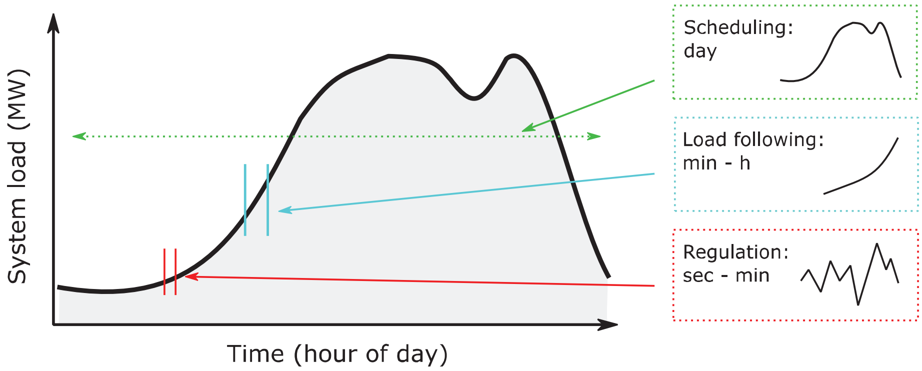


Figure 1.7 – Analogy from the load perspective. Adapted from: [9].

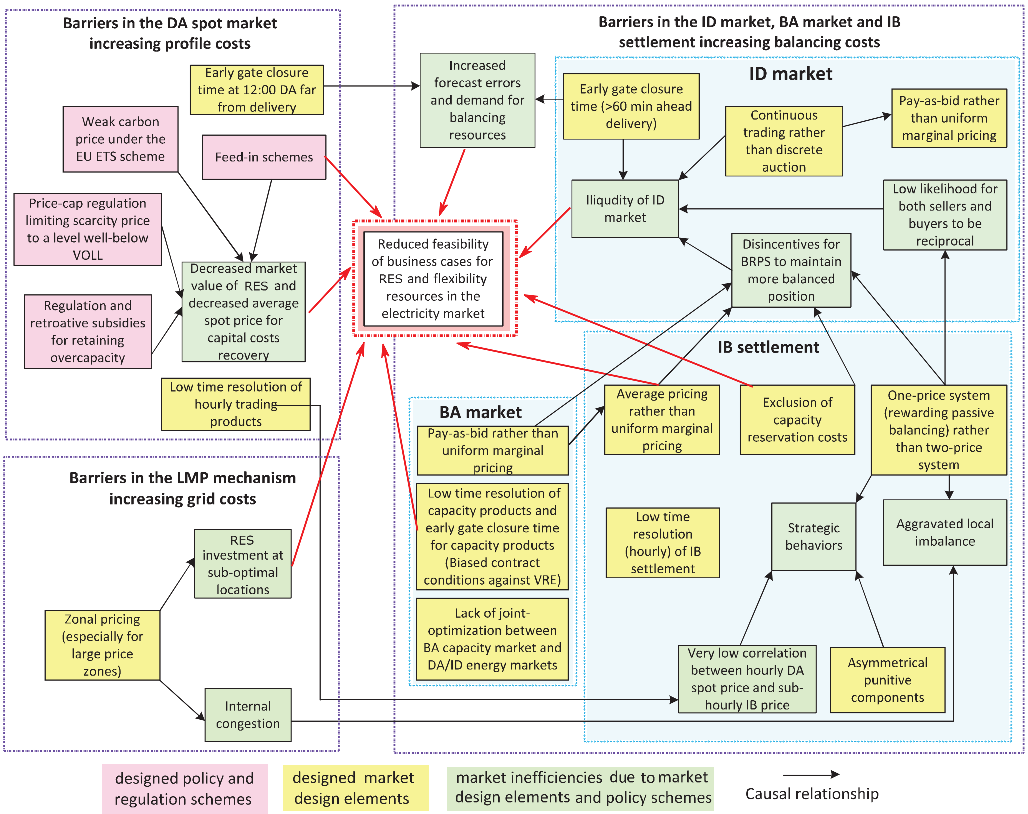


Figure 1.8– Barriers in market design and regulation schemes. Adapted from [33].

Furthermore, it should be noted out that excessive FITs, subsidies for fossil or coal plants, capacity payments, and/or CO2 emission allowances prices create market price distortions [24], [45] and thus, these factors increase these integration costs [33].

Otherwise, establishing reasonable FIT schemes [33], defining suitable price signals [46], and encouraging new flexible resources will help to support and cover investment and operating costs of new RES generators, as well as reducing integration costs. In order to achieve an efficient market, market price signals should support short-term operation and also provide sufficient long-term investment incentives for all new needed capacity, according to the European Commission's recommendations [46].

In the last years, FITs have been reduced drastically or eliminated in most European countries [47], [48]. For example, all installed Spanish RES plants are remunerated through an investment term and an operation term established by the government. From now on, as a result of latest capacity auctions in 2017 [49], [50], new RES plants will be installed without any additional financial support. Thus, these new plants will be remunerated directly by market revenues (although with an annual floor price of 35 €/MWh).

As conclusion, it is necessary to remove current market barriers in order to increase the business cases for RES in electricity markets, in which other flexible resources could play a key role to improve their profitability, such as the ESS.

1.1.4 Necessity of energy storage systems

As exposed through this chapter, RESs have difficulties in participating and operating suitably under current electricity markets from a technical and economic point of view compared to traditional and controllable generators, due to their lower controllability and predictability. Moreover, some technical drawbacks in the network may happen with massive and/or uncontrolled RES penetration and without innovative grid control, among others [51]–[56]: the increase of uncertainties in energy predictions due to the highly dependence on weather conditions, the increase of the variability of the energy generation, and the decrease of the total system inertia of power grid, due to generators connected through power converters are increasing to a greater extent than synchronous generators. These factors may affect the energy balance and thus, the grid stability, reliability and security could be worsened.

In order to deal with the new challenges related to power system planning and operation, several effective electricity market designs and regulatory frameworks are proposed to integrate renewable energy sources in the grid [33], [52], [57], related to a more active participation of the demand-side

[17], capacity market designs, common market rules [34] or market bidding structures, as well as incentives to support and encourage new flexible sources (e.g. storage devices) [54], among others measures.

In this context, ESS can play a significant role in future electricity networks [51]–[56], by: 1) managing the uncertainty in the generation forecast, 2) regulating and smoothing power variability and volatility, 3) improving RES power quality, 4) adding more flexibility and controllability to their operation, 5) improving their operating capabilities and functionalities, 6) ensuring high reliability and energy security, 7) deferring and reducing infrastructure investments, 8) reducing greenhouse gas emissions, 9) lowering operating cost and, 10) improving economic viability.

In particular, ESS has been also praised for supporting RES plants and meeting their integration and operation challenges, by delivering utility-oriented services, in particular: 1) RES capacity firming to smooth power variability and volatility, 2) production predictability to manage the uncertainty in the generation forecast, mitigate large forecast errors and reduce energy imbalances, and above all, 3) provision of frequency ancillary services to maintain the energy balance between generation and load. Therefore, RES+ESS can contribute to the system stability and reliability, while from the RES owner point of view, their participation in ancillary services can increase the market revenues for the RES asset.

1.2 Energy storage systems

This section is focused on reviewing the ESS potential and opportunities in future networks. Firstly, a review of potential energy storage systems services is exposed. Secondly, the suitability of each energy storage technology for the abovementioned services is evaluated. Some of these services demand low power and/or energy requirements, whereas other services are more demanding and require higher energy and/or power specification. For that reason, depending on the objectives, desired functions or services of the given application, some storage technologies may be more suitable than others. Thirdly, currently operational projects and installations are identified which assure the technical feasibility of integrating them and support renewable energies. Finally, the most suitable ESS technology in order to support RES operation is assessed based on its potential services, required functionalities, technical requirements operational conditions, and future deployment perspectives and research interests.

Furthermore, the main barriers and recent policy changes are analyzed from the economic and market perspective in order to identify the suitable future RES+ESS market framework. This throughout revision will enable to define the scope of this PhD dissertation.

1.2.1 Energy storage systems services

There is a wide range of potential energy storage applications [34]–[36], [51], [52], [58]–[62] at all grid levels from energy generation, transmission, and distribution up to the customer side. In this section, ESS are classified according to the TSO-DSO services, ancillary services (non-frequency and frequency ancillary services), generator/renewable-utility services and customer services, as can be observed in Figure 1.9.

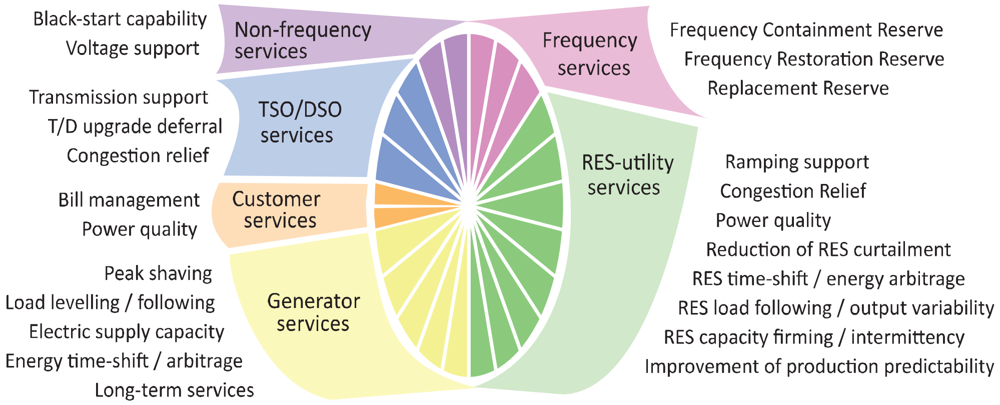


Figure 1.9 – Classification of potential services from ESS.

1.2.1.1 Ancillary services

Ancillary services are those services necessary to support the transmission or distribution system, in order to maintain reliable operation of the interconnected transmission system and to ensure the management of the system maintaining system stability.

On the one hand, focusing on frequency ancillary services, they are managed through their associated markets described in Section 1.1.2.2. Their sequence and their impacts on system frequency are shown in Figure 1.10. The frequency controls are classified as follows:

- Primary frequency control provided by FCR.
- Secondary frequency control provided by FRR.
- Tertiary frequency control provided by RR.

In light of the fast response of ESS, their participation in frequency ancillary services could be a market opportunity to improve the profitability of ESS projects, as well as helping to achieve a more reliable operation, by supporting the system frequency.

And on the other hand, non-frequency ancillary services are those services provided by the TSO or DSO for steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability [34]. The most important ones are the followings:

- Voltage support has the purpose of restoring or maintaining voltage levels with the required stability by means of the injection or absorption of reactive power from the ESS.
- Black-start capability allows restoring a power station without an external electric power transmission network. ESS can be used to generate a reference frequency for synchronization of other generators and at the end, energize the affected lines.

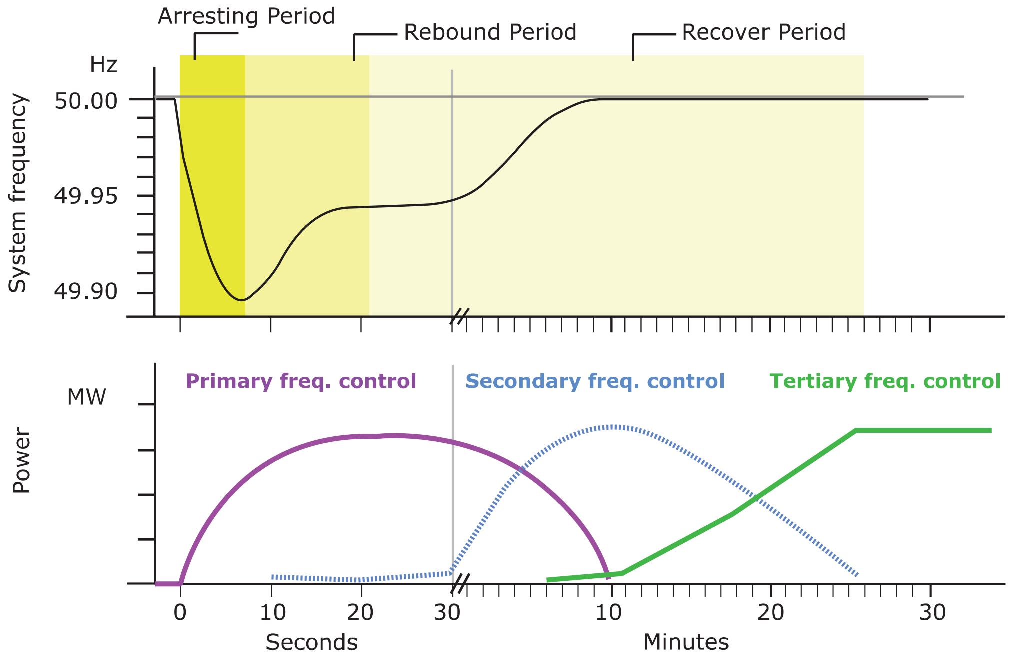


Figure 1.10 – System frequency and activation of frequency controls. Adapted from: [36][63][64].

1.2.1.2 TSO/DSO grid services

ESS can provide other TSO/DSO-oriented grid services, such as:

- Transmission and/or distribution upgrade deferral is related to the use of a relatively small amount of the stored energy in overloaded grid nodes to: i) defer or avoid the need to replace or oversize existing equipment, ii) upgrade existing capacity or iii) increase the existing equipment's service life.
- Transmission support is the use of energy storage to improve the performance of the transmission system by compensating for electrical anomalies or disturbances such as unstable voltage, or sub-synchronous resonance.
- Congestion relief has the purpose of storing energy when there is no transmission congestion and be discharged (during on-peak periods) to reduce transmission capacity requirements and reduce line congestion. The storage system is located downstream from the congested area of the transmission system, in order to reduce or avoid congestion charges or locational marginal pricing.

1.2.1.3 Generators and utility-renewable services

The services that ESS can provide to improve the operation of conventional generators, are the followings:

- Long-term services are defined to compensate for a longer-term supply disruption or seasonal variability on supply and demand sides. Seasonal storage can compensate seasonal fluctuations in renewable power supply, for example storing excess solar energy in summer and suppling to the grid in winter through a large energy storage capacity.
- Energy time-shift or energy arbitrage involves purchasing inexpensive electrical energy to charge the storage system during

lower (off-peak) prices, so that the stored energy can be sold later during higher (on-peak) prices.

- Load levelling aims to reduce fluctuations in energy demand for one day. That fact involves storing energy during periods of low demand and delivering it during period of high demand (on-peak periods). During these periods of high demand, the energy storage system supplies power, reducing the required peak-generating facilities. Thus, this service may reduce on-peak prices.
- Peak shaving is similar to load levelling but for the purpose of delaying or avoiding investment in grid upgrades or new generating installed capacity. The ESS will supply the peaks of a highly variable load during on-peak periods, instead of other conventional plants.
- Electric supply capacity could be increased by adding energy storage systems and therefore reducing or delaying the need to build new generators.

Focusing on the services that the energy storage system can provide to the integration of renewable energies into the grid, the following services are the most remarkable:

- Renewable energy time-shift or energy arbitrage is related to store excess energy generated by grid-connected wind and solar plants during low demand times (off-peak prices) in order to dispatch it during high demand times at higher on-peak prices. In particular, ESS could be charged from wind energy at night hours, and later, this energy may be sold when it is more valuable.
- Renewable energy load following has to deal with the output variability and fluctuations with long duration (lasting for several minutes to a few hours). Increasing renewable generation penetration in the electric grid increases the need for load following service that could be provided by energy storage systems.
- Renewable energy capacity firming addresses to mitigate rapid power output changes, generation intermittency and output volatility over short periods (for a few seconds to a few minutes) of time from

renewable generation due to: i) wind speed changes produced by wind gusts and ii) sudden shading of solar generation.

- Improvement of production predictability, which depends directly on the quality of the weather forecast. If the forecast accuracy is poor, it may cause larger penalties in the electricity markets. Production predictability can be improved (in consequence penalties decrease) with energy storage systems which can compensate and smooth to some extend unforeseen changes in the generation. This service requires that excess energy is stored and released when the amount of renewable energy is insufficient to fulfil the market requirements.
- Reduction of RES curtailment presents a key opportunity for utility-scale ESSs to enable greater utilization of these resources by energy time-shifting. There could be two different reasons to curtail or reduce RES generation: i) a lack of enough grid infrastructure capacity related also to the transmission and/or distribution upgrade deferral and congestion relief, and ii) provide load levelling in case of high RES share in the energy mix, and/or the inability of reducing generation from conventional plants mostly during off-peak periods.
- Ramping support through energy storage is eminently suitable for damping the variability of wind and solar systems. Technically, the operating requirements for a storage system in this application are the same as those needed to respond to a rapidly or randomly fluctuating load profile.
- Congestion relief caused by renewable generation can be achieved through the installation of ESS in nodes with significant amounts of RES power capacity that may cause congestion in high generation periods because the transmission line is not able to transfer the energy generated by all RES capacity.
- Power quality can be improved with the integration of ESS in renewable power plants in order to fulfil performance standards and interconnection requirements, and also in order to reduce the negative effects of output variability, generation intermittency, output volatility and power fluctuations.

1.2.1.4 Customer services

Finally, customer energy management services are designed with the aim of reducing the invoice of final end-users or customers according to:

- Time-Of-Use (TOU) bill management can be considered in order to make arbitrage between on-peak and off-peak prices. This customer energy time-shift involves storing energy when TOU price is low. Later, this stored energy is consumed, instead of purchasing high-priced energy during on-peak prices.
- Demand charge can be reduced. Demand charges are typically assessed based on the time-of-day or on specified days. The stored energy is consumed to reduce the maximum power during peak demand times, mainly at mid-day or weekdays.
- Peak shaving can be pursued with the objective of consuming the stored energy in order to reduce the maximum power need and reduce the power-term bill charge.
- PV self-consumption can be increase, reducing energy dependency.
- As residential/customer backup power when the customer is off-grid.
- There are other services provided by the DSO oriented to customers, such as power quality, reliability, and security of supply, which could use the ESS to: i) remain connected during severe grid faults, ii) support customer loads during the utility outage, iii) transfer to on-site generation resources, iii) protect customer on-site loads against short-duration events that affect the quality of power delivered and iv) support customer loads during an outage.

1.2.2 Comparison of energy storage technologies

Some of the exposed services defined in Section 1.2.1 demand low power and/or energy requirements, whereas other ones are more demanding and require higher energy and/or power specification. For that reason, the ESS opportunity definition should be clarified in order to select the most suitable energy storage technologies according to application of interest, strategic objective, desired or potential services, the possibility of market participation, required functionalities, and operational conditions [65].

The following categories for ESS technology are usually considered:

- Electro-chemical ESSs gather several types of batteries: Lead-Acid (LA), Nickel-based (Ni-), Sodium Sulfur (NaS), Lithium-based (Li-ion), Vanadium Redox flow Batteries (VRB), etc.
- Chemical ESS which corresponds with hydrogen (H2) or gas.
- Mechanical ESSs composed by Pumped-Hydro Storage (PHS), Compressed Air Energy Storage (CAES) or flywheels.
- Thermal ESSs, for instance, molten salt thermal storage.
- Electrical ESSs, such as supercapacitors or superconducting magnetic coil-based energy storage.

The choice of energy storage technology directly depends on the particular application and the desired functionality or services to be provided. The most relevant technical parameters must be taken into consideration to select the energy storage system for an application: power capacity (MW) and energy capacity (MWh). The power and energy capacity rates per technology are summarized in Figure 1.11.

According to the main feature of ESS, they can be also classified into: power-type and energy-type ESS. In order to smooth and manage the renewable generation, energy-type ESS are more suitable. Under this assumption, power-type ESS will be omitted henceforth which include mostly flywheels and electrical ESS.

Moreover, other key features must be considered in order to determine the suitable technology depending on the service, functionality and technical requirements, such as: the efficiency (%), discharge and response times (sec), lifetime (years) and life cycles. Some of these technical parameters can be found in the literature [64], [66]–[73]

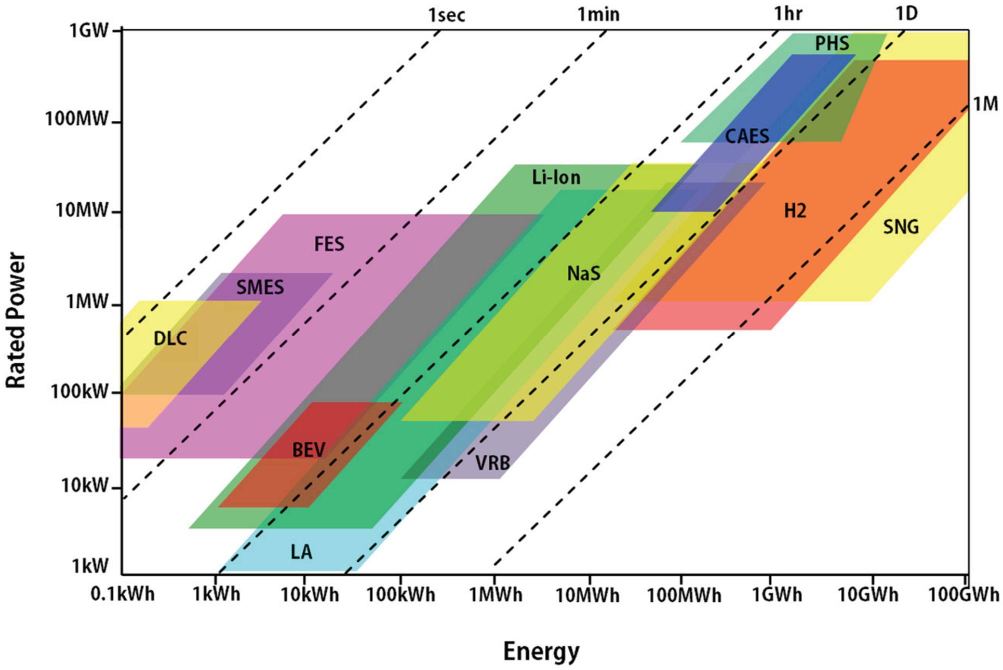


Figure 1.11 –Power and energy of ESS technologies. Source: [73].
Acronyms: Double Layer Capacitor (DLC), Superconducting Magnetic Energy Storage (SMES), Flywheel Energy Storage (FES), Battery Electric Vehicle (BEV) -composed by Lithium-ion (Li-ion), and Nickel Metal Hydride (NIMH)-, Lead-Acid (LA), Sodium Sulfur (NaS), Vanadium Redox Flow Battery (VRB), Compressed Air Energy Storage (CAES), Hydrogen Storage (H2), Pumped-Hydro Storage (PHS), Synthetic Natural Gas (SNG).

Afterward, the main technical requirements or features of the desired services or market participation should be defined in order to identify which ESS technologies can fulfill these technical needs [59]. For example, the minimum size of market offers, the required discharge and response times, or the time-scale of the selected services. Therefore, the suitable selection of energy storage technology should be decided after analyzing and comparing the technical parameters of the ESS technology and the technical features of the application and services.

A summary of the most suitable ESS technology according to different services and functionalities can be observed in Table 1.2, from [67]–[69].

Table 1.2 – Comparison of ESS technologies and services.

	Electrochemical				**Mechanical**		**Thermal**
	LA	Li-ion	NaS	VRB	CAES	PHS	-
Power quality and reliability	✓	✓	≈	≈	✘	✘	✘
Voltage support	✓	✓	✓	≈	✘	✘	✘
Ramping support	✓	✓	✓	✓	✘	✘	✘
Customer energy management	✓	✓	✓	✓	≈	✘	✘
Frequency response or FCR	✓	✓	✓	✓	≈	✘	✘
Frequency regulation or FRR	✓	✓	✓	≈	✓	≈	✘
Reserve capacity or RR	✓	✓	✓	≈	✓	✓	✘
Black-start capacity	✓	✓	✓	✓	≈	≈	≈
Congestion relief	✓	✓	✓	✓	✓	✓	✓
Upgrade deferral	✓	✓	✓	✓	✓	✓	✓
Electric supply capacity	✓	✓	✓	✓	✓	✓	✓
Load leveling	✓	✓	✓	✓	✓	✓	✓
Production predictability	✓	✓	✓	✓	✓	✓	✓
RES energy capacity firming	✓	✓	✓	≈	✓	✓	≈
RES energy load following	✓	✓	✓	≈	≈	✓	✓
RES time shift / arbitrage	≈	≈	≈	≈	✓	✓	✓
Peak shaving	✘	✘	≈	≈	≈	✓	✓
Long-term service	✘	✘	✘	✘	≈	✓	✓

1.2.3 Operational projects of ESS with RES plants

In this section, a more practical review is carried out paying attention on operational projects whose main aim is to support RES integration and operation. A large number of storage projects and installation are being launched for the following years, including projects under construction, announced and contracted. The current operational projects and future trends are shown in Table 1.3.

As can be observed from Table 1.3 and in Figure 1.12, some technologies are not really deployed or are under research and development, such as, H2, CAES or SNG. A few projects have been recently contracted to support RES in the short term.

On the other hand, the number of installations of PHS and thermal storage are almost half of the current operational installation, as well as having in most cases large capacity. The maturity level of these technologies is considered high as can be observed in Figure 1.12, and they are usually commercialized, generally to support hydroelectric power or thermal solar plants.

Both technologies (PHS and thermal), as can be observed before in Table 1.2, have low dynamic and they are not suitable for fast responses (voltage and ramping support, and RES intermittency), as well as being large projects which are not able to provide customer end-user services.

Table 1.3 – Worldwide operational and expected ESS installations or projects. Source: DOE Global Energy Storage Database [74]. Last update: 10/07/2019

* Expected projects include under repair/offline, contracted, announced and under construction ones.

	Operational	RES-oriented	Expected*	Future inst.
Electro-Ch (LA)	76	40 (52%)	4	80 (+5.2%)
Electro-Ch (Li-ion)	411	162 (39%)	120	531 (+29%)
Electro-Ch (NaS)	67	32 (48%)	3	70 (+4.5%)
Electro-Ch (VRB)	63	45 (71%)	22	85 (+34%)
Chemical (H2)	9	0 (0%)	3	12 (+33%)
Others/ Not specified	116	56 (48%)	62	178 (+53%)
(Electro)chemical	**742**	**335 (45%)**	**214**	**956 (+29%)**
Mechanical (PHS)	325	11 (3.4%)	23	348 (+7.1%)
Mechanical (CAES)	1	0 (%)	2	3 (+200%)
Mechanical	**326**	**11 (3.4%)**	**25**	**351 (+7.6%)**
Thermal	**206**	**56 (27%)**	**10**	**216 (+4.8%)**
Total ESS install.	**1274**	**402 (31.5%)**	**249**	**1523 (+19.5%)**

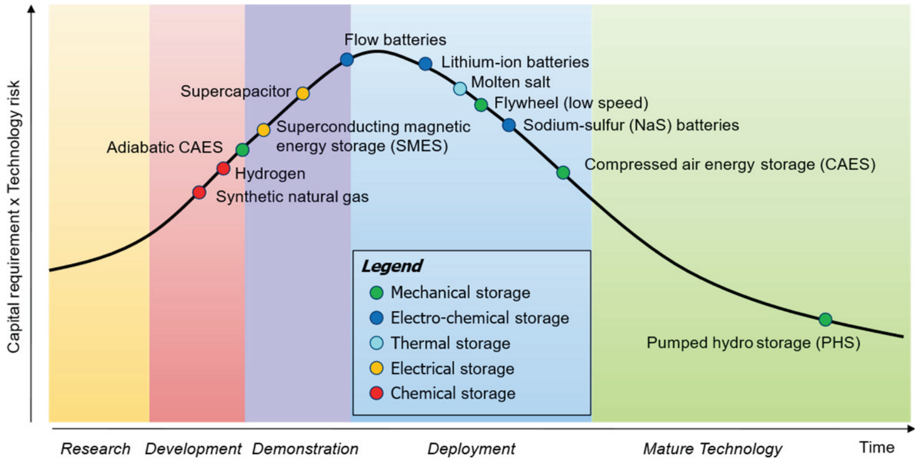


Figure 1.12 – Technology maturity curve of ESS.
Source: SBC Energy Institute [75],[52]

Although more than 95% of the total installed (in terms of MWh) storage capacity corresponds to PHS, these projects are not prioritized in this study, because this type of ESS technology is the most mature, developed and inexpensive technology, as in Figure 1.12. In number of operational projects, they reach 325 projects out of 1266 as of July 2019. Nowadays, PHS are mostly considered as conventional and controllable power plants that operate in electricity markets by selling and buying energy from an economic point of view (energy arbitrage services or long-term services) and they have not been previously designed and operated specifically to counteract short-term drawbacks which appear in the electric system due to the increase of renewable energy plants.

Finally, electrochemical storage or batteries are also evaluated. On the one hand, LA are considered inexpensive technologies but with low energy and power density, and NaS could be experiment operational problems related to the corrosion, security and safety due to high operational temperatures [76][64]. It is expected not to have a huge deployment in the following years on these ESS technologies. On the other hand, Li-ion and VRB will be deployed to a great extent in the coming years. However, VRB are not really suitable for RES support, frequency control or other fast services as can be observed in Table 1.2.

In contrast, Li-ion battery will be largely installed according to the DOE Database in Table 1.3, with a tendency of increase the number of projects by 29%. Li-ion technology is and will be the most installed technology in numbers, under pilot and/or commercial projects. Li-ion batteries are considered to be suitable for RES support and ancillary services.

Several noted storage projects of each type are listed in Table 1.4, including the date of commissioning, the short name of the project, the location, the energy storage technology, the final application, the owner and the provided services. Most of these projects listed below are designed in order to fulfil the necessities of the integration of renewable energies into the grid, and a careful revision of them is exposed below. Other specific projects are included due to their peculiarity or special interest to be discussed.

The following assessments could be concluded from these projects:

- Focused on wind and photovoltaic power plants integration, battery storage systems (in most cases lithium-ion batteries, 162 projects) are widely installed to control RES generation (renewable energy capacity firming and renewable energy time shift) and also provide additional grid services, such as: balancing services, ramping support, voltage support, and congestion relief, among others.
- Molten salt thermal storage is destined to operate and support Concentrated Solar Power (CSP) plants. This thermal storage enables stable and dispatchable power delivery without the need for any fossil fuel. Moreover, thermal storage provides the ability to shift electricity generation to meet different needs and operate uninterruptedly during the night due to their large ESS capacity.
- One PHS project is of interest to analyze in an island grid. This PHS is installed in Canary Island jointly with a WP in order to manage the renewable generation according to the demand, with the objective of increase the share of RES energy in the island and reduce the RES curtailment and conventional generators.

- Some coal plants also include storage systems (mostly lithium-ion batteries) in their installations in order to provide balancing services, improving their operation, and therefore, increasing the profitability of this conventional plant.
- In island grids (generally weak grids), such as Hawaii, Sicily and Sardinia, different types of batteries provide ancillary services (frequency services and voltage support), as well as RES capacity firming and RES time shift.
- In substations and transmission lines Lithium-ion batteries are mainly used to a great variety of services: frequency response, frequency regulation, voltage support, black-start capacity, electric supply capacity, renewable energy capacity firming and renewable energy time shift.
- Regarding unmatured mechanical ESS, the first CAES was commissioned in 2015 as a technical R&D demonstration project in a grid-connected environment. This CAES provides an ongoing testbed for long-term analyses.

As can be concluded, among different energy storage systems, batteries are considered as the main enabling technology to face the new functionalities needed to integrate more RES into the grid and provide a fast response to the RES intermittency. Furthermore, batteries could provide other additional services, such as: frequency services, ramping support, voltage support, and congestion relief, as exposed above.

Although the capital requirement and technology risk of Li-ion is really high due to their high investment costs and the difficulty to estimate the lifetime according to their degradation, their potential services and compatible technical features could be the reason why the operational projects of Li-ion ESS will be increase from 411 to 531 in the short-term, surpassing in number all other ESS technologies (see Table 1.4).

For long term services and energy arbitrage, PHS or thermal are widely deployed and their technological maturity and cost of investment is enough competitive.

Consequently, it can be stated that integrating technically storage systems is feasible. Moreover, storage systems can provide nearly all ancillary services, grid services and renewable energies-oriented services. Some of these operational installations are generally demonstrators which evaluate and validate their functionality. In Figure 1.13, the geographical distribution of operational electro-chemical ESS installations is shown. Otherwise, ESS operational assets are increasingly participate in equality in electricity markets or new flexibility markets, like in USA and UK, from an economic point of view. Thus, it is convenient to investigate about recent RES+ESS energy management strategies for their joint market participation.

Figure 1.13 – Operational electro-chemical ESS installations (733 projects in July 2019). Source: DOE Global Energy Storage Database [74]. Last update: 10/07/2019.

Table 1.4 – Operational projects. Source: DOE Global Energy Storage Database [74] and several press articles.

Year	Project	Location	Energy storage technology	Application	ESS provider &/ or project developer	Services
2008	Rokkasho	Aomori, Japan	NaS battery (34 MW; 238 MWh)	WP (51 MW)	Futamata Wind Development Co.	Reserve capacity, RES capacity firming and RES time shift
2011	AES Laurel Mountain	Virginia, USA	Li-ion battery (32 MW; 8 MWh)	WP (98 MW)	AES Wind Generation	Frequency regulation and ramping support
2011-2012	Zhangbei	Hebei, China	Li-ion and VRB (14 MW; 71 MWh)	WP (500 MW) PV (100 MW)	State Grid Corp. of China (SGCC)	Frequency regulation, voltage support, RES capacity firming and RES time shift
2012	Kaheawa	Hawaii, United States	Lead-acid battery (10 MW; 7.5 MWh)	Island grid. WP (21 MW)	First Wind LLC	Frequency regulation, reserve capacity, ramp control, RES curtailment reduction, RES capacity firming and RES time shift
2012	ILIS Project (Decommiss.)	Navarre, Spain	Li-ion battery (1 MW; 0.56 MWh)	PV (1.2 MW)	Acciona, SAFT, Ingeteam	Frequency response, frequency regulation, ramping support, voltage support and RES capacity firming
2012	AES Angamos Coal Plant	Antofagasta, Chile	Li-ion battery (20 MW; 6.7 MWh)	Coal plant (544 MW)	AES Gener	Frequency regulation, reserve capacity, black-start capacity
2012	Miyako	Miyakojima, Japan	NaS battery (4 MW; - MWh)	4 MW RES portfolio	Okinawa & NGK	Frequency regulation, RES capacity firming

2013	SmartRegion Pellworm	Island Pellworm, Germany	Vanadium Redox F (0.2 MW; 1.6 MWh)	WP (0.7 MW) / PV (0.3 MW)	Hansewerk AG	Electric supply capacity, RES capacity firming and RES time shift
2013	SmartRegion Pellworm	Island Pellworm, Germany	Li-ion battery (1.1 MW; 0.56 MWh)	WP (0.7 MW) / PV (0.3 MW)	Hansewerk AG	Electric supply capacity, RES capacity firming and RES time shift
2013	Yerba Buena	California, United States	NaS battery (4 MW; 9 MWh)	Distribution network	Pacific Gas and Electric	Frequency response, power quality RES capacity firming and RES time shift
2013	Endesa STORE	Canary Islands, Spain	Li-ion battery (1 MW; 3 MWh)	Island grid	Endesa, Saft, Ingeteam	Electric energy time shift, electric supply capacity, voltage support
2014	Bardzour Project	La Réunion, France	Li-ion battery (4.5 MW; 9 MWh)	PV (1.2 MW)	Akuo Energy, Saft & Ingeteam	RES capacity firming and RES time shift
2014	Terna Storage Lab	Sicily and Sardinia, Italy	Several batteries (16 MW; 25 MWh)	Island grid	Terna S.p.A.	Frequency response, frequency regulation, voltage support, TSO/DSO grid services, black-start capacity
2014	Gorona del viento	El Hierro, Spain	PHS (6 MW; 150 dm3)	Island grid	Cabildo de El Hierro, Endesa	Electric Supply Capacity, RES capacity firming and RES time shift
2014	Tehachapi Wind Energy Storage	California, USA	Li-ion battery (8 MW; 32 MWh)	WP (660 MW)	Southern California Edison	Frequency regulation, voltage support, TSO/DSO grid services, RES capacity firming and RES time shift
2014	WEMAG	Mecklenburg, Germany	Li-ion battery (5 MW; 5 MWh)	Substation	WEMAG AG & Younicos	Frequency response, voltage support, black-start capacity
2014	Slepe Farm	Dorset, England	Li-ion battery (0.6 MW; 0.2 MWh)	PV (0.2 MW)	Anesco	Reserve capacity, RES capacity firming and RES time shift
2014	Guodian	Liaoning, China	Vanadium Redox F (2 MW; 4 MWh)	WP (100 MW)	Liaoning, Rongkem	Frequency regulation, voltage support, RES capacity firming and RES time shift
2015	Grand Ridge	Illinois, United States	Li-ion battery (31 MW; 12 MWh)	WP (210 MW) / PV (20 MW)	Invenergy LLC	Frequency response and regulation

Year	Project	Location	Energy storage technology	Application	ESS provider &/ or project developer	Services
2015	Beech Ridge	West Virginia United States	Li-ion battery (31 MW;12 MWh)	WP (100.5 MW)	Invenergy LLC	Frequency regulation, ramping support and RES capacity firming
2015	Feldheim (RRKW)	Brandenburg, Germany	Li-ion battery (10 MW;11 MWh)	WP (81 MW)	Energiequelle & Enercon	Frequency regulation, RES capacity firming and TSO/DSO grid services
2015	AES Vlissingen	Zeeland, Netherlands	Li-ion battery (10 MW; 10 MWh)	Transmission grid	AES Netherlands	Frequency response
2015	AES Kilroot Coal Plant	Northern Ireland, United Kingdom	Li-ion battery (10 MW; 5 MWh)	Coal plant (520 MW)	AES Kilroot Power Limited	Frequency response
2015	NOOR	Souss-Massa-Drâa, Morocco	Molten Salt Thermal (160 MW;480 MWh)	CSP plant (160 MW)	ACWA, Acciona & Sener	RES capacity firming and RES time shift
2015	Okinawa BESS	Okinawa, United States	Lead-acid battery (1.5 MW; 1.5 MWh)	Island location Diesel and WP	Okinawa & Hitachi	Frequency response, RES capacity firming and RES time shift
2015	Anahola	Hawaii, United States	Li-ion battery (6 MW; 4.6 MWh)	Island location PV (12 MW)	KIUC, ABB, Saft, Kauai	Frequency regulation, voltage support, RES capacity firming and RES time shift
2015	Toronto-CAES	Toronto, Canada	CAES (0.6 MW; 1 MWh)	Demonstration plant	Hydrostor	Electric energy time shift, back-up power
2016	Minami Soma substation	Fukushima, Japan	Li-ion battery (40 MW; 40 MWh)	Substation	Tohoku Electric Power Comp.	Frequency regulation, RES capacity firming and RES time shift
2016	Aliso Canyon Mira Loma	California, USA	Li-ion battery (20 MW; 80 MWh)	Substation	Southern California Edison	Electric supply capacity

2016	Lünen Coal Plant	Westphalia, Germany	Li-ion battery (15 MW; 22 MWh)	Coal Plant (507 MW)	STEAG GmbH	Frequency regulation
2016	Crescent Dunes	Nevada, United States	Molten Salt Thermal (110 MW; 1100 MWh)	CSP plant (110 MW)	Tonopah Solar Energy	RES capacity firming and RES time shift
2016	Xina Solar One	Northern Cape, South Africa	Molten Salt Thermal (100 MW; 500 MWh)	CSP plant (100 MW)	Abengoa Solar	RES capacity firming and RES time shift
2016	Rice Solar	California United States	Molten Salt Thermal (150 MW;1200 MWh)	CSP plant (150 MW)	SolarReserve LLC	RES capacity firming and RES time shift
2016	Helen BESS	Helsinki, Finland	Li-ion battery (1.2 MW, 0.6 MWh)	PVs (1.2 MW)	Helen Ltd, Toshiba & Landis	Frequency regulation, voltage support, RES capacity firming and RES time shift
2017	DeGrussa	Meekatharra, Australia	Li-ion battery (6 MW; 129MWh)	Diesel (19 MW) PV (11 MW)	Neoen & Sandfire	Customer services, frequency regulation, microgrid capability, RES capacity firming and RES time shift
2017	Barásoain WP experim. area	Navarre, Spain	Two Li-ion battery (1.7 MW; 1.1 MWh)	WP (3 MW)	Acciona & Ingeteam	Frequency response, frequency regulation, ramping support, RES capacity firming and RES time shift
2017	Yeongheung	Yeongheung, South Korea	Li-ion battery (4 MW; 16 MWh)	WP (46 MW)	Korea South-East Power Co.	RES capacity firming and RES time shift
2017	Lawai	Hawaii, United States	Li-ion battery (20 MW; 100 MWh)	Island location PV (28 MW)	KIUC, ABB, Saft, Kauai	Frequency regulation, voltage support, RES capacity firming and RES time shift
2017	Burbo Bank [77]	Liverpool, United Kingdom	Battery (2 MW; 2 MWh)	Off-shore WP (90 MW)	Dong, Carnegie Road	(Enhanced) Frequency Response, RES capacity firming, production predictability
2018	Carboneras [78]	Almería, Spain	Battery (20 MW; 10 MWh)	Coal Plant (2x580 MW)	Endesa	Frequency regulation, RES capacity firming and RES time shift
2018	Hornsdale	Jamestown, Australia	Li-ion battery (100MW; 129MWh)	WP (100 MW)	Neoen, Tesla & Australian Gov.	Frequency regulation, RES capacity firming and RES time shift

Year	Project	Location	Energy storage technology	Application	ESS provider &/ or project developer	Services
2018	Battery@PyC [79]	Pen y Cymoedd, South Wales	Li-ion battery (22 MW; 33 MWh)	WP (228 MW)	Vattenfall	(Enhanced) Frequency Response
2018	Batwind [80]	Peterhead, Scotland	Battery (1 MW; 1MWh)	Off-shore WP (30 MW)	Equinor & Masdar	RES capacity firming and RES time shift
2018	Jardelund [81]	Jardelund, Germany	Li-ion battery (48 MW; 50 MWh)	Stationary type system	NEC, EnspireME, Mitsubishi, Eneco	Frequency Response, RES capacity firming
2018	Stocking Pelham [82]	Hertfordshire, United Kingdom	Li-ion battery (50 MW; 50 MWh)	Stationary type system	SMA & BSR EPC	(Enhanced) Frequency Response, RES capacity firming
2018	Ørsted [83]	Liverpool, United Kingdom	Li-ion battery (20 MW; 10 MWh)	Stationary type system	NEC, Shaw Energi, Ørsted	(Enhanced) Frequency Response, RES capacity firming
2019	Whitelee [84]	Glasgow, United Kingdom	Li-ion battery (50 MW; 50 MWh)	WP (539 MW)	ScottishPower	(Enhanced) Frequency Response, RES capacity firming

1.2.4 Energy storage systems in electricity markets

ESS has the potential to make a significant contribution to the planning and operation of the power systems. ESS are able to provide a wide range of services presented in Section 1.2.1, through the selection of the suitable ESS technology from Section 1.2.2. In particular, it is a key component in providing flexibility and supporting RES integration in the energy system, while also contributing to energy security.

However, their widespread use has been restricted by their high technology costs, lack of deployment and commercial projects, as has been exposed above in Section 1.2.3. In addition, several barriers caused by the current electricity market design and regulatory structures [33],[85]–[87] also discourage their usage, because they were designed for conventional electricity systems and for only bulk storage participation. This market design will need to be updated to allow the participation of ESS in electricity markets.

1.2.4.1 Barriers for ESS in electricity markets

The major barriers related to regulation and economics are as follows:

- ***Little incentive*** for investment in ESS is still given due to the high priority and financial compensation provided to renewable generators. Generally, support mechanisms and priority dispatch increase the uptake of RES. However, these mechanisms do not include and compensate for the controlled dispatch of renewable energy to meet demand and supply variations on the grid. Thus, RES owners may be not encouraged to firm their capacity or participate in balancing markets for extra revenue, like conventional generators.
- ***FIT schemes*** can disincentivize the good performance of RES generators in the electricity market. With excessive FITs or no responsibility of their own energy imbalances, the profile costs will increase, because the RES operation is not optimized to maximize

their market value and improve their RES forecasts. Wind plants do not bear their extra balancing costs in France or they are partially responsible in Germany [32], or they can contractually delegate their responsibility to another BRP [31]. In addition to the FIT support, these issues could be the reason why RES plants do not participate usually in European CIM [26],[33]. Including more RES responsibility could reduce the illiquidity in CIM and the reduction of the amount of frequency balancing services required.

- ***ESS asset classification*** is undetermined under present regulatory frameworks. ESS is multifunctional and can serve as a generator, transmission or distribution asset, or as an end-user, depending on the required end goal. Therefore, there is an uncertainty in determining if ESS is a load (and should pay tax payments) or if it is an asset which contributes to RES penetration (and may benefit from the subsidies attached to RES schemes or from a specific ESS scheme). In the second case, the storage could be considered a generation asset (giving the opportunity to participate in liberalized markets if possible) or a network asset (whose property belongs to the network operators and they are restricted to participate in electricity markets). According to EU legislation, the European Commission explicitly states that "*neither distribution system operators (DSOs) nor transmission system operators (TSOs) should be allowed to own, develop, manage, or operate energy storage facilities*" [34]. Therefore, the ESS ownership should belong to a generation asset, being able to participate in the wholesale market or balancing service, improving feasible business cases for ESS.
- ***Accurate techno-economic viability*** is difficult to determine due to multitude of potential services and different European markets, and consequently, quantifying the overall value of ESS investments. That is, assessing the potential revenues from ESS providing several services in different electricity markets is complex due to the risks and uncertainties of unstable and diverse market policies, or insufficient or uncertain remuneration. Therefore, the return on investment for ESS private owners is questionable and high volatile.

- ***The uncertainty regarding price forecasts*** on the energy and balancing market is a key challenge for large-scale ESS facilities. On the one hand, the increasing installation of variable RES generation would increase future demand for balancing services, while would reduce market prices. On the other hand, enhanced interconnection, grid expansion, and new flexible resources as Balancing Service Providers (BSP) could decrease future price expectations [88].
- ***Electrical ESS is a developing technology***. There is few deployment and long-term operational experiences. Moreover, there is a lack of necessary standards and practices, system deployment and connection, and operating procedures. There is a lack of specific electrical ESS regulation in current markets.

The identified electricity market design barriers are:

- ***Energy arbitrage***: The difference between energy prices during peak and off-peak periods provides revenues for ESS owners from energy arbitrage. In case of the excess RES energy is produced during peak periods the peak price is reduced and consequently arbitrage profits can be decreased. Moreover, energy arbitrage is a profitable service for ESS when the difference between peak-price and off-peak prices is considerable, until an excessive participation of ESS is reached, known as “cannibalization”. Even more, energy arbitrage does not directly support the suitable integration of RES.
- ***Ancillary services design***: AS were designed for conventional generation and sometimes impose technical restrictions that limit the participation of non-conventional resources, small renewable producers or distributed storage systems. Unnecessary barriers and obstacles are currently imposed, such as: auctions periodicity, closure times, minimum bid size, size of generation or delivery duration.
- ***System flexibility***: As electricity systems move toward more intermittent resources, the need for flexible operations (i.e. the power system’s ability to quickly respond to changes in demand and supply) is increasing. Flexibility of operation requires more flexible market

mechanisms like some ancillary services (Frequency Containment Reserve and Frequency Restoration Reserve) or close gate closure times. In light of the fast response and other suitable characteristics of ESSs, market design should include the participation in ancillary services of new flexible resources. However, ESS can only participate currently in FRR in the Netherlands, Switzerland and UK [40].

- ***Maximum market bid***: In some liberalized electricity markets, AS market can be attractive for ESS owners and increase their revenues. However, ESS owners' bids might be ambiguous at market auction time and might not consider real operational limits of the ESS. In some markets (FERC Order 841 [89]), a legal framework is established in terms of maximum capacity bid and other bid parameters according to the ESS characteristics. Even so, the fully compliance of balancing services in operation should be assured.
- ***Underperformance in operation***: To participate in capacity markets or tertiary reserve markets (which require huge amount of energy during several consecutive hours or unlimited time), the owner must manage their resources in a way that permits it to fulfil its obligations when is needed or otherwise, pay a penalty for underperformance. These performance needs and associated penalties can hinder storage participation. Moreover, the service would be difficult to guarantee due to their limited capacity. For example, in UK and PJM markets, capacity obligations do not have a defined time period, thus increasing the penalty risk for ESSs. Moreover, this participation is still restricted in several European markets, for example, Portugal, Spain, Belgium and Poland.
- ***Few hours in service***: If ESS only participate in congestion management or capacity mechanism, it may often operate for shorter periods during the year and will be highly dependent of the marginal prices. Therefore, the opportunity to recover investment and operating costs is uncertain due to high price volatility.
- ***Market illiquidity***: Illiquidity and limited participation in intraday market can increase the transaction costs of market participants

because it is likely that their purchases and/or sales influence the market price and reduce the trading benefits.

Consequently, these barriers related to regulatory and market design are considered and tried to solve with recent policies and changes in electricity markets, in order to facilitate the integration of RES and ESS.

1.2.4.2 Recent changes in electricity markets policies

European policies considering ESS

The expected increase of the share of energy from RES has led to require these plants to contribute to provide system needs and services in the same way as other power plants. In this line, "*A network code on requirements for grid connection of generators*" [90], updated in April 2016, establishes a network code which lays down the requirements for grid connection of power-generating facilities (synchronous power-generating modules and power park modules). A power park module is defined as a unit or ensemble of generating units, which is either non-synchronously connected to the network or connected through power electronics, with a single connection point to the transmission or distribution system, like wind farms and photovoltaic plants.

However, this network code ingores their application to storage devices except for pump-storage generators. Electric ESS can also supply more flexibility and balancing to the grid and can firm and control intermittent renewable generation. Therefore, they will be necessary to fulfil the current and future requirements of power park modules.

According to the barriers related to European internal markets, a proposal for a Directive COM(2016)864 on "*Common rules for the internal market in electricity*" [91] was published in November 2016. This proposal states that the demand response as well as energy storage should participate in ancillary services to ensure a secure, reliable and efficient electricity system. The European Parliament accepted this directive during a plenary session [92] and published provisionally in March 2019 [91]. Member States must transpose the agreed directive into national legislation by 31 December 2020, in order to make profound changes in national rules.

Several highlighted issues that include this Directive are the following:

- This proposal finds a need to adapt and change electricity markets and grid operation in a more flexible manner and to "*ensure effective participation of all market players including: renewable energy sources, demand response, energy storage facilities and aggregators in the procurement of balancing services*".
- The proposal shall "*ensure non-discriminatory participation of all market participants, including market participants offering energy from renewable sources, market participants engaged in demand response, operators of energy storage facilities and market participants engaged in aggregation.*" Therefore, this directive also includes the aggregation of RES and inclusion of ESS.
- Regarding the ownership of ESS, this directive defines that *"TSOs and DSOs shall not be allowed to own, develop, manage and operate".* Furthermore, according to the public consultation, assessed by the regulatory authority, it indicates that *"third parties are able to own, develop, operate or manage such facilities in a cost-effective manner".* Therefore, future market design will integrate ESS in a profitable way in markets without discriminatory participation.
- With the objective of progress towards a completely decarbonized electricity sector that is fully free of emission, pumped-hydro plants will *"be necessary to make progress in seasonal energy storage and variability of production".* Regarding all ESS facilities, *"they be required to comply with the same strict limitations for system operators to own, develop, manage or operate those facilities to provide important services for network security and reliability".*

During the agreement procedure of this Directive COM(2016)864, other supporting documents have been published in the same direction. For example, the Supporting Document for the "*Network Code on Electricity Balancing*" [91], updated in 2017, aims at facilitating the participation in balancing services of a wide range of new technologies including small-scale generation, energy storage, demand side aggregators, and renewable energies resources. This document encourages to "*allow third parties and owners of power generating facilities from conventional and renewable energy sources and owners of energy storage units to become balancing service providers*".

At this point, there is no doubt that energy storage is a key component in providing flexibility and supporting renewable energy integration in the energy system. In order to gather all its potential services and propose a regulatory framework and market design for energy storage, the European Commission published a Staff Working Document "*Energy storage – the role of electricity*" [93] in February 2017.

Until now, energy storage (pumped hydro storage) has already contributed to the operation of the electricity system over decades, based on the technical and economic arbitrage functions. However, the situation is changing with the growing share of renewable energies in electricity generation. Energy storage can ensure effective and secure operation of the grid and provide fast response times in case of rapid power drops or power fluctuations. In the future system, energy storage will provide ancillary services and support RES generation in competitive and more flexible way.

However, energy storage has not yet developed its full potential in the energy markets. This is because, on the one hand some of these technologies were not widely developed, and on the other hand the regulatory framework was not in place to accommodate new flexible solutions, as has been analyzed in Section 1.2.4. This Working Document [93] states that "*storage operators should be allowed to provide multiple* *services to electricity system operators and also simultaneously participate in other commercial activities with other economic actors*". Regarding their inclusion on electricity markets, it states that "*Storage services should be traded in competitive markets, where new flexibility products would provide a market value reflecting the system benefits of storage*". And finally, in line with the Directive COM(2016)864, it suggests "*owners of storage facilities should be independent from the grid operators*".

In recent years, due to this European recommendations, guidelines and directives, several countries have introduced policies related to the support and development of ESS technologies and have made changes in their market design frameworks [85], [86], [88], [94]. These policies have made progress towards more inclusive and flexible electricity markets. Several of these recent remarkable policies will be exposed as follows.

One clear example is United Kingdom. "*Electricity Market Reform*" [95], [96] is a government policy to incentivize investment in secure and low-carbon electricity, improve the security of supply, and reduce the cost of energy to consumers, established in 2013. Several measures were implemented: Feed-in Tariffs with Contracts for Difference to invest on low emissions technologies, capacity market auctions, a carbon price floor tax to increase the emission carbon price in the Emission Trading System (ETS) and an Emission Performance Standard for new fossil fuel plants.

In order to strengthen the security of supply and address the problem of RES intermittency, this reform encourages investment in new capacity, including storage technologies. Consequently, the needed capacity is determined by the government and then, the first capacity auction was settled in 2014 (starting to operate in October 2017).

With the rise of variable RES and the gradual decommissioning of fossil fuels or nuclear plants, the total system inertia of power grids is reducing and therefore, the frequency response times are becoming too slow for the needs of modern power grids. For this reason, another new ancillary service has been developed by National Grid in United Kingdom to encourage new technologies to provide a fast response solution to system volatility. "*Enhanced Frequency Response*" (EFR) service is capable of responding to grid fluctuations in less than one second [95]–[97]. National Grid announced an auction of 201 MW for Enhanced Frequency Response in 2016 [98]. The auction winners would incorporate batteries, between 49 and 10 MW, in their coal plants, fossil fuel plants but also in wind farms.

In Germany, the "*Energiewende*" (Energy Transition) [99] aims a transition to a low carbon, environmentally sound, reliable and affordable energy supply. The integration of fluctuating renewable energies into the electricity grid demands innovative storage solutions and major investment in the transmission grid. Moreover, with the intention of retiring to a larger extent coal-fired and nuclear generation and the limited possibility of pumped storage capacity, other energy storage systems will play a fundamental role in integrating RES into the energy infrastructure to maintain grid security, from large-scale to small-scale rooftop PV arrays.

Consequently, around 385 MW of battery storage has been installed to date [88]. Focused on large-scale battery systems, the German balancing markets (primary and secondary control) are attractive for large battery system operators, and therefore, a number of public and private initiatives are currently cooperating on the development of energy storage systems [100],[101]. STEAG coal power plants put into service large lithium-ion battery storage units by 2017, without any support of subsidies or grants. One of these installations is included in Table 1.4. The batteries will be used for grid stabilization and capable of storing energy from the grid within seconds of an oversupply scenario and to feed electricity back into the grid as required.

Since 2016, the Spanish regulation [41] allows the participation of renewable energies, cogeneration and waste-to-energy plants in the ancillary services of the electricity system, such as secondary reserve service (Frequency Restoration service) and tertiary reserve service (Replacement Reserve service). However, there was no citation or reference to electro-chemical energy storage systems' participation.

In France, the Energy Transition Law [88],[102] in 2015 refered to ESS as a necessary actor to achieve environmental policy objectives and RES generation targets. However, except for PHS, energy storage remains limited. In particular, the current regulatory framework allows energy storage, but there is a need to establish an appropriate stable legal and regulatory framework which ensure the profitability of investments and incentivize in light of the number of new initiatives coming forwards.

In 2018, the Dutch Climate Act [88], adopted as an ambitious initiative, was launched with a wide range of stakeholders including a substantial role for various ESS technologies, establishing a clear pathway to full decarbonization by 2050. The National Action Plan in 2019 provides valuable guidance with respect of necessary changes for equity and profitable participation in the Dutch regulatory framework.

Annually, a complete survey [40] by ENTSO-E regarding the balancing markets in Europe is used to monitor their implementation and to report on the development towards a European balancing market. Despite the European Directives proposals, the current regulatory and legal frameworks are distant nowadays from these recommendations.

The providers of FCR and FRR by country, the most suitable frequency ancillary services for batteries, are shown in Figure 1.14, Figure 1.15 and Figure 1.16. Regarding the FCR provision, United Kingdom, France, Switzerland, Germany, the Netherlands, Denmark and Finland allow ESS participation. In case of the aFRR (automatic) provision, ESS can only participate and provide services in Switzerland and the Netherlands. While, ESS can only participate in Switzerland and the United Kingdom in mFRR (manual). Only the Netherlands allow the participation of ESS in all frequency ancillary services (including also RR).

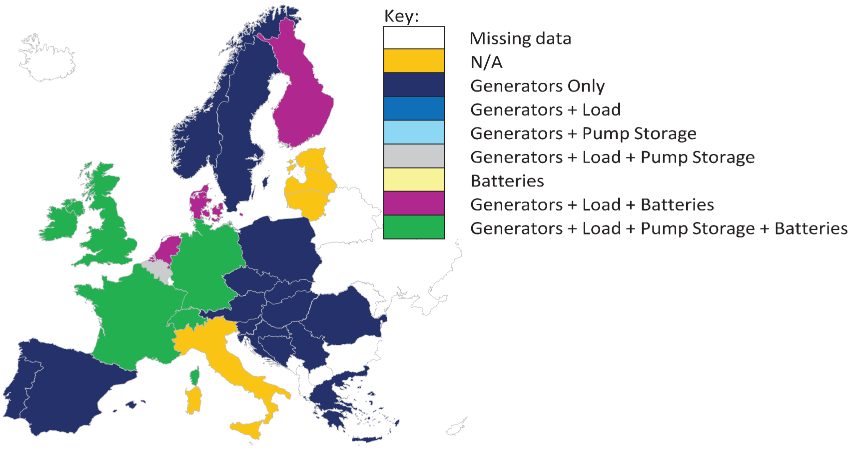


Figure 1.14 – FCR providers. Source: ENTSO-E Survey [40].

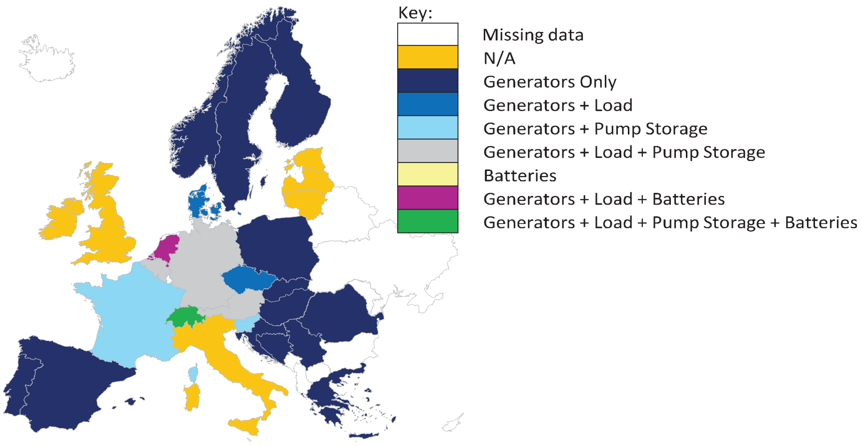


Figure 1.15 – aFRR providers. Source: ENTSO-E Survey [40].

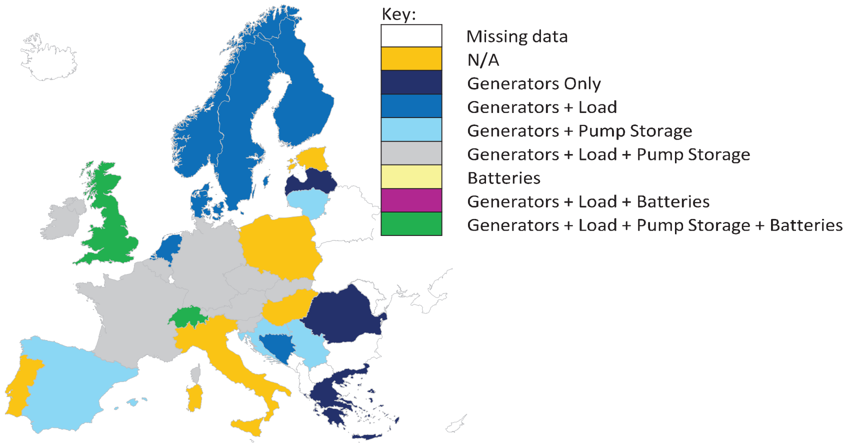


Figure 1.16 – mFRR providers. Source: ENTSO-E Survey [40].

Other policies outside the European Union

In USA, the FERC also supports the implementation of market designs that guarantee energy storage eligibility to participate in electricity markets. Each Regional Transmission Operator (RTO) and federal states have approved new policies or, at least, included storage in their energy plans, created programs and co-funded storage projects [103]–[105].

By December 2017, there was approximately 708 MW of large-scale battery storage operational in the U.S. energy grid. Most of this storage is operated by independent, federally-regulated non-profit organizations responsible of balancing the power grid, such as Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs). These facilities are used for grid reliability, to integrate renewables into the grid, and to provide relief to the energy grid during peak hours.

However, ESS is also regulated in energy and ancillary markets for private utility ownership. CAISO, PJM, ISO-NE and NYISO are open to storage participation. The penalty exposure of ESSs might also be mitigated by allowing small resources (including storage assets) to offer their capacity in aggregation. This solution is already implemented in several regions including PJM, where capacity storage resources are eligible to aggregate with other resources when bidding in the markets.

FERC approved several orders (like Order 784 and 755) in 2013 which increase the remuneration “pay-for-performance” in frequency regulation markets for fast and flexible responding sources like batteries or flywheels, rewarding their speed and accuracy, similar to the “Enhanced Frequency Response” in United Kingdom.

In February 2018, Order 841 [89] was approved with measures to remove barriers to entry for ESS technologies in the capacity, energy, and ancillary service markets, to improve their competition in the energy grid sector: appreciate the physical and operational characteristics of ESS and establish a minimum size requirement of 100 kW for participation in the RTO/ISO markets, among other policy changes.

Table 1.5 summarizes different policies, initiatives or ESS targets across the United States regarding the ESS. New participants were created to integrate the ESS in the markets, as well as regional bills were approved to support the deployment of ESS facilities.

In Australia, the Australian Standard (AS4777) provides adequate guidelines and standards ESS connection, including design, installation, testing, maintenance and safe housing of battery systems. In 2017, the South Australian Government announced a partnership to install a large ESS, known as Hornsdale (see Table 1.4 for details) to stabilize the Australian electricity grid in an area characterized by high wind resource.

China is making investments on large battery storage pilot projects to maximize clean energy output and improve grid stability. For example, in the northwestern province of Gansu, ESS is being installed with a total capacity of 720 MWh.

The Ministry of Economy of Japan believed that the RES integration could be aided by using storage to manage peak supply and demand as well as stabilizing power supply. Starting in 2012, Japan approved subsidy programs to provide incentives for ESS, which can be implemented into solar installations, substations, household, commercial business or stand-alone renewable installations. In April 2016, Energy and Environment Innovation Strategy was announced. The main innovative technologies are related to the efficient power generation, the reduction of the cost of renewable energies and lithium-based storage energy batteries.

Table 1.5 – Recent regional policies or initiatives in USA regarding the ESS

RTO or states	Policies, initiatives or targets
MISO	Electric Storage Resources (ESRs) for the provision of regulating reserve.
CAISO	Non-Generator Resource (NGR) to promote the ESS market integration
NYISO	ESSs may participate in the DM as Energy Limited Resources (ELRs).
PJM	Fast frequency regulation service oriented to ESS participation.
Washington	Bill HB 1296 (2013-14): requires utilities to include energy storage assessments in their integrated resource plans to provide ancillary services and/or to complement renewable energy facilities.
Texas	Senate Bill 943 (2011): ESS can provide energy and/or ancillary services. Moreover, ESS is exempted from transmission and ancillary services charges interconnection or supplemental fees, distribution upgrades costs, and standby charges (2014).
California	Assembly Bill 2514 (2013): 1325 GW target for ESS by 2020. Assembly Bill 1150 (2014): Incentive program for self-generation. H.4568 (2018): 1325 MWh target for ESS by 2024.
Florida	Recognized the role of ESS during power outages. SunSmart Schools and Emergency Shelters Program: 115 PV + ESSs.
Hawaii	Hawaiian Electric Company (an investor-owned utility) includes ESS in their assets to support additional renewable energy capacity. Industrial projects come in at 8 c$/kWh, half price of fossil fuels.
New Jersey	Energy storage incentives and finance resilient power projects, to support increased renewable energy penetration (2014). A3723 (2018): 2000 MWh of ESS by 2030.
New York	Supported financially research and development initiatives (2010). NY Energy Storage Roadmap in 2018 1500 MWh of ESS by 2025.
Massachusetts	H. 4857 (2018): 1000 MWh of ESS by 2025.
Arizona	H State Commissioner proposed 3000 MWh of ESS by 2030.

Conclusions and favorable market design

As a conclusion from the above analysis, the current regulatory framework in some countries allows ESS grid participation, but there is a need to establish an appropriate stable legal framework which ensure the profitability of investments and incentivize in light of the number of new initiatives and commercial projects coming forwards.

After analyzing the potential services, barriers and recent policies, fast frequency ancillary markets are the most attractive for incorporating energy storage systems.

Recent changes show the interest and suitability of ESS for frequency response and regulation, such as the "*Enhanced Frequency Response*" in United Kingdom and FERC Order 755 which increases the remuneration "*pay-for-performance*" in frequency regulation markets for fast and flexible responding sources like batteries or, in particular, fast frequency regulation service oriented to ESS participation in PJM.

With the rise of variable RES and the gradual decommissioning of fossil fuels or nuclear plants, the total system inertia of power grids is reducing and therefore, the frequency response times are becoming too slow for the needs of modern power network.

ESS are able to support the integration of RES plants, but not only compensating the drawbacks and negative impacts of RES generation as an independent asset. EU recommends that third parties and owners of renewable energy sources and energy storage units become an active role as balancing service providers, in addition to comply with the same requirements for grid connection as other generating facilities.

In this way, ESS can support the market participation and operation of RES plants, in order to achieve a reliable operation and provide network security and reliability. Moreover, an increasing use of Continuous

Intraday Market also will assure a better RES performance in real-time operation, which enable re-scheduling every hour.

With this aim, non-discriminatory participation of all market participants is suggested and barriers for new resources will be eliminated, such as: auctions periodicity, closure times, minimum bid, size of generation or delivery duration.

And finally, operators of energy storage facilities and market participants are encouraged to be engaged in aggregation. This opportunity enables distributed generators or different technologies to be managed and controlled in a centralized way.

1.2.5 General conclusions of energy storage systems

Throughout this Section 1.2, the potential ESS services have been analyzed from the literature, focusing on ancillary services, TSO-DSO services, generators or renewable sources-oriented services and customer services. The most suitable ESS technology in order to support RES operation should be assessed based on its potential services, required functionalities, technical requirements operational conditions, and future deployment perspectives and research interests.

Among the existing ESS technologies, electrochemical batteries are considered as the main enabling technology to face the new functionalities needed to integrate more RES into the grid, according to the previous aspects analyzed in this Section 1.2.

They provide fast power response that enables them to control RES intermittency and variability, as well as improving the power quality and providing frequency regulation services with high economic value [37]. Therefore, their technical features match with the required services and functionalities to support renewable sources.

Particularly, Li-ion technology is the most developed and largely deployed technology, under pilot and/or commercial projects, according to Table 1.4, with a tendency of increasing the number of operational projects by 29%, in the short term, surpassing in number all other ESS technologies.

In this context, Li-ion batteries are considered one of the key flexible technologies which enable high renewable penetration in power systems, by delivering RES utility services, such as: 1) RES capacity firming to mitigate generation intermittency and output volatility, 2) RES capacity firming to smooth power variability and volatility, 3) RES production predictability to reduce energy imbalances, and 4) provision of frequency ancillary services to maintain the energy balance between generation and load. Thus, they also contribute to the system stability and reliability.

However, current operational installations are generally demonstrators, with some exceptions, which validate and test the desired services, rather than real operational assets which participate and compete in equal conditions in electricity markets from an economic point of view.

From an economic point of view, the capital requirement and technology risk of Li-ion (from Figure 1.12) is really high due to their high investment costs and the difficulty to estimate the lifetime according to their degradation. It is known that the ESS acquisitional, operational and replacement costs increase substantially the asset costs.

Additionally, renewable energy sources and energy storage units are increasing their active role as balancing service providers and it is expected more future opportunities in these markets. However, contrary to energy markets, frequency ancillary services are characterized by uncertain or unpredictable real-time operation, which hinder a high fulfillment of market requirements. Because of this feature, advanced Energy Management Strategies (EMS) which manage all energy resources in the market participation are required in order to achieve a reliable operation in energy and reserve markets, and consequently, a profitable exploitation for utility-scale RES+ESS plant. For this purpose, the initial ESS sizing selection and its optimal operation are two crucial factors to assure a viable, profitable and efficient operation of these plants.

Firstly, the selection of ESS capacity plays an important role in assuring a more reliable and profitable operation which leads to increase the market revenues. However, the high ESS acquisition cost could results in a reduction of the overall asset profitability. In contrast, a smaller ESS capacity could not provide or operate successfully according to the technical requirements of the application, despite its acquisitional cost is reduced compared to the oversized ESS selection.

Secondly, to become a cost-effective solution and recover the additional ESS investment, the joint operation of RES+ESS in multiple markets could increase their economic and technical value. In that way, the provision of frequency ancillary services, characterized of being high-value services and highly rewarded, will be another market opportunity for RES+ESS owners, achieving additional sources of revenues.

Therefore, how the ESS is designed and managed during their lifetime operation is essential for the ESS cost-effectiveness. An optimal EMS will optimize market scheduling, assess optimal ESS sizing, provide a controllable and reliable real-time operation, and after all, maximize portfolio or asset profitability. During its lifetime, ESS degradation increases or decreases directly according to their operation. Thus, the EMS should reach a trade-off between the asset revenues and costs.

"The value in storage is not necessarily in the amount of energy you can store, but how you optimize, control and offer smarter energy solutions" stated Sebastian Bringsvaerd, development manager for Batwind at Equinor.

1.3 RES+ESS energy management strategies

In this section, the overall concept about EMS is defined and explained. Different optimization methods or techniques of EMSs are reviewed in the field of the market participation of renewable energies and storage systems. The most relevant approaches found in the literature are critically reviewed.

1.3.1 Concept and approach

The EMS has a global vision of the system to be managed where all the necessary information of the system is collected. In this outermost level, EMS encompasses strategies that allow jointly operating and managing all energy resources available in the system to obtain the strategic objective or desired functionalities in a medium or long-term time horizon. For this aim, these decisions are applied to determine the points of operation of the resources and send the set of power control parameters to manageable resources. As can be observed in Figure 1.17, the EMS manages power flow and exchanges between all resources and the utility grid. For example, economic dispatch or market participation can be implemented. The particular application and their strategic objectives are the factors that determine and define the EMS, that is, each application requires a particular EMS for a given objective [106],[107].

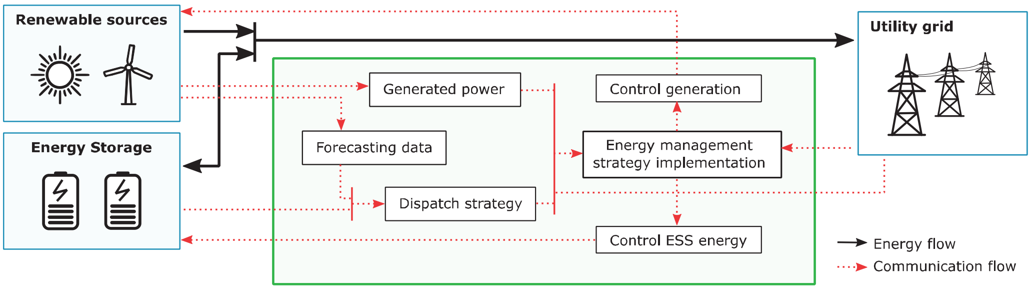


Figure 1.17 – Simplified EMS for market participation. Adapted from [106],[107]

To develop a cost-effective solution and recover the additional ESS investment, the joint operation of RES+ESS in multiple markets could increase their economic and technical value. In that way, the provision of frequency ancillary services, characterized by being high-value services and highly rewarded, will be another market opportunity for RES+ESS owners, achieving additional sources of revenues. However, the uncertainty of real-time delivery of frequency ancillary services could hinder a high level of fulfillment of these Real-Time (RT) market requirements, resulting in market penalties.

Because of this intrinsic feature, the adoption of advanced optimization techniques included inside a thorough and detailed EMS is essential in order to achieve a profitable participation in energy and reserve markets for utility-scale RES+ESS plant, as well as a flexible, controllable and reliable RT operation. Therefore, a proper EMS shall include the implementation of an energy management strategy through a market bidding optimization, reliable and controllable real-time operation, as well as the technical and economic modelling of all the involved systems.

1.3.2 EMS for energy market participation

Considering the scope of RES market participation, the main objectives ought to maximize the economic opportunities of each electricity market, provide a controllable and reliable real-time operation, and minimize overall system costs. After all, EMS will reduce the overall return on investment and maximize portfolio profitability.

Until now, renewable plants participate mainly in energy markets. Firstly, some researches are focused on scheduling the RES generation on Day-Ahead Market (DM), in which a certain hourly amount of energy is bidden beforehand and delivered later. In this application, ESS helps RES to deliver a steady output generation based on firming control strategies or optimization techniques from the literature [108],[109]–[112]. One of these firming controls can be observed in Figure 1.18.

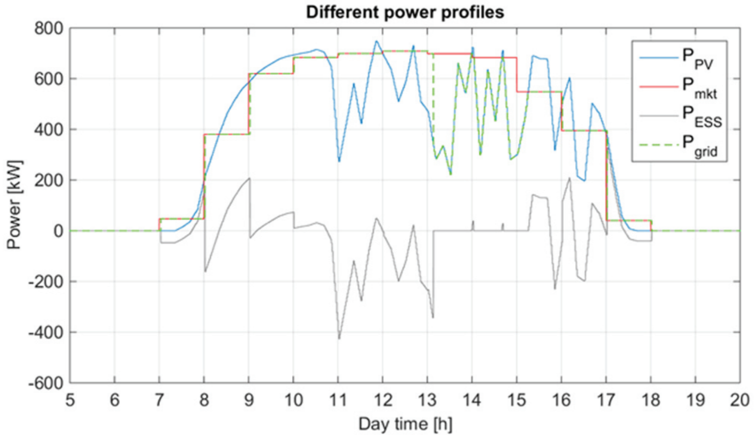


Figure 1.18 – Daily market operation with rule-based control strategy. Source: [108].

In order to deal with the inherent forecast uncertainty of RES, successive Intraday Markets (IM) [28], [113]–[119] allow RES to correct large energy deviations from the DM obtaining feasible final schedules which reduce large energy imbalances, improve their daily operation, and thus, maximize their market revenues.

The main objectives to schedule RES generation in energy markets are to maximize the overall profits and reduce energy imbalances [28], [113], [116], [120], make arbitrage in energy market [121], [122], or otherwise, evaluate the optimal sizing for ESS at microgrid level [123] or considering thermal solar plants [124].

The growth of RES generation has increased the importance of efficient markets. For that reason, European Cross-border Intraday Market project in Europe [125] was launched to create a single pan European cross zonal intraday market. Therefore, RES can reschedule their generation closer to real-time operation through the Continuous Intraday Market (CIM). Until now, Spanish or Italian IMs cleared by auctions are widely analyzed [116], [121], [126]. Recent studies take advantage of CIM in order to schedule industrial processes [127], make arbitrage with a ESS [128] or operate a wind farm but incurring in energy imbalances in case it is more profitable than fulfilling market scheduling [30].

Some researches analyze the impact of the low liquidity in Nord Pool CIM [28], [29], while Spanish IM trading volume through auctions is relevant, around 20% of the generation. Some of the reason of this illiquidity are the weight of bilateral contracts (with fixed price agreements) and/or the pay-as-bid pricing procedure (instead of marginal price). This market design discourages to re-schedule daily market generation. Despite these facts, according to the expected future trend of RES participation in intraday markets, CIM participation tends to increase due to its better features (closer gate closure) than IM through auction. RES+ESS facilities are supposed to participate in future CIM with enough liquidity over time to match their bids. Therefore, with a suitable implementation and enough liquidity, CIM will be a useful market to reduce energy imbalances and improve RES operation.

1.3.3 EMS for grid services

With increasing renewable generation, it is expected that large-scale RES and ESS will contribute to provide system needs and frequency ancillary services in the same way as other conventional generators. As an example, a recent change in the Spanish market rules that allows the participation of RES in ancillary services of the Iberian market since 2016 [41] reflects this current trend. Other recent policies for ESS integration in ancillary services in several countries was explained in Section 1.2.4.2.

Therefore, researches that are only limited to accommodate RES energy do not reflect the potential value of ESS. With a massive RES share, more ancillary services will be required in short-term [27], [33], [42], [51], [129] [106], [130]–[132], to tackle the variable production and ensure a safe and reliable operation. Thanks to the fast response of ESS, its provision of frequency ancillary services [132] will be another market opportunity for RES+ESS owners, achieving additional sources of revenues.

Focusing on FRR, it provides market-based compensation to resources which have the ability to adjust output production according to the AGC signal in order to maintain system stability and restore the frequency.

Contrary to energy markets, the AGC signal required at real-time operation is uncertain when the power availability is assigned at the auction time. Thus, as exposed above, advanced EMS must be required in order to achieve a reliable operation and fulfill real-time market needs according to the committed power availability. In that way, RES+ESS can take part actively in FRR provision to improve the grid stability and reliability [133], instead of being one of the sources of system imbalances.

In this line, PHS plants or thermal power plants have been widely analyzed to participate in FRR, from an economic point of view [134]–[138] thanks to their high controllability and “unlimited” energy capacity due to the stored water or coal reservoirs.

Therefore, market participation and operation strategies considered for PHS are not at all suitable for intermittent renewable plants with electrical ESS, because they have peculiarities and more restrictive constraints than PHS, i.e. the uncertainty and intermittency of the generation or more limited stored energy. Thus, ensuring an optimal and reliable operation of RES+ESS is an approaching challenge.

Apart from PHS, only a few studies have tackled the joint operation of intermittent renewable plants or electro-chemical ESS. Some authors analyze the operation of a single RES plant [139], [140], or otherwise, manage independently multiple ESSs [141]–[144] in the network.

Furthermore, the joint participation of RES+ESS in reserve market is calculated and most papers [145]–[149] demonstrated that the profitability of the whole plant increases. Even aggregated ESSs in vehicle-to-grid applications achieve reasonable revenues [150]–[152], which reduce the EV owner’s bill. However, it should be highlighted that these studies do not consider all essential aspects for a complete EMS: some of them are more focused on the market schedule stage, consider historical hourly or known values of energy requirement, validate the market strategy only in a few days, do not estimate the battery degradation and operating costs, do not assess all technical aspects related to the FRR real-time operation or do not analyze the ESS sizing. All these aspects from diverse approaches found in the literature are critically reviewed in Section 1.3. Here, some aspects related to the grid services and FRR modelling are discussed.

Firstly, regarding the market optimization for FRR capacity reservation, some strategies give priority of downward bids [146], offer a small FRR band compared to the RES installed capacity [147], assure a low robustness for FRR compliance [143], [144], [148] or operate under the maximum available power [139], [140], [149]. The FRR capacity should be optimized at FRR auction time without knowledge of RT needs and with high reliability and robustness, ensuring there is no RES curtailment.

Secondly, during real-time operation (RT), uncertain AGC signal must be followed by the BSP generators. This AGC is the upward or downward deployment needs in RT according to FRR auctioned capacity. While some researches show a low level of FRR compliance which results in high penalties [143], [144], [146]–[148], other authors achieve a high technical FRR reliability without considering RES forecast uncertainty [147], [149] or AGC signal uncertainty [126], [141], [145]. Moreover, other studies do not consider the joint WP+ESS operation for FRR market [126], and actually, only ESS takes part in ancillary services. Other authors show that energy imbalances increase significantly in case of FRR participation [126], [146], which is contradictory with the essential objective of FRR.

Thirdly, some papers show in detail the fluctuations of AGC signal during a period of time with a high resolution (intra-hour behavior) and propose EMSs for a single [142], [144] or several ESSs [143] in multiple markets. Others authors share the AGC signal between conventional generators and ESS due to its limited capacity [130] or with a hydro plant [131]. But these EMSs are designed without any market participation.

Consequently, in order to validate and evaluate properly their joint FRR participation, the uncertainties of RES generation forecast as well as the real uncertainty of AGC signal should be considered in the RT operation. Moreover, energy imbalances and FRR penalties should be minimized as much as possible.

1.3.4 EMS for distributed energy resources

Increasingly, renewable energy resources are more technological diverse, numerous and distributed along a geographic area. Consequently, novel EMS aims at controlling and optimizing the joint operation of all diverse energy resources in a centralized way. In this direction, Micro-Grids (MG) and Virtual Power Plants (VPPs) are two suitable concepts to manage diverse distributed energy resources [106], [108], [132], [153]–[155]. The features of VPPs or MGs is shown in Figure 1.19 according to different criteria: energy resources or stakeholders, power type, operation mode, supervisory and hierarchical control, application, and strategic objective.

Application	Indv. consumer	Residential	System operator	Utility generator
Energy resources/ architecture/ stakeholders	Renewables	Storage	Utility Grid	System operators
	Generators	(Residential) loads	Interruptible loads	Retailer
Strategic objective	Self-consumption	Operation costs	Environmental	TSO/DSO service
	Ancillary services	Arbitrage	RES control	Power quality
Power type / phases	DC	AC	Single phase	Three phase
Operation mode	Grid-tied	Grid-connected	Islanded	
Hierarchical control	Tertiary	Secondary	Primary	
Supervisory control	Centralized	Distributed	Cooperative	Decentralized
Control technique	Rule-based	Optimization-based		

Figure 1.19 – VPP or MG classification. Adapted from [153], [154].

In particular, VPP concept is more suitable for market participation in which energy generation (and/or consumption) is schedule based on maximization of the strategic objective subject to the constraints of the system. VPP could be a bridge to the wholesale market of different energy resources located in a large geographic area. On the other hand, MG are more suitable in a limited geographical area focused on the retail distribution with the aim of energy cost minimization. Moreover, they usually require a level of storage to be energetically self-independent, and usually face more legal hurdles. Anyway, both existing researches are of interest to analyzed. Moreover, according to the Directive COM(2016)864 on "*Common rules for the internal market in electricity*" [91], all market participants -including renewable sources and storage facilities- are encouraged to participate in multiple markets in aggregation.

The diversification and aggregation of different RES plants present complementary generation profiles [156]–[159]. Consequently, RES production uncertainty is reduced, and more reliable real-time joint operation can be ensured. VPP are generally composed by renewable sources, storage systems, conventional generators and/or loads, whose aims can be to achieve a minimum cost operation allowing demand response [160], maximize electricity self-consumption [161], reduce daily RES variability by ensuring constant power [162], make arbitrage including interruptible load [163], manage pumped-storage to maintain internal grid frequency [164] or optimize the system with respect to CO_2 prices [165]. However, all of these researches have not included or integrated their EMSs completely under an electricity market framework.

Taking a step forward, various studies of VPP [166]–[173] aim at maximizing the incomes by optimizing the market scheduling and planning the overall operation in the market environment including frequency reserve markets. Nevertheless, possible RES deviations are accommodated by their own conventional and controllable plants (thermal power plants, microturbines or hydro units), interruptible loads or other reserve allocations. Consequently, RES do not play an active role in the frequency reserve provision, they are plainly considered the source of the internal energy imbalances which other controllable plants and/or ESS partially [167]–[169] should cope with in operation. These above studies are more focused on the market scheduling optimization stage and ignore RES dynamic fluctuations and uncertainties in RT.

For the above literature, controllable plants (thermal power plants, microturbines or hydro units) are always taken into account in the VPP, reducing the unpredictable RES nature and hugely restrictive technical constraints for RT operation. Due to this fact, they do not require to implement, to a great extent, RT techniques which enable to make quick decisions according to instantaneous system conditions. As can be observed in the current literature, no research was focused on developing EMS for an utterly RES portfolio with ESS which participate in multiple markets, manage their internal RES deviation through ESS operation and contribute to maintain system frequency through FRR market participation. Moreover, these studies do not consider to re-schedule their generation intra-daily because they have enough reserve allocation provided by conventional plants. Due to this fact, they do not give attention to RT control. Although RT rule-based techniques are widely considered as suboptimal decisions, they enable to make quick decisions and improve the RT operation according to instantaneous RT state.

Focusing on RT operation, other researches are more focused on RT control strategies for RES. Model Predictive Control (MPC), also known as receding horizon control, is widely used as real-time control in order to make decisions under uncertainty and adjust the pre-defined RES operation according to instantaneous system measurements and perform corrective actions when uncertainties or unexpected events appear in real-time operation. For example, authors in [174] aim at increasing the self-consumption, reducing imbalance errors of RES [120] or system operating costs through controllable loads [175], maximize revenues in islanded microgrids [176], or optimize scheduling in a microgrid [177], [178].

In other applications, MPC is also generally used as real-time control [113], [124], [141], [143]. Although the scope of these latest studies is out of the scope of market participation, MPC technique demonstrates its potentiality and usefulness in market application to assess the impact of uncertain or RT parameters according to previous market scheduling.

Therefore, in order to evaluate their operation, it is necessary to simulate and validate the EMS in RT operation as much accurate and realistic as possible, in which the influence of uncertain RT parameters (market prices, forecast errors, AGC signal from FRR market and ESS capacity loss in operation) are validated in technical and economic terms.

Another aspect that should improve RT operation is the applied RT controls. Regarding the supervisory control of VPPs in RT operation, the centralized control scheme is mostly implemented to manage all energy resources as a whole, and schedule or control the renewable generation [106], [132], [166]–[173]. However, it is worth analyzing in detail which RT controls are implemented when several ESSs should be coordinated. In the literature, distributed ESSs are preferred rather than aggregated ESSs (like one larger ESS) [143], [144], [179]. This fact allows more flexible and optimal integration of different RESs and increase the system redundancy and stability in faulty or extreme conditions.

Some authors propose supervisory controls for multiple ESSs to equalize all State of Charge (SOC) that means ensure uniform charge/ discharge ratios for all ESSs [179] or regulate them around the expected average SOC [143] to prevent individual saturation or depletion. Moreover, allowing power curtailment or load shedding [179] is also implemented to avoid ESS overcharging or deep discharging. In other studies, when ESSs are about to be fully (dis)charged due to high AGC requirements, they participate in intraday or real-time markets [144]. This kind of EMS are only implemented for multiple ESSs without other energy resources or inside a VPP. In contrast, previous VPP studies analyzed in the literature do not consider ESS coordination or SOC controls [106], [132], [166]–[173].

1.3.5 ESS modelling in EMSs

There is a last issue that should be considered in the EMS to ensure the asset profitability. In order to evaluate the feasible profitability of the ESS for the operation of RES+ESS in energy and reserve markets, ESS acquisition and degradation costs should be taken into account. Even more, some authors state clearly that the ESS integration is not profitable under current investment cost and market design [126],[128], [129], [180].

The acquisition cost should be considered to economically justify its deployment. This consideration was hardly analyzed in most literature. Regarding the optimal ESS capacity to be installed, several researches are focused on the optimal sizing in order to support renewable integration or local demand [181],[182] or to participate in electricity markets [180],[183] in order to maximize the profitability or reduce the overall system cost. On the other hand, selecting the optimal ESS capacity enables a reduction of investment ESS costs, as long as optimal market scheduling and reliable RT operation is preserved. However, among all of the literature analyzed in this field, the influence of ESS sizing in energy and reserve markets with RES plants has not been yet assessed, considering all the factors mentioned above.

On the other hand, degradation costs should be evaluated to estimate the ESS lifetime and their associated replacement costs. The authors in [179] suggest considering safe operating limits for ESS to prevent fast damage or degradation. Other authors [176] want to limit, as much as possible, the variations of the battery power exchange, to reduce the number of cycles. There are few studies that estimate the ESS degradation costs expressed as a function of battery cycles and Depth-Of-Discharge (DOD) as in [184]–[188], without calendar issues. Finally, the research in [142] estimates the ESS usage costs with semi-empirical calendar and cycling models without a ESS lifetime estimation. However, the interrelationships between the ESS sizing, ESS degradation, expected ESS lifetime and long-term ESS costs during the operation has not been yet analyzed.

1.4 Main motivation of the PhD thesis

The aim of the presented State of Art was to summarize the background knowledge of ESS and their potential services and applications. Moreover, diverse approaches, strategies and methodologies oriented to the energy management of RES with ESS are analyzed, focusing on their market participation and provision of frequency services.

Regarding the first section, the recent deployment of RES plants was contextualized. To reduce the dependence on fossil energy sources, decrease GHG emissions, and mitigate the climate change, renewable energy -mainly solar and wind- is increasingly considered and deployed in the three main energy consumption sectors (electricity, heating/cooling and transport). Both renewable technologies have undergone an exponential growth and they will increase significantly their presence in the electricity grid in next decades, in line with the global targets toward a low or zero carbon economy.

However, several network concerns raise in case of a massive or uncontrolled RES penetration related to the system stability and reliability. One measure to solve this problem is to schedule, control and deliver their generation in the same way as conventional plants through the electricity markets. For this purpose, ESS are considered one of the key technologies which support high renewable penetrations in power systems, by adding more flexibility and controllability to their RES operation in electricity markets, among other services suitable for ESS.

Therefore, throughout the second section, a review of the potential ESS services has been presented, focusing on frequency ancillary services and renewable-oriented services. Among the existing ESS technologies, electro-chemical ESS are considered as the main enabling technology to face the new functionalities needed to integrate more RES into the grid, because they provide a fast power response that enables them to control and smooth RES intermittency and variability, as well as improving the power quality and providing frequency regulation services.

Based on the most representative operational projects, it can be concluded that Li-ion technology is the most developed and largely deployed technology, under pilot and/or commercial projects in the short term.

Additionally, the main barriers for ESS in electricity market have been identified and the recent changes in aforementioned markets have been exposed. Although ESS is been integrated in some countries though recent regulatory frameworks, there is a need to establish an appropriate stable and legal framework which ensures the profitability of the investments in light of the number of new initiatives and commercial projects coming forwards. After analyzing the market barriers and recent policies, fast frequency ancillary services are the most attractive markets for ESS to increase their economic viability. Although these ancillary markets have high degree of uncertainty in RT operation, they are high-value and well-remunerated services.

Apart from electricity market barriers, the high investment, operational and replacement costs of the electro-chemical ESS, and the difficulty to estimate their lifetime and the best strategy to control them for a given application or desired functionality are the main drawbacks to the wide inclusion of this technology. Together with a RES plant, as exposed before, their joint operation could increase the overall profitability of the asset and increase the feasible business cases in electricity market.

Therefore, the objective of the last section has been to present a thorough literature review which allows identifying a suitable methodology to assess and validate an ESS cost-effective solution under the scenario considered in the scope of this PhD thesis: the RES+ESS participation and operation in energy and frequency reserve markets. According to the analyzed publications, currently it is still challenging to obtain significant profits from the integration of electrochemical ESS on grid-connected applications, in particular, when frequency reserve markets are included.

For this purpose, the adoption of advanced techniques and coordinated EMS of the utility RES+ESS facility should be developed in order to achieve a controllable and reliable operation which leads to a profitable exploitation through the joint participation in energy and reserve markets.

As discussed along the State of Art, researches that are only limited to accommodate or smooth RES energy do not reflect the potential value of ESS. Thanks to the fast response of ESS, its provision of frequency ancillary services will be another market opportunity for RES+ESS owners, achieving additional sources of revenues.

Among the literature gaps discussed in the literature review, after the optimization process for dispatch strategy or market scheduling, it is necessary to simulate the proposed EMS in RT operation as much accurate and realistic as possible, in which the influence of uncertain RT parameters (market prices, forecast errors, FRR market and ESS capacity loss) can be accurately modelled, and later, validated in techno-economic terms. Without an accurate evaluation of the ESS operation and degradation, any technical evaluation would be less realistic or inaccurate. Thus, their suitability and profitability for any particular application could be hardly assured and validated properly.

Regarding the features of the ESS, its efficiency, acquisition and operating costs, technical constraints due to limited capacity, degradation model or capacity/power sizing analysis should be included in the methodology. Among all the literature analyzed in this field, the influence of ESS sizing, operation and degradation issues in energy and reserve markets supporting renewable plants has not been yet fully assessed.

Thus, the main problem found out in the current literature is the lack of a methodology for the proper sizing and operation of a renewable asset management with ESS in energy and reserve markets for the long-term planning and short-term operation assessment, giving a suitable and accurate framework to evaluate the cost-effectiveness of ESS integration for different RES technologies for grid-connected applications. Therefore, the development of *Optimal Energy Management and Sizing Strategies for Large-Scale Electrical Storage Systems supporting Renewable Energy Sources* are proposed as the main contribution of this PhD thesis. For all key aspects mentioned above, this dissertation develops an advanced EMS by fulfilling all above identified gaps from a global perspective:

- ***RES+ESS market scheduling*** will be calculated to maximize market revenues in line with previous VPP composed by renewable and conventional plants. In contrast, in this dissertation, ESSs will manage entirely the RES variability based on forecast service provider information. Moreover, RES forecast generation, ESS efficiency, ESS acquisition and operating costs and technical constraints due to limited ESS capacity are included in the optimization problem. Furthermore, the proposed EMS tries to minimize as much as possible energy imbalances (not purely economic optimization) with a forced strategy [120] to guarantee high market compliance and RT reliable operation.
- ***Continuous Intraday Markets*** (CIM), in addition to DM, will be applied in order to re-schedule RES generation, control forecast deviation and manage ESSs. CIM has not yet analyzed under Spanish market, since its inclusion in 2018.
- ***The participation in reserve markets (FRR)*** will be a profitable additional service, with the aim of increasing the asset profitability. However, FRR market bids and AGC power signal should be modelled, calculated and validated properly, in which reliable operation is achieved, despite the high RT uncertainty of the market.
- ***MPC approach*** will improve the RT operation performance. Moreover, the influence of uncertain RT parameters on market performance and operation can be evaluated. The MPC approach, as a closed-loop control, together with the RT operation and DM+CIM+FRR participation, was not previously implemented.

- Moreover, ***several RT supervisory controls*** for VPP operation will be applied to validate that SOC equalization techniques and their techno-economic improvements in operation and exploitation.
    - In a decentralized control, the final portfolio market schedule and RT operation is the aggregate of the decisions and controls of each individual plant. Thus, they operate as separated or individual plants, which could result usually in suboptimal decisions and/or faulty or extreme RT operation conditions.
    - Otherwise, RES complementarity and SOC equalization techniques were taken into advantage in centralized portfolio operation to reduce SOC fluctuations, and the usage of ESS.
- ***An ESS aging model analysis*** should be included in order to estimate the ESS lifetime (through proper and customized cycling and calendar aging models) and their associated operating and replacement costs. An oversized ESS will allow RES plant to increase market revenues, to reduce energy imbalances, to achieve a high compliance of FRR requirements and to reduce FRR penalties. However, its high ESS costs could not be compensated with additional market profits.
- ***An ESS sizing sensitivity analysis*** should be carried out to determine the optimal ESS sizing in relation to the VPP profitability. The ESS capacity will impact on the market scheduling and operation (i.e. ESS costs and ESS limitations). The overall ESS costs related to the optimal ESS operation are included in the objective function in order to achieve a trade-off between an intensive ESS operation and an extended ESS lifetime. The expected ESS lifetime and overall ESS costs are calculated thanks to the ESS aging model analysis. Additionally, future market prices, different system costs, or market operation are also considered in order to evaluate the ESS cost-effectiveness to support RES operation under different scenarios.
- ***Two case studies*** are selected in order to apply and validate the EMS. Firstly, this EMS enables to operate individual RES+ESS plants, and additionally, renewable portfolio with distributed ESS can be scheduled, operated in a decentralized or centralized way.

Chapter 2 Short-term and long-term EMS for RES+ESS

In this section, the combined short-term and long-term Energy Management Strategy (EMS) for RES+ESS is explained and developed, according to the identified gaps and potential opportunities for ESS.

This proposed EMS addresses the renewable asset management in the long-term planning and short-term operation, giving the framework to evaluate the cost-effectiveness of ESS integration for different RES technologies and applications.

The main objectives of the proposed EMS are the following: i) optimize energy and reserve market scheduling and minimize expected energy imbalances, regarding most recent forecast information considering ESS degradation, ii) re-schedule RES generation intra-daily to control large RES forecast deviations and manage the energy stored in ESSs, and iii) operate at real-time to follow energy schedule and AGC signal, while smoothing RES variability and intermittency.

The EMS is validated for two scenarios. Firstly, this EMS enables to schedule and operate independently individual RES+ESS plants (photovoltaic solar plants and wind plants), and secondly, renewable portfolio with distributed ESS can be scheduled, and operated through different portfolio supervisory controls.

2.1 RES+ESS energy management strategy

In this section the proposed Energy Management Strategy (EMS) is explained in depth and implemented according to the identified gaps found in the literature. This EMS is divided into five blocks, as can be observed in Figure 2.1: i) scenario definition, ii) upper level in which the optimization process is applied, iii) ESS aging analysis, iv) lower level control in which real-time operation is applied, and v) Model Predictive Control, applied as a closed-loop control. This EMS is designed and implemented in Matlab environment (version R2018b).

In the scenario definition, the main design and operation variables are defined, regarding the RES installed capacity and RES generation forecast which come from the forecast service provider, and other design variables related to the ESS and system costs. Moreover, the market framework is defined regarding market rules, gate closures times and market operation horizons for each market. Particularly, current Spanish electricity markets are considered and modelled, such as the DM, CIM and FRR.

In the upper level control, a Mix-Integer Linear Programming (MILP) optimization (using *intlinprog* Matlab toolbox) is applied to calculate the joint operation and market participation for DM, CIM and FRR. The main objectives are to maximize daily market revenues and minimize overall ESS costs, by calculating optimal DM and CIM scheduling and

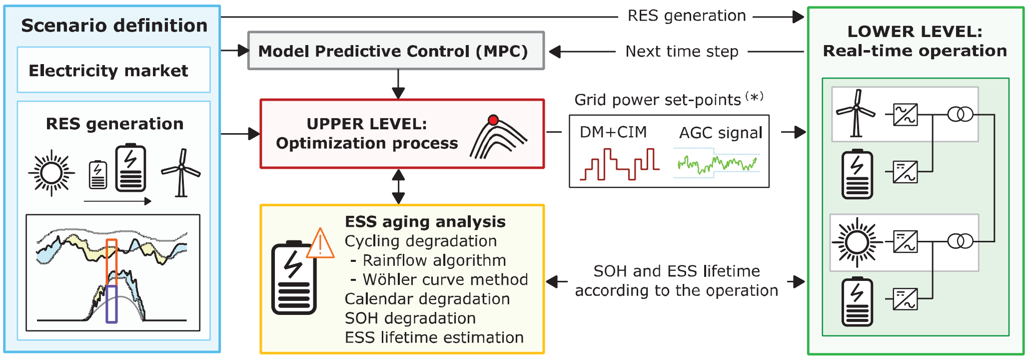


Figure 2.1– Proposed RES+ESS Energy Management Strategy.

more profitable hourly FRR band availability, while in technical terms it is tried to avoid as much as possible positive energy imbalances, negative energy imbalances and FRR penalties. Moreover, the objective function controls the SOC around 50% at the end of the day in order to start next day with enough ESS energy. Expected CIM and FRR market prices are estimated with the publication of DM prices for each day. These prices are updated in the objective function to maximize revenues.

Regarding the FRR requirements at real-time operation, the AGC signal modelling is carried out based on public data from hourly energy requirements. This AGC signal applied in RT operation is modelled following the behavior of several AGC signals found in the literature.

Additionally, in the ESS aging analysis, an ESS cycling degradation is estimated based on the ESS operation according to Wöhler curve-based aging model through a Rainflow cycle counting algorithm [117]. Moreover, the ESS lifetime and its associated costs are calculated based on cycling aging, as well as calendar aging models. This ESS aging analysis is repeated iteratively when CIM+FRR bids are jointly optimized in order to achieve a trade-off between an intensive ESS operation and a reduction of ESS degradation costs due to an extended ESS lifetime. Moreover, this ESS analysis is also carried out at the end of the day and at the end of the evaluation period with the annual ESS operation values.

After the market scheduling process, the lower level control is applied, in which real-time operation is carried out to validate the optimal values calculated in the upper control. Any energy deviation or RES forecast errors that occur during RT operation have influence on the optimal market operation and optimal ESS energy profiles. The main challenge of the RES operation is to avoid large energy imbalances caused by unpredicted forecast errors and to provide a high technical compliance in FRR market. Therefore, the objective of RT operation is to fulfil grid power set-points composed by the most recent DM+CIM schedule and the current AGC signal be means of the instantaneous RES generation measure and the energy stored in ESSs.

To reach this aim, advanced portfolio supervisory controls should be implemented in real-time operation. While individual RES+ESS plants must be operated independently, renewable portfolio with distributed ESS can be also operated and controlled in a centralized way to provide the both grid power set-points according to the total available RES generation and ESSs' stored energy, with the objective of minimizing SOC changes, reducing ESS usage, and extending their lifetimes.

Finally, MPC is applied as a closed-loop control. MPC is widely used as real-time control in order to adapt the pre-defined RES operation according to instantaneous system measurements and perform corrective actions when uncertainties or unexpected events appear in RT operation. Therefore, only the first grid power set-points are requested in RT operation, and a following market optimization is carried out.

2.2 Scenario definition

In the scenario definition, the input data parametrization is carried out, in which the main design and operation variables are defined. Figure 2.2 represents in detail the required input data of the EMS regarding the market framework and renewable generation, and the interconnection of scenario definition with the other blocks.

2.2.1 Renewable generation

RES generation forecasts and instantaneous generation data are inputs for the EMS in the scenario definition. This data can be loaded from public data or for a given particular RES plant of interest. When this EMS is applied in a real application, instantaneous RES generation will be monitored from the existing installation and be loaded as input for the EMS, as well as, the DM or updated generation forecast profiles.

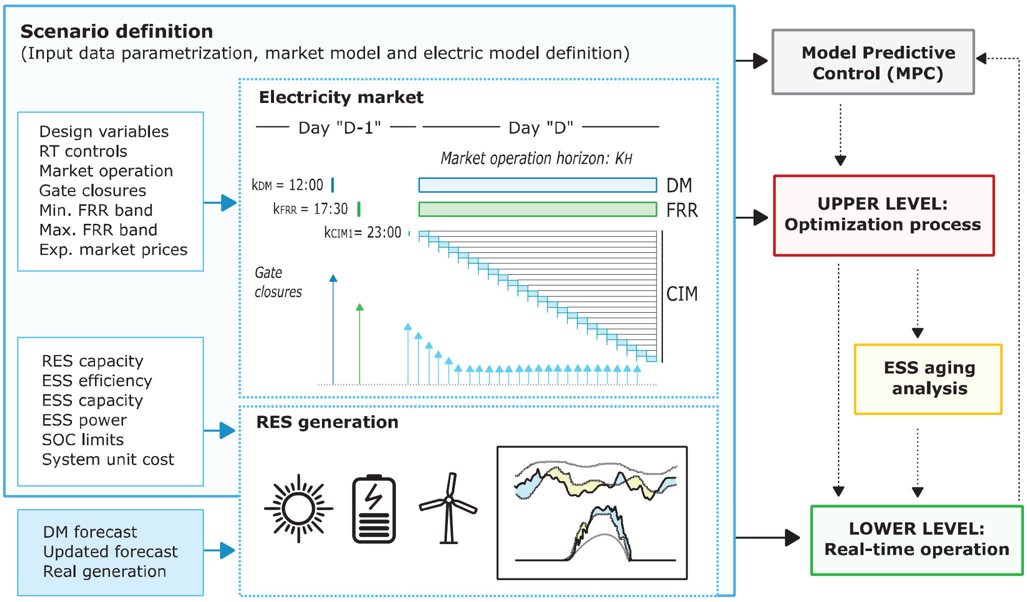


Figure 2.2 – Scenario definition in detail.

RES generation forecasts ($P_{r,k}^{pred}$) are needed to calculate the optimal market participation. These data come from the forecast service provider information and they are updated depending on the time of the day. At the time of DM and FRR auctions, the RES generation information is the day-ahead generation forecast. At the time of CIM auctions, that it, during the operation day, the RES generation information is updated and corresponds to the most recent (or intra-day) generation forecast, being more accurate than day-ahead forecasts, as can be observed in Figure 2.3.

Then, instantaneous (or measured, real) RES generation values ($P_{r,k}^{real}$) are applied to the real-time operation. These power signals represent the real energy generated by RES plants. The suffix r represents each RES plant considered in the model.

Parametrization is the process of defining or choosing parameters. In this EMS, design variables are parametrized as well as the ESS and RES+ESS costs. These values are defined by the user or asset owner, depending on their design preferences and power facility characteristics.

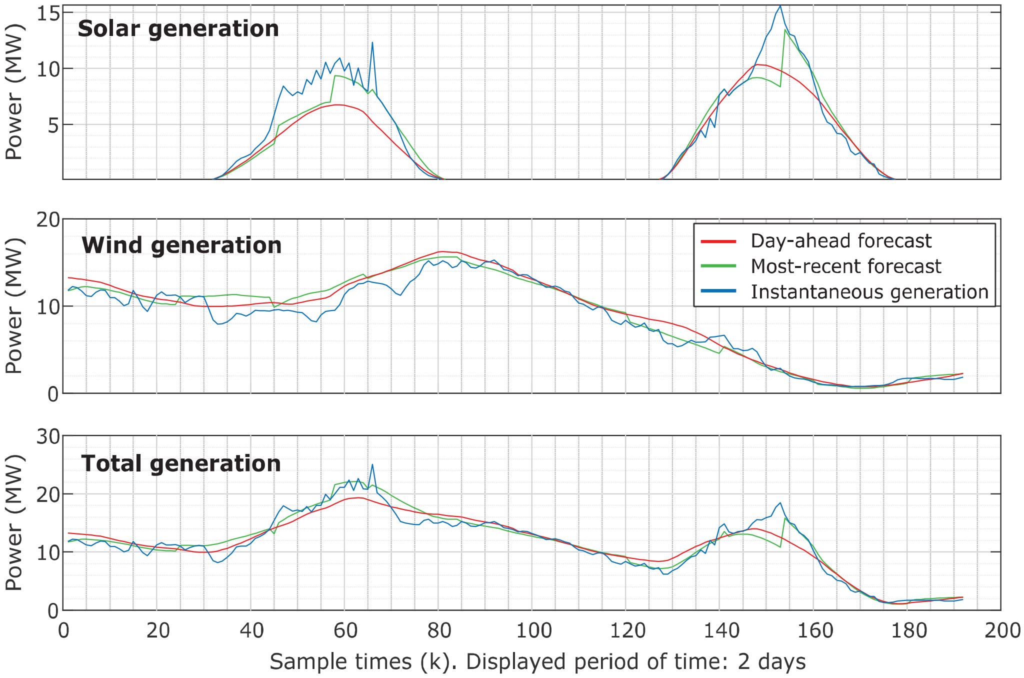


Figure 2.3 – Solar and wind generation profiles for two given days.

The design variables are the following:

- ESS nominal capacity: C_r^{nom} [in MW]
- ESS maximum power assumed as the converter power: P_r^{conv} [in MW]
- ESS charging and discharging efficiency: $\eta^{ch/dch}$ [in %]
- SOC limits for safe operation: $\underline{SOC}^{opt}$ and $\overline{SOC}^{opt}$ [in %]
- SOC limits for FRR participation: $\underline{SOC}^{FRR}$ and $\overline{SOC}^{FRR}$ [in %]
- SOC limits for RT operation: $\underline{SOC}^{rt}$ and $\overline{SOC}^{rt}$ [in %]
- Possibility to increase SOC limits for RT operation when AGC is being provided, in order to reduce more FRR penalties.
- SOC range at the end of the day: $\underline{SOC}^{end}$ and $\overline{SOC}^{end}$ [in %]
- The acquisition costs of the RES: c^{PV}, c^{WP} [in €/MW installed]
- The acquisition power-related costs of the ESS: c^{MW} [in €/MW]
- The acquisition energy-related costs of the ESS: c^{MWh} [in €/MWh]
- Expected converter and RES lifetimes: $\Psi^{conv}, \Psi^{PV}, \Psi^{WP}$ [in years]

As MPC approach is applied, as a closed-loop control for the EMS, several inputs are required to define its time resolution, such as:

- Sample k and time step $\Delta k=1$
- Real-time period: i.e. $\Delta t = 0.25$, that is, 15 minutes

It is recommended having the same or less real-time period than the resolution for RES generation profiles. In real application, RES generated energy and other RT parameters are monitored and updated constantly (seconds or minutes) and therefore, the real-time period in a real implementation should be reduced, in order to calculate the system response at the same pace as the input and measured data are updated.

However, the resolution for RES generation profiles in the research is extracted from historical data with a 15 minutes-basis. Therefore, the resolution for the optimization, real-time operation and MPC approach was defined on 15 minutes-basis, known as real-time period. Detailed information about MPC approach can be found in Section 2.6.

2.2.2 Electricity market

Electricity market models should be defined regarding market rules, gate closures times and market operation horizons for each considered market in the EMS. The electricity market model implemented in the EMS can be genetic, that is, any market model from a given country or application can be included. In particular, the Spanish market is modelled as example, and their details can be shown in Figure 2.4. To model the market participation, the following main design parameters should be defined:

- Consideration of constant, hourly mean (historical) or expected market prices. Expected prices will be taken into account the publication of the DM prices [189] to estimate the prices for CIM and FRR prices.
- Decision to participate in DM, CIM and/or FRR.
- DM, IM, CIM, FRR market gate closure times.

- The minimum hourly FRR availability (P_r^{bmin}) according to minimum bid size defined by the market design of each country.
- The maximum FRR availability (P_r^{bmax}) related to the ESS capacity.
- Decision of RT portfolio supervisory control.

Energy markets

Spanish DM is the main energy trading market to meet demand of the following day. Sellers of electricity present energy bids to the Market Operator (MO) for each of the production units they own. The MO collects purchase and sale bids, and calculate the price using a market-clearing pricing procedure. Energy products are auctioned at marginal price (€/MWh), and the time resolution is 1 hour (in hourly intervals). Therefore, the energy delivered in one hour should be constant. DM gate closure time is settled at midday of the previous day (“D-1”), and its market operation horizon comprised one day (“D”) as can be observed in Figure 2.5. This market design is repeated every day.

IM is similar to the day-ahead market but cleared closer to power delivery and it covers a shorter trading horizon. There are two main intraday markets: IM through discrete auctions (at marginal price) or Continuous Intraday Market (CIM) (based on pay-as-bid price). Energy time resolution in Spain is 1 hour in both cases.

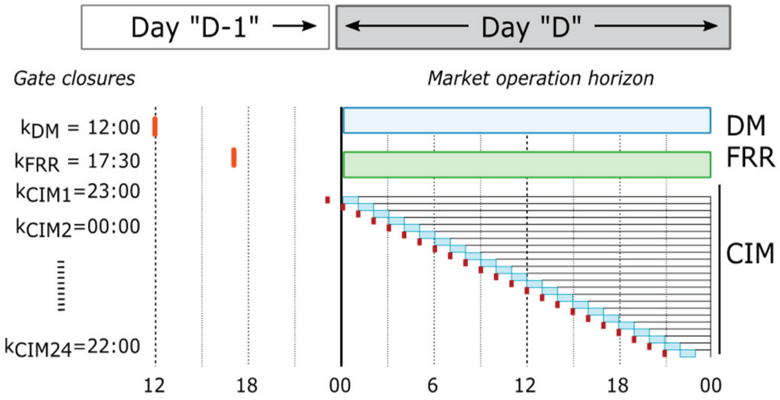


Figure 2.4 – The Iberian Electricity Market schedule for DM, CIM and FRR.

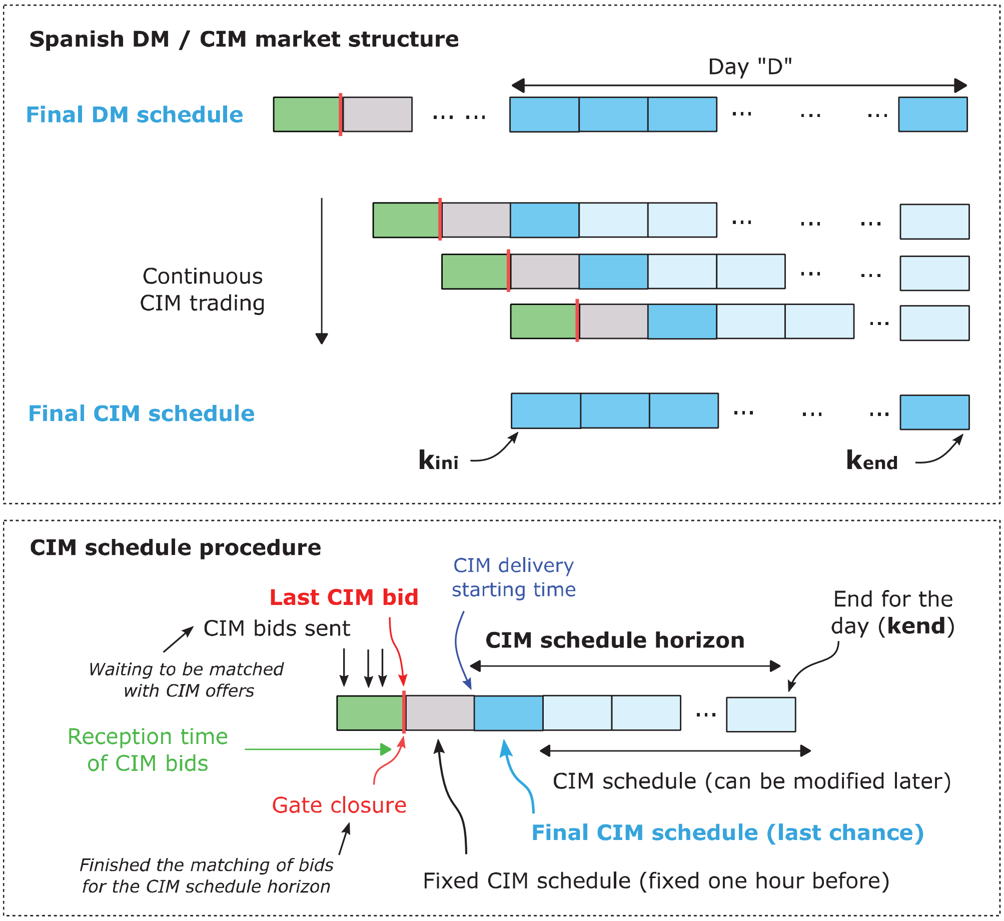


Figure 2.5 – Energy market schedule procedure, structure and operation.

In particular, CIM market is modelled in this PhD dissertation, represented in Figure 2.5 (IM by auctions is presented and modelled in Appendix 1). CIM bids can be sent at any time, one hour in advance of its delivery (and in hourly basis). In that way, final CIM schedule is defined during the operation day “D”.

Frequency regulation reserve

Regarding the Spanish frequency regulation reserve, the auction time and operation requirements are explained and described below.

Since 2016, the Spanish regulation [41] allows the participation of renewable energies, cogeneration and waste-to-energy plants in the ancillary services of the electricity system, such as secondary reserve service (known as Frequency Regulation Reserve, FRR) and tertiary reserve service (known as Replacement Reserve, RR). Regarding the ESS technical features and limited capacity, the FRR is more suitable to ESS participation in Spanish electricity markets.

Frequency Containment Reserve (FCR, corresponding to primary regulation) is omitted in this PhD thesis, because it is a non-remunerated compulsory service for conventional plants, and it is not cleared through any market auction. Additionally, RR is also solved through daily auctions. In contrast to FRR, RR requires higher energy delivery, so therefore, ESS (i.e. PHS) or conventional generators with high energy density are required. In particular, Spanish wind plants together with other controllable plants participate in FRR, but mainly providing downward tertiary energy, reducing their wind generation. Therefore, the reserve market of interest for RES+ESS plant is FRR. In particular, Spanish FRR is modelled in this PhD thesis.

As can be observed in Table 2.1, in Spain, 158 power plants participate in FRR to maintain the system frequency, (update in March 2018), known as Balancing Service Providers (BSP). The total installed capacity of Spanish BSP for FRR is 68.36 GW (67.5% of Spanish total installed capacity) and they are gathered in 18 Regulation Zones (RZ) [190]. As depicted in Table 2.1, fossil power plants (from coal, gas and oil sources) and hydraulic power plants participate mostly in FRR (78.4% of total capacity). 18 wind parks have been authorized to participate in balancing services (11% of total capacity) and only 1 PV plant is recently added inside one of these RZs, but its capacity continues being insignificant compared to the total capacity of all RZs (0.02%).

Although the authorized WPs reach 11% of the total plants in FRR service, nowadays, the real contribution of WP in the FRR service is residual since the FRR available capacity is assigned for each RZ. The reason of the difference between the wind installed capacity and their real contribution in real-time operation is that real-time requirements can be distributed between all power plants inside the RZ, according to their availability and the criteria of the owner of these assets.

Due to this market design, the asset owner decides the contribution of the WP depending on their real-time generation and flexible capacities to follow this AGC signal, while the rest of controllable plants are regulated to provide the energy necessary up to the total FRR requirement.

Therefore, the contribution of WP to the FRR requirements in operation is less than 0.2% although the Spanish legislation enabled the renewable participation in balancing markets by the end of 2016 (see Figure 2.6). In contrast, the aim of this EMS is to control and operate the RES+ESS portfolio reliably as other controllable plant which is responsible of their own energy imbalances (like BRP generators) and provides FRR service (like BSP generators).

Table 2.1 – FRR participation and total installed capacity in the system per technology. Source: REE. Update: March 2018

Technology	**FRR participation**			**Installed capacity**	
	nº	**MW**	**%**	**MW**	**%**
Fossil	92	35016.3	51.22%	40524	41.32%
Hydroelectric	37	18578.5	27.18%	20322.3	20.72%
Wind	18	7557.6	11.06%	22855.8	23.30%
Nuclear	7	7117.2	10.41%	7117.2	7.26%
Thermoelectric	1	50	0.07%	2301.2	2.35%
Biomass	2	26.9	0.04%	531	0.54%
Photovoltaic	1	13.4	0.02%	4432.9	4.52%
Others	-	-	-	3.185.60	3.25%
Total	158	68359.9	100.00%	98084.4	100%

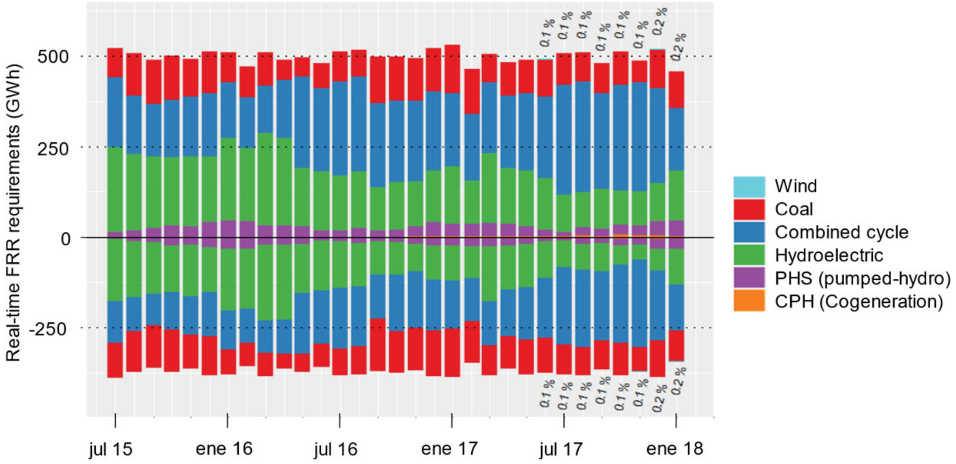


Figure 2.6 – Real-Time FRR requirements. Source: DVL-GL.

For the considered case study in this dissertation, PV and WP plants are considered inside a new RZ, with the average capacity of the existing RZs and a similar energy mix than the Spanish system, in which PV, WP and ESS assets have more presence, as can be seen Figure 2.7. The total capacity of this new RZ will be 3798 MW (considering the average of current Spanish RZ), with several photovoltaic and wind power plants of 30 MW each one (considering the average of Spanish RES plants).

In contrast to the current operation of the RZs, the objective is to be able to control RES generation and provide FRR services with an asset composed only by renewable and storage resources.

The Spanish TSO (Red Eléctrica de España, REE) publishes hourly upward and downward FRR needs $(P_{need,h}^{up}$ and $P_{need,h}^{dw})$ at 16:00 of the day before (D-1) and the FRR auction closes at 17:30, according to the Spanish requirements to handle energy deviations in both directions. Firstly, FRR bids are sorted by price merit order and less expensive bids are usually fully assigned, considering several rules and bids' conditions (indivisibility, ramp, size, etc.). Throughout all the assignation process, the hourly upward and downward FRR needs $(P_{need,h}^{up}$ and $P_{need,h}^{dw})$ relation should be maintained for the whole system and for each RZ.

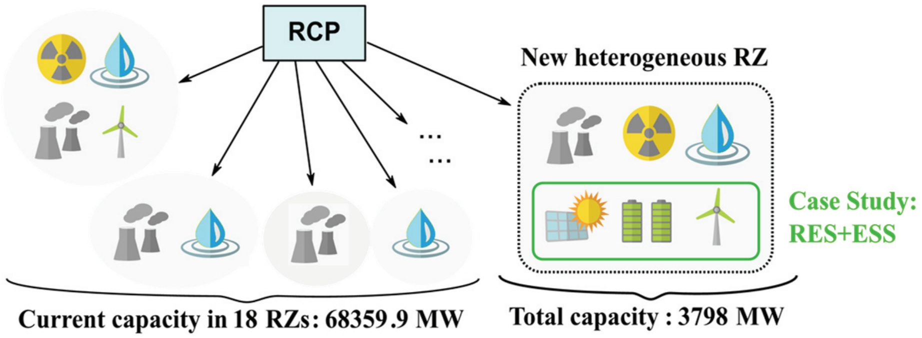


Figure 2.7 – Spanish current RZs and the new heterogeneous RZ. Source: REE.

The relation is defined by eq. (2.1), as the hourly Reserve Rate (RR_h). Another way to define this term is through the ratio between upward and downward FRR bands ($r^{up}_{RZ,h}$ / $r^{dw}_{RZ,h}$), and therefore, the assigned power capacity per RZ ($P^{up}_{RZ,h}$ / $P^{dw}_{RZ,h}$) as in eq (2.2). The assignation process is completed when the total hourly assigned power capacity for all RZ is placed between +/-10% of $P^{up}_{need,h}$ and $P^{dw}_{need,h}$, respectively.

As it has been exposed above, this RR_h value must be fulfilled by each RZ, and in this model, by each RES+ESS plant (or portfolio). Therefore, each RES plant sends its power availability (the sum of upward and downward FRR bands ($P^{uw}_{r,h}$ and $P^{dw}_{r,h}$)) and initially, each RES plant will maintain this hourly rate RR_h. This constraint is due to the aim of controlling and operating the RES plants with ESS reliably by themselves and without any support of other controllable plants.

$$RR_h = P^{up}_{need,h} \, / \, P^{dw}_{need,h} = r^{up}_{RZ,h} \, / \, r^{dw}_{RZ,h} = P^{up}_{RZ,h} \, / \, P^{dw}_{RZ,h} \tag{2.1}$$

$$P^{band}_{RZ,k} = P^{up}_{RZ,h} + P^{dw}_{RZ,h} = \Sigma_r \left(P^{up}_{r,h} + P^{dw}_{r,h}\right) \tag{2.2}$$

The minimum hourly bid size in Spain is 10 MW. That is, each production unit must participate with a minimum band of 10 MW. A production unit is the group of generators or facilities of the same technology (solar, wind, hydro, fuel, etc.) which shares the same Point of Common Coupling (PCC) and gathers the minimum capacity to participate in the market.

This minimum FRR bid size discourages small generators or distributed facilities to participate. However, it is expected that the minimum offer will be reduced, due to:

- Future market design with a reduction of minimum size. Across central and north Europe, the minimum size is established between 1-5 MW, or less than 1 MW. With the increasing RES distributed generation, it is expected to be reduced to 1 MW or less [40].
- The consideration of a larger portfolio of the same technology in which the considered production unit(s) are integrated in this model. Therefore, all generators and energy resources included in the VPP will participate with a total FRR capacity band at least of 10 MW.
- The possibility of participating in balancing services with a common bid for a portfolio composed by different technologies. This rule is established in most European countries, such as, Austria, Denmark, Finland, Germany, The Netherlands, or Switzerland [40]. In contrast, France, Belgium, Portugal, Spain and United Kingdom divide the market bids per technology. This rule does not allow to control different resources and technologies inside a VPP.

Thus, each BRP (single RES plant) is supposed to participate with a minimum bid of 1 MW.

The Shared Peninsular Regulation (RCP) [35] is the master controller and operates at real time hierarchically. The RCP computes an Area Control Error (ACE) for the whole Spanish control area and calculates the ACE power signal, according to: 1) the deviation of the power generated from the scheduled power, 2) the frequency variation and 3) the Automatic Generation Control (known as AGC) in real-time operation.

After the assignation process, a Participation Coefficient is defined ($PC_{RZ,h}$) per RZ, as the portion or percentage of ACE signal that should be provided, according to eq. (2.3). In operation, all RZs receive a proportional AGC power signal each 4 seconds, according to their corresponding Participation Coefficient.

$$PC_{RZ,h} = P_{RZ,h}^{up} \,/\, P_{need,h}^{up} = P_{RZ,h}^{dw} \,/\, P_{need,h}^{dw} \tag{2.3}$$

Contrary to energy markets, the AGC signal required at real-time operation is uncertain when the power availability is assigned at the auction time. The procedure to model the real-time FRR requirements (AGC signal in this PhD thesis), after optimizing the FRR band availability schedule, will be described in Section 2.3.3.

In order to clarify the FRR schedule procedure, structure and operation, Figure 2.8 shows the difference between the FRR availability bids composed by upward and downward power capacity bids ($P_{RZ,h}^{up}, P_{RZ,h}^{dw}$), and the AGC power signal, required in RT operation.

As can be observed, the AGC signal is a power signal uncertain and unsteady and applied in RT operation, whose limits are contained between the upward and downward power capacity bids ($P_{RZ,h}^{up}, P_{RZ,h}^{dw}$).

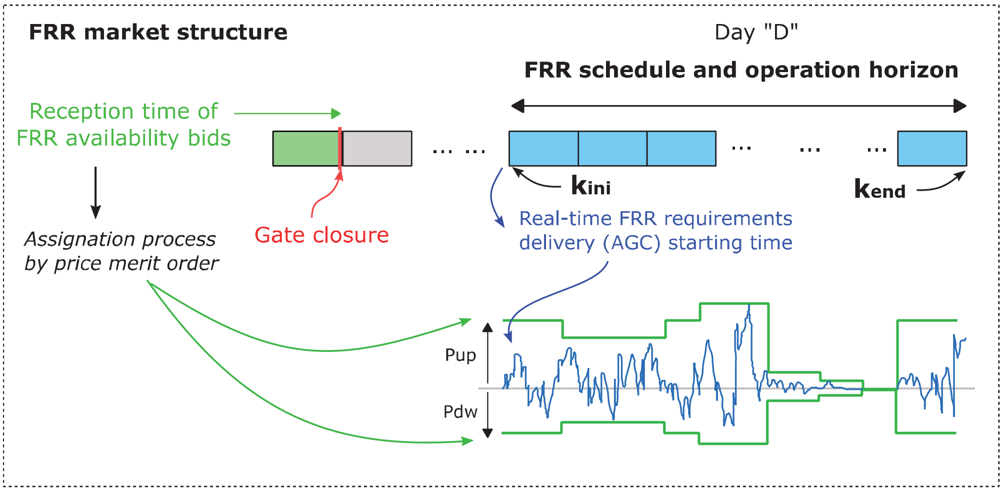


Figure 2.8 – FRR schedule procedure, structure and operation.

2.3 Upper level control: optimization process

This section describes the upper level control in which the optimization process is calculated. As can be observed in Figure 2.9, the design variables and current system conditions are firstly initialized: i) RES forecast profile is calculated based on the most recent forecast provider information and an additional terms in added in order to include unexpected FRR energy deviation, ii) current ESS state is updated based on SOC and SOH, iii) market model is defined according to owner's business case (i.e. market participation), iv) evaluate market gate closure time and current sample time, and v) optimize market participation, or otherwise, maintain the previous market scheduling until next market gate closure time.

As exposed before, in case of market auction is going to be cleared (at market gate closure time), the objective function is maximized in order to calculate the optimal DM, CIM and/or FRR market scheduling. In this case, equality and inequality constraints are defined according to current RES+ESS and market design. Moreover, upper and lower bounds for optimization variables. The core of the optimization process (the optimization formulation and calculation) is explained in Section 2.3.1 and 2.3.2. Afterward, ESS aging analysis is carried out with the ESS operation to estimate the ESS lifetime (included in the obj. function).

After the optimization calculation, data post-processing is carried out, with two purpose: i) estimate the ESS lifetime, and ii) calculate the AGC signal according to Section 2.3.3 that will be applied in RT operation.

Finally, the optimal grid set-points are sent to the lower control level in which real-time operation is applied. Thanks to the MPC, the upper level control based on an optimization process is repeated for each sample time.

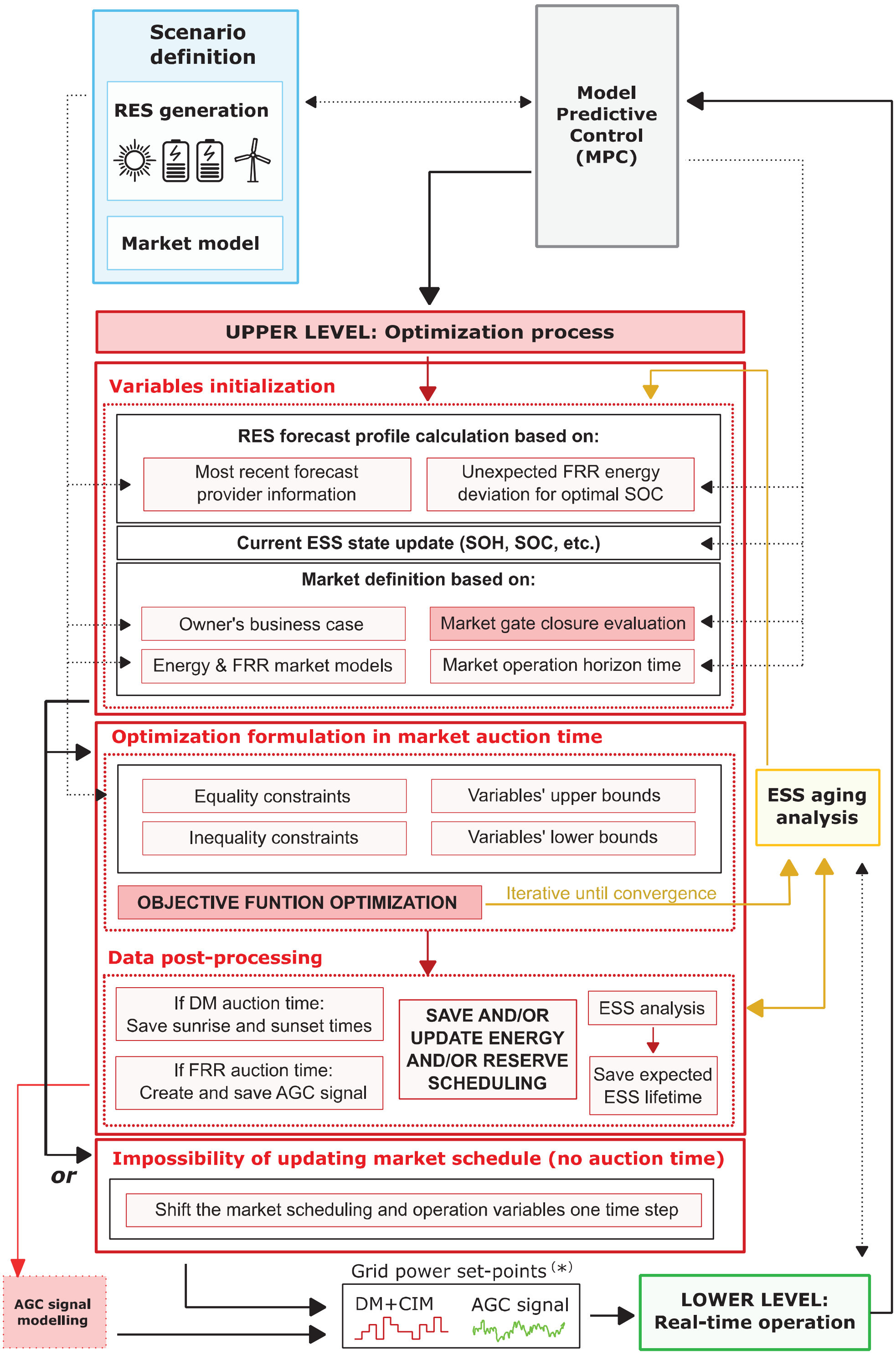


Figure 2.9 – Upper level control (optimization process) block in detail.

2.3.1 Objective function

A mix-integer linear programming (MILP) optimization is applied following eq. (2.4) to maximize daily market revenues and reduce overall ESS costs, by calculating optimal DM and CIM scheduling ($P_{r,k}^{DM}, P_{r,k}^{CIM}$) and more profitable FRR band availability ($P_{r,k}^{band}$) according to mean upward and downward FRR energy required ($E_{r,k}^{uw}, E_{r,k}^{dw}$), and reducing expected energy imbalances ($P_{r,k}^{imb+}, P_{r,k}^{imb-}$). This objective function mixes economical and technical terms to be maximized. The optimization horizon is optimizing for the variable subset K_H from current sample k up to the end of the day (k_{end}), and for all RES plants in the portfolio (r).

$$max \left\{ \sum_{\forall r \epsilon R} \sum_{\forall k \epsilon K_H} \left[\begin{array}{c} -\dfrac{c^{MW} \cdot P_r^{conv}}{\psi^{conv} \cdot d^y} - \dfrac{c^{MWh} \cdot C_r^{nom}}{\Psi_r^{ESS} \cdot d^y} \\ +\Delta t \cdot \ (M \cdot E_{r,k_{end}}^{ESS} + \ \lambda_k^{DM} \cdot P_{r,k}^{DM} + \lambda_k^{CIM} \cdot P_{r,k}^{CIM} \\ +\gamma_k^{band} \cdot \lambda_k^{band} \cdot P_{r,k}^{band} + \lambda_k^{uw} \cdot E_{r,k}^{uw} - \lambda_k^{dw} \cdot E_{r,k}^{dw} \\ -M \cdot (\gamma_{r,k}^{+} \cdot \lambda_k^{imb+} \cdot P_{r,k}^{imb+} + \gamma_{r,k}^{-} \cdot \lambda_k^{imb-} \cdot P_{r,k}^{imb-})) \end{array} \right] \right\} \tag{2.4}$$

The main objective is to maximize daily market scheduling ($P_{r,k}^{DM}, P_{r,k}^{CIM}$, $P_{r,k}^{band}$), calculated with a variable window horizon up to 36 h (starting at the DM auction at midday up to the end of the optimization day (k_{end}), according to graphical representations from Figure 2.5 and Figure 2.8. Therefore, market revenues are calculated by market offers ($P_{r,k}^{DM}, P_{r,k}^{CIM}$, $P_{r,k}^{band}$) and expected market prices ($\lambda^{DM}, \lambda^{CIM}, \lambda^{band}$), and the mean FRR energy revenues or costs at RT are included ($E_{r,k}^{uw}, E_{r,k}^{dw}$) by their expected prices ($\lambda^{uw}, \lambda^{dw}$). The market scheduling is customized for each RES+ESS plant and each day based on forecast service provider information ($P_{r,k}^{pred}$). The generation forecast is updated depending on the current time step. In DM schedule, it corresponds to DM forecast, and most recent forecasts are included for CIM schedule, being more accurate than DM forecasts. Moreover, real-time period (Δt) is included to calculate hourly market revenues, as the market prices are in €/MWh and market power in MW.

Regarding costs terms, power and energy-related ESS costs aims to be minimized, according to two optimization variables: the maximum converter power required for each ESS (P_r^{conv}) and expected ESS lifetime (in which ESS lifetime Ψ_r^{ESS} depends on the ESS operation E_r^{ESS}, as will be explained in Section 2.4). These variables are multiplied by the ESS converter lifetime (Ψ^{conv}) (considered as RES project lifetime, 25 years), nominal ESS capacities defined as design parameter (C_r^{nom}), economic terms related to ESS costs (c^{MW} and c^{MWh}), days per year ($d^y = 365$).

Moreover, technical objectives are included to avoid energy imbalances ($P_{r,k}^{imb+}, P_{r,k}^{imb-}$) even if it could be a more profitable operation. If RES+ESS portfolio will participate in FRR with the objective of reducing overall grid energy imbalances and maintaining the system frequency, it is counter-productive that the RES+ESS deliver their own imbalances sorely due to economic reasons. Moreover, if energy imbalances occur, FRR penalties are also produced. Therefore, a “forced strategy” [120] is modelled. Expected energy imbalances prices are included ($\lambda_k^{imb+}, \lambda_k^{imb-}$) and the multiplier M is necessary to minimize energy imbalances, although it guarantees feasibility in the optimization model in case the ESS is fully (dis)charged and/or unable to operate. Energy imbalances may occur with high RES intermittency or large forecast errors. In contrast, economic criterion ($M = 1$) is applied as in Appendix 1, producing high energy imbalances, high FRR penalties and non-compliance at the same time.

Consequently, forced strategy is implemented to guarantee a high reliability of FRR participation in RT operation. Therefore, risk factors ($\gamma_{r,k}^{+/-/b}$) are included in order to avoid participating in FRR when energy imbalances are expected, or otherwise, manage all solar and wind fluctuations with the ESSs when profitable FRR participation is expected. Several iterations of the optimization process are carried out, and these risk factors are increased or reduced according to the expected energy imbalances or desired FRR participation.

Finally, another technical term ($M \cdot E_{r,k_{end}}^{ESS}$) enables to reach the middle SOC at the end of each day ($E_{k_{end},r}^{ESS}$) to avoid undesirable final discharges. As consequence, market bidding schedule is maximized as long as the middle SOC at k_{end} is achieved.

These technical terms (avoiding energy imbalances and controlling final SOC value) must be highly weighted through the multiplier M in order to increase their relative value compared to economic terms regarding market scheduling: $P_{r,k}^{DM}, P_{r,k}^{CIM}, P_{r,k}^{band}$. In contrast, these technical terms included the objective function are not considered to be maximized or minimized according to a purely economic perspective. They are included in order to achieve a better technical performance of the RES+ESS operation, with the objective of reducing the amount of expected energy imbalances and controlling the SOC profile at the end of each day.

This market bidding optimization calculates the ESS power profile ($P_{r,k}^{ch}, P_{r,k}^{dch}$) and available ESS energy profile ($E_{r,k}^{ESS}$) in order to satisfy all constraints based on most recent forecast generation.

2.3.2 Equalities and inequalities

Concerning equality constraints, power balance equation between RES forecast, ESS power and energy market schedule is represented in eq. (2.5). The DM and CIM scheduling power ($P_{r,k}^{DM}, P_{r,k}^{CIM}$) plus the ESS power ($P_{r,k}^{ch}, P_{r,k}^{dch}$) must be equal to the RES generation forecast ($P_{r,k}^{pred}$), in case of no energy imbalances ($P_{r,k}^{imb+}, P_{r,k}^{imb-}$).

$P_{r,k}^{pred}$ corresponds to the RES generation forecast and $\Delta P_{r,k}^{pred}$ corresponds to the accumulated energy deviation produced by the FRR needs in RT operation and it is distributed in two next hours, to counteract this deviation. In the DM optimization, $P_{r,k}^{pred}$ corresponds to DM forecasts, because DM auction is cleared at midday the previous day, and DM generation forecast information should be considered at that time. During the day for CIM optimization, most recent forecasts are considered from the forecast provider information. RES generation forecasts and instantaneous profiles can be loaded from any source.

Another constraint to implement is the energy flow of the ESS represented in eq. (2.6), including efficiencies (η^{ch}, η^{dch}). These equations define ESS energetic model. ESS energy profiles ($E_{r,k}^{ESS}$) are the result of the ESS power output ($P_{r,k}^{ch}, P_{r,k}^{dch}$) eq. (2.5), without including FRR energy.

The AGC signal is unknown before the auction and for future operation steps, but it does not surpass the capacity assigned in FRR auction market the day before. The AGC value will be applied in RT operation and it will be managed by the ESS capacity and CIM re-scheduling. This AGC value will deviate the optimal ESS charge and discharge profile, but this energy will be corrected during successive CIM re-schedules. However, as this AGC is unknown, it cannot be included in equalities.

Therefore, FRR bands ($P_{r,k}^{uw}, P_{r,k}^{dw}$) are included as the worst-case power in inequality constraints to limit the ESS power and energy resulting from the RT operation. Hence, market and operation solution feasibility is ensured for all possible realizations of AGC signal needs under the most recent renewable forecast.

The ESS power limitation is defined in inequalities (2.7)-(2.8) according to the maximum converter power required for each ESS (P_r^{conv}).

$$P_{r,k}^{ch} - P_{r,k}^{dch} + P_{r,k}^{DM} + P_{r,k}^{CIM} + P_{r,k}^{imb+} - P_{r,k}^{imb-} = P_{r,k}^{pred} + \Delta P_{r,k}^{pred} \tag{2.5}$$

$$E_{r,k}^{ESS} - E_{r,k-1}^{ESS} - \Delta t \cdot \left(P_{r,k}^{ch} \cdot \eta^{ch} - P_{r,k}^{dch} / \eta^{dch}\right) = 0 \tag{2.6}$$

$$-P_{r,k}^{ch} + P_{r,k}^{dch} + P_{r,k}^{uw} - P_r^{conv} \leq 0 \tag{2.7}$$

$$P_{r,k}^{ch} - P_{r,k}^{dch} + P_{r,k}^{dw} - P_r^{conv} \leq 0 \tag{2.8}$$

ESS energy profile ($E^{ESS}_{k,r}$) is constrained between safe operating limits ($\underline{SOC}^{opt}$=10%, $\overline{SOC}^{opt}$=90%, for example) following inequalities (2.9),(2.10) which represent the optimal ESS operation in order to maximize FRR bands revenues. The ratio between upward and downward FRR bands (r^{uw}_k, r^{dw}_k) is defined by eq. (2.11)-(2.12), according to the Spanish TSO needs [192] to handle energy deviations in both directions. The ratio (r^{uw}_k, r^{dw}_k) is extracted from hourly needs from eq. (2.1).

$$-E^{ESS}_{r,k} + \underline{SOC}^{opt} \cdot C^{ESS}_{r,k} + P^{uw}_{r,k} \cdot \Delta t \le 0 \tag{2.9}$$

$$E^{ESS}_{r,k} - \overline{SOC}^{opt} \cdot C^{ESS}_{r,k} + P^{dw}_{r,k} \cdot \Delta t \le 0 \tag{2.10}$$

$$r^{uw}_k \cdot P^{band}_{r,k} - P^{uw}_{r,k} = 0 \tag{2.11}$$

$$r^{dw}_k \cdot P^{band}_{r,k} - P^{dw}_{r,k} = 0 \tag{2.12}$$

Ineq. (2.13) avoids ESS charging from the grid when there is not RES production. During the night, ESS is only able to be discharged (negative power). Thus, ESS will be charged only from RES.

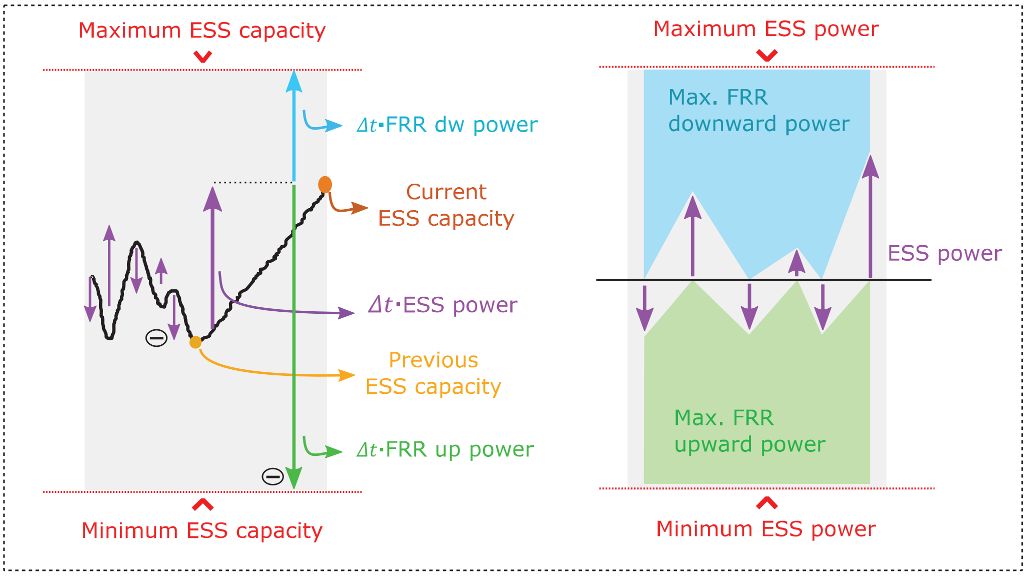


Figure 2.10 – Graphical representation of equations (2.6) - (2.10).

Moreover, to avoid undesirable deep discharging and in order to start next day with enough ESS energy to fulfill AGC signal during the night, SOC at the end of the day (k_{end}) is limited up to middle SOC ($\overline{SOC}^{end}$=50%) thanks to ineq. (2.14). The multiplier M in the objective function is included to reach this aim. The objective function tends to be maximized because a high final energy E^{ESS}_{kend} near to $\overline{SOC}^{end}$, multiplied by M, increase substantially the objective function.

Additionally, ineq. (2.14) and (2.15) control the SOC at the end of the day around the optimal values defined as $\underline{SOC}^{end}$=20% and $\overline{SOC}^{end}$=50%. The objective is to avoid undesirable discharging and in order to start next day with enough ESS energy to be able to fulfill FRR market requirements during the night until the sunrise.

$$P^{ch}_{r,k} - P^{dch}_{r,k} \leq P^{pred}_{r,k} + \Delta P^{pred}_{r,k} \tag{2.13}$$

$$-E^{ESS}_{kend} + \underline{SOC}^{end} \cdot C^{ESS}_{kend} \leq 0 \tag{2.14}$$

$$E^{ESS}_{kend} - \overline{SOC}^{end} \cdot C^{ESS}_{kend} \leq 0 \tag{2.15}$$

Regarding market participation, the optimal market offers for DM, CIM and FRR must be constant during each hour (due to hourly trading products in Spain), in the same way as (2.16) particularized for $P^{DM}_{r,k}$.

$$\begin{cases} P^{DM}_{r,k} - P^{DM}_{r,k+\Delta k} = 0 \\ P^{DM}_{r,k+\Delta k} - P^{DM}_{r,k+2\cdot\Delta k} = 0 \\ \quad\vdots \\ \quad\vdots \\ P^{DM}_{r,k+\frac{1}{\Delta t}-\Delta k} - P^{DM}_{r,k+\frac{1}{\Delta t}} = 0 \end{cases} \qquad \forall k : \frac{k-1+\Delta t}{\Delta t} \mid k \in \mathbb{N} \tag{2.16}$$

Regarding the ESS degradation, eq. (2.17) defines the maximum expected daily degradation of the ESS. Moreover, eq. (2.18) and (2.19) approximate

ESS degradation limits through linear calendar and cycling coefficients (z^{cy}, z^{cal}), as in [117].

$$SOH_r^{min} \cdot C_r^{nom}/(\Psi^{ESS} \cdot d^y) - C_{r,k}^{ESS} \leq 0 \tag{2.17}$$

$$-[SOH_r^{ini} \cdot C_r^{nom}]_{k=k_{ini}} + z^{cal} \cdot C_r^{nom} + C_{r,k}^{ESS} - C_{r,k-1}^{ESS} \leq 0 \tag{2.18}$$

$$\begin{gathered} -[SOH_r^{ini} \cdot (1 - z^{cy} \cdot SOC_r^{ini}) \cdot C_r^{nom}]_{k=k_{ini}} + z^{cal} \cdot C_r^{nom} \\ -z^{cy} \cdot (E_{r,k}^{ESS} - E_{r,k-1}^{ESS}) + C_{r,k}^{ESS} - C_{r,k-1}^{ESS} \leq 0 \end{gathered} \tag{2.19}$$

As ESS charge and discharge power variables are defined to include the efficiency in the above model, a binary variable per RES plant ($u_{r,k}$) allows to charge or discharge the ESS, but not simultaneously, according to eq. (2.20) and (2.21). As consequence, the introduction of binary variables results in a MILP optimization.

$$P_{r,k}^{dch} - \overline{P_r^{conv}} \cdot u_{r,k} \leq 0 \quad ; \quad u_{r,k} = \{0(ch), 1(dch)\} \tag{2.20}$$

$$P_{r,k}^{ch} + \overline{P_r^{conv}} \cdot u_{r,k} \leq \overline{P_r^{conv}} \quad ; \quad u_{r,k} = \{0(ch), 1(dch)\} \tag{2.21}$$

The minimum band availability (P_r^{bmin}) in Spain is 10 MW [192], but 1 MW is defined due to expected future market design [40], as reported in Section 2.2.2. Meanwhile the Spanish band size is being reduced, another consideration can be assumed that the RES+ESS plant participates with other plants inside a portfolio which bid more than 10 MW. Therefore, each plant is assumed to provide at least 1 MW (P_r^{bmin}).

On the other hand, the maximum hourly value is restricted to P_r^{bmax} related to the ESS capacity (for example, $20 - 25\% \cdot C_r^{ESS}$), in order to be capable of providing the entire band capacity in the following two hours before updating next CIM schedule. The remaining capacity, as well as eq. (2.22) and (2.23), is destined to manage RES forecast errors and not to excess safe SOC limits defined in the optimization to avoid penalties. In order to model the FRR participation, binary variable $v_{r,k}$ is included.

$$-P_{r,k}^{band} + v_{r,k} \cdot P_{r}^{bmin} \leq 0 \quad ; \quad v_{r,k} = \{0(no), 1(yes)\} \tag{2.22}$$

$$P_{r,k}^{band} - P_{r}^{bmax} \cdot v_{r,k} \leq 0 \ ; \ v_{r,k} = \{0(no), 1(yes)\} \tag{2.23}$$

Finally, another energy flow constraint should be also defined. Based on the ESS energy flow represented in eq. (2.6) at each time step, in addition to the ESS energy constrained by SOC operating limits from ineq. (2.9),(2.10), the presented energy flow equations have the objective to restricting the maximum energy deviation for a period of time, taking into account the SOC operating limits and the maximum energy deviation due to the AGC requirements. This maximum energy deviation due to the AGC requirements for a period of time is represented by the FRR bands.

Therefore, ineq. (2.24) and (2.25) limit the maximum energy variation from expected ESS operation ($E_{r,k}^{ESS}$) due to AGC signal between the time at which one CIM decision (latest CIM bid) is made and the time at which this CIM schedule is fixed in RT operation. From this point, the CIM bidding can be re-scheduled. Figure 2.11 shows the fixed CIM schedule period, between the gate closure time and CIM delivery starting time, or otherwise, when RES generation is available.

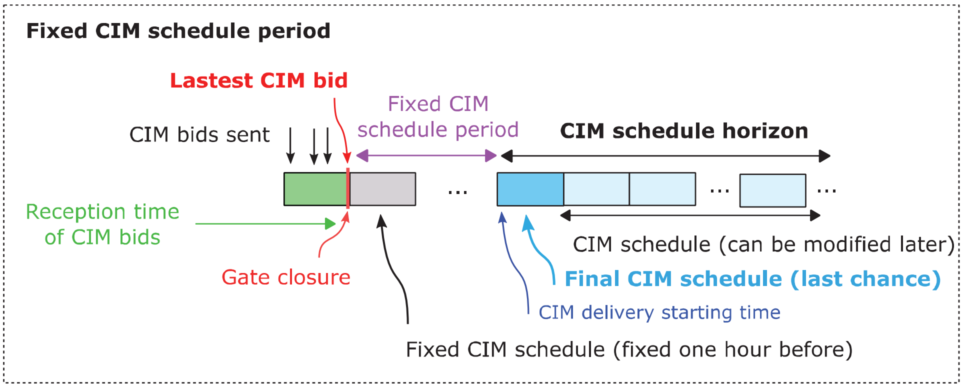


Figure 2.11 – Representation of fixed CIM schedule period.

As said before, FRR bands ($P_{r,k}^{up/dw}$) are included as the worse-case scenario in order to maintain the ESS energy profile inside its operating limits during each period of time. Therefore, these constraints aim to maximize FRR band as long as the ESS energy is between SOC limits.

Figure 2.12 represents these inequations to restrict maximum energy deviation more in detail. All values (i) belong to set K_r being a subset from K_H, defined as K_{WP} for the WP plant and K_{PV} for the PV plant defined in eq. (2.26) and (2.27). The initial and final step of the optimization day (k_{ini}, k_{end}) should be included, and the sunrise time (k_{sr}), and the sunset time (k_{ss}) for K_{PV} subset.

$$\begin{gathered} -E_{r,i}^{ESS} + \underline{SOC}^{FRR} \cdot \Sigma_{i'=\min\{i''\in K_r | i''>i\}} \left[C_{r,i'}^{ESS}\right] \\ -\Delta t \cdot \Sigma_{k|i\leq k\leq i',i'\in K_r} \left[\, P_{r,k}^{ch} \cdot \eta^{ch} - (P_{r,k}^{dch} + P_{r,k}^{uw})/\eta^{dch} \,\right] \leq 0 \\ \forall k \in K_H \,,\ \ \forall i \ \in K_r \subseteq K_H \,/\, \exists\, i' \in K_r, i' > i \end{gathered} \tag{2.24}$$

$$\begin{gathered} E_{r,i}^{ESS} - \overline{SOC}^{FRR} \cdot \Sigma_{i'=\min\{i''\in K_r | i''>i\}} \left[C_{r,i'}^{ESS}\right] \\ +\Delta t \cdot \Sigma_{k|i\leq k\leq i',i'\in K_r} \left[-P_{r,k}^{dch}/\eta^{dch} + (P_{r,k}^{ch} + P_{r,k}^{dw}) \cdot \eta^{ch}\right] \leq 0 \\ \forall k \in K_H \,,\ \ \forall i \ \in K_r \subseteq K_H \,/\, \exists\, i' \in K_r, i' > i \end{gathered} \tag{2.25}$$

$$K_{WP} = \{k_{ini}, k_{ini} + \Delta t^{-1}\,, k_{ini} + 2 \cdot \Delta t^{-1}\,, \dots, k_{end} + 1\} \subseteq K_H \tag{2.26}$$

$$K_{PV} = \{k_{ini}, k_{sr}, k_{sr} + \Delta t^{-1}\,, \dots, k_{ss} - \Delta t^{-1}, k_{end} + 1\} \subseteq K_H \tag{2.27}$$

where $k_{ini} = \min\{i \in K_r\},\ k_{end} = \max\{i \in K_r\}$

Based on this optimization, optimal bidding and operation variables can be obtained. Nevertheless, one of the inputs of the objective function is the ESS lifetime (Ψ_r^{ESS}) which is calculated based on the Rainflow cycling counting algorithm [193] by means of the depth of discharge data provided by the battery manufacturer and complemented with battery degradation tests carried out in the research group's laboratory. After the first optimization, one of the outputs of the optimization ($E_{r,k}^{ESS}$) has influence on another input (Ψ_r^{ESS}) described in Section 2.4. The ESS aging analysis is repeated iteratively for CIM+FRR bids optimization in order to achieve a trade-off between an intensive ESS operation and a reduction of ESS degradation costs due to an extended ESS lifetime. In that way, the optimal operation profile $E_{r,k}^{ESS}$ is obtained for the maximization of market revenues minus the ESS costs associated with their Ψ_r^{ESS}.

Once the DM auction is cleared, the $P_{r,k}^{DM}$ schedule is fixed. Afterward, FRR auction is held, knowing expected CIM and FRR prices, FRR market offers ($P_{r,k}^{band}, P_{r,k}^{uw}, P_{r,k}^{dw}$) are fixed in the optimization process. Next optimizations calculate and update CIM based on most recent forecast.

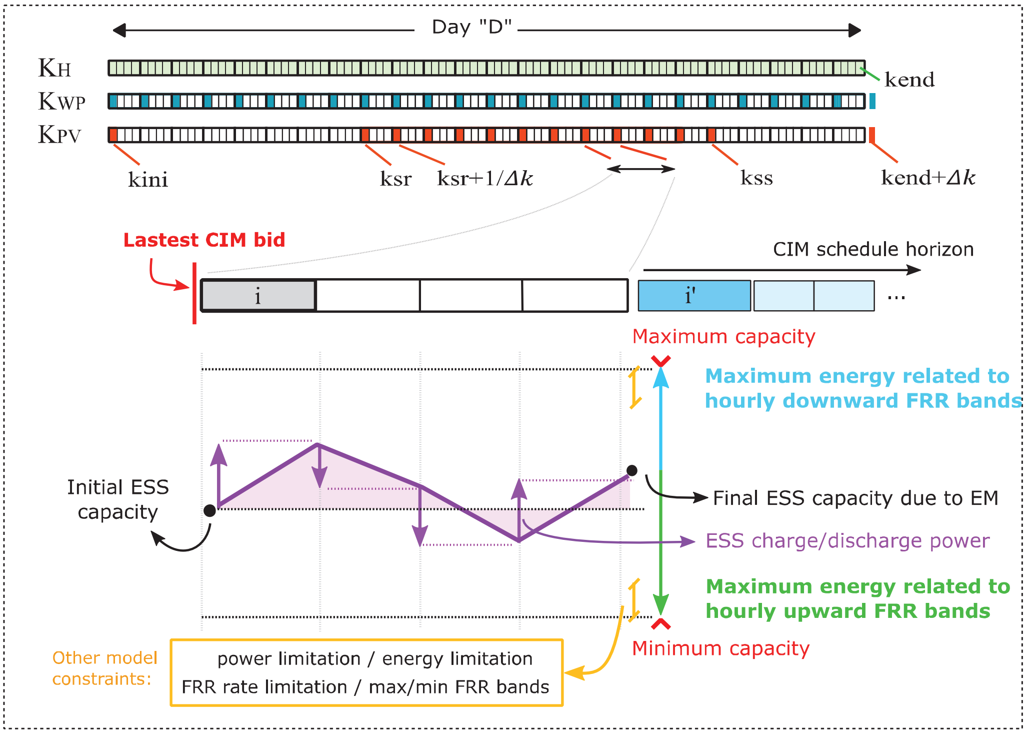


Figure 2.12 – Visual representation of maximum energy deviation.

2.3.3 AGC signal modelling

After FRR auction, this FRR schedule is fixed, and consequently, AGC signal should be followed next day according to the FRR bands. AGC signal is sent by the TSO to the involved generators at RT operation, but these data are partially or not publicly available. In order to model realistic AGC signal to be introduced and applied in the EMS, this additional block is included to model the AGC signal in a more realistic way possible. Otherwise, the AGC signal can be an external signal when the EMS is implemented in a real application, without the need of this AGC signal modelling block, where real AGC signal would be given and updated each 4 sec by the TSO at RT operation.

Under this assumption, historic hourly data from Spanish TSO [189] are used to simulate and validate the EMS in a more realistic scenario according to the FRR bands from the upper level control. This AGC signal modelling procedure enables to generate more realistic FRR needs which are applied later in RT operation.

In FRR, all generators inside a RZ receive a proportional AGC power signal each 4 seconds, according to their assigned *PC*, as in eq. (2.3). However, this AGC power signal at each 4s is not publicly available, while hourly Upward and Downward Secondary Reserve Use data are published by the Spanish TSO [189]. These hourly energy values do not give information of the AGC power signal behavior or fluctuations inside the hour. Furthermore, considering a net energy value (the sum of both values) for each hour does not represent the real operation of the battery under this ancillary service. Most of the literature considered a simulation time step of 1 hour, without intra-hour changes [135], [137], [138], [145], [146], [148], [194]–[196], while other authors considered a smaller time step (10 or 15 min) for the operation [134], [197].

However, AGC signal is actually a power signal sent by the RCP each 4 seconds. With the objective of establishing a suitable time step, the behavior of the FRR power signal should be analyzed. While the FCR deals with quick frequency fluctuations from the nominal value and their power output should be proportional to the instantaneous frequency deviation [39], [198][199], the power signal in FRR is not so oscillating and fluctuating than FCR, as can be observed in several signals found in the literature [130], [131], [139], [144], [200]–[206]. Some examples are displayed in Figure 2.13.

In order to be accurate to the real operation, as well as considering an acceptable computational time to optimize while reflecting the intra-hour AGC signal behavior, a real-time period (Δt) of 15 minutes is proposed in this model. The consideration of shorter time steps (less than one hour) leads to more realistic power profiles. This consideration allows a more accurate techno-economic analysis of battery operation, energy imbalances and reserve penalties due to AGC non-compliances. Also, the RES generation profiles should have the same resolution as other variables.

Therefore, if the proposed real-time period is minor than the resolution of the available ACE power signal (given by the TSO in hourly-basis public data, ACE_h), it is necessary to model the intra-hour behavior of the AGC power signal and create an AGC power signal ($AGC_{r,k}$) with the same time step than the defined for the optimization. For that, the features of several real AGC signals exposed in Figure 2.13 are tried to imitate.

Consequently, $AGC_{RZ,h}$ and $AGC_{r,h}$ are hourly energy signals (MWh) which are directly related to the hourly public data ACE_h by the $PC_{RZ,h}$, according to eq. (2.28). $AGC_{r,h}$ can be evaluated as the sum of the hourly positive and negative values ($AGC_{r,h}^{+}$ and $AGC_{r,h}^{-}$), as in eq. (2.29). These two values are also available in TSO website, and they are necessary to model the positive and negative intra-hour needs. $AGC_{r,k}$ power values per hour are calculated according to the Δt, based on hourly energy values, $AGC_{r,h}^{+}$ and $AGC_{r,h}^{-}$. These power signals do not surpass the capacity bands ($P_{r,h}^{up}$, $P_{r,h}^{dw}$), as in eq. (2.30).

$$AGC_{RZ,h} = \Sigma_r \ AGC_{r,h} = PC_{RZ,h} \cdot ACE_h \qquad \forall h \in [1,24] \tag{2.28}$$

$$AGC_{r,h} = AGC^+_{r,h} - AGC^-_{r,h} = \Sigma_{k|\frac{(h-1)}{\Delta k}+1 \le k \le \frac{h}{\Delta k},} \left[AGC_{r,k} \cdot \Delta t\right] \tag{2.29}$$

$$AGC^+_{r,h} \le P^{dw}_{r,h} \quad ; \quad AGC^-_{r,h} \le P^{up}_{r,h} \tag{2.30}$$

where subscript h corresponds to the time of the day (in hours, h) and subscript k corresponds to the sample time for the simulation of the EMS.

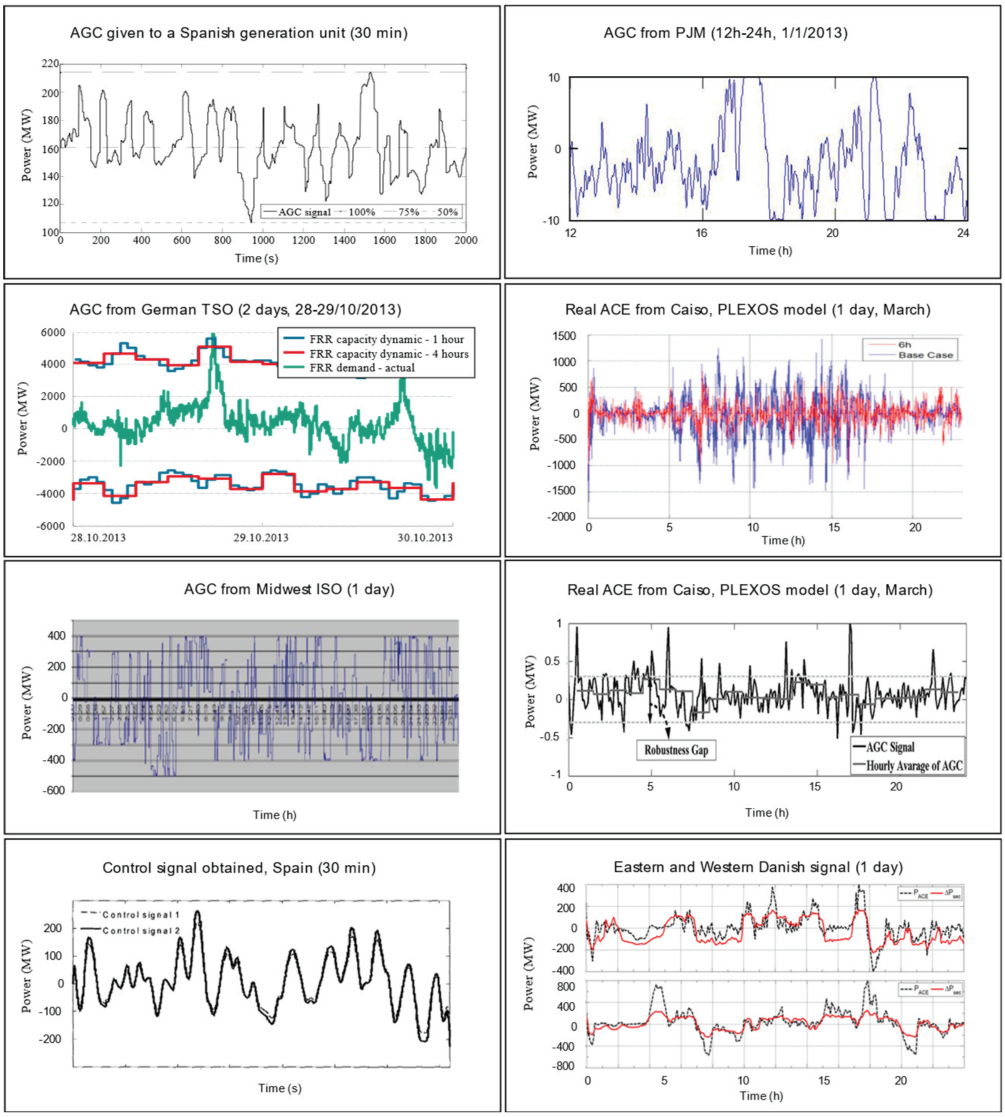


Figure 2.13 – Different AGC signals found in the literature.

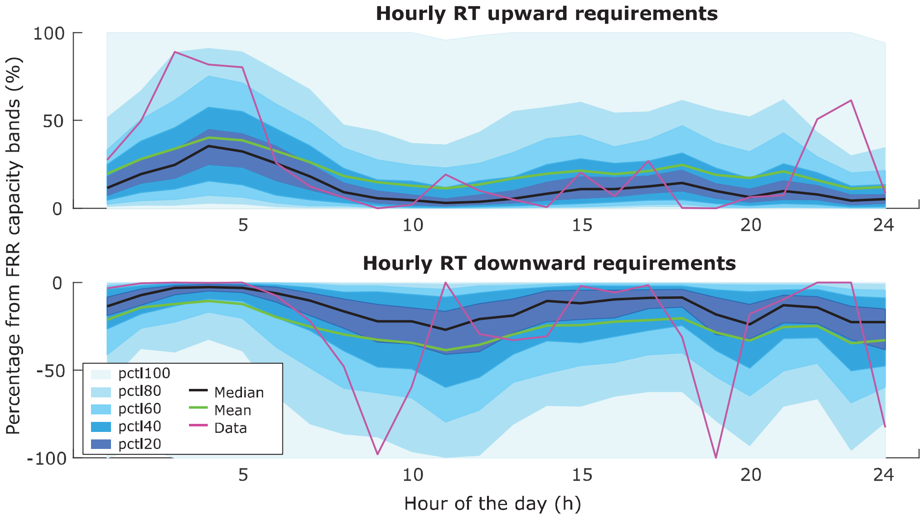


Figure 2.14 – Annual percentiles of hourly upward and downward AGC signal, mean value, median value, and real-time requirements of a given day.

Figure 2.14 shows annual percentiles of hourly upward and downward AGC signal from 2017. Additionally, the mean values and median values are included, as well as the hourly AGC energy values ($AGC_{r,h}^{+}$ and $AGC_{r,h}^{-}$) for a given day (4th January 2019). This figure demonstrates the high degree of uncertainty that FRR market has. These historic percentiles are expressed in percentage between the real-time hourly AGC energy values ($AGC_{r,h}^{+}$ and $AGC_{r,h}^{-}$) and the assigned capacity bands ($P_{r,h}^{dw}$ and $P_{r,h}^{up}$).

According to Spanish market prices [189], they can be estimated linearly based on the DM prices or can be estimated using another method (e.g. machine learning techniques or “smoothing splines” method).

In order to compare the accuracy of both results. Firstly, the linear relation between DM prices and other market prices for 2017 is as follow:

$$\lambda_k^{band} = x^{band} \cdot (\lambda_k^{DMmax} - \lambda_k^{DM}) \rightarrow \lambda_k^{DMmax} = 80, x^{band} = 0.394 \tag{2.31}$$

$$\lambda_k^{uw} = x^{uw} \cdot \lambda_k^{DM} \quad \rightarrow \quad x^{uw} = 1.069 \tag{2.32}$$

$$\lambda_k^{dw} = x^{dw} \cdot \lambda_k^{DM} \quad \rightarrow \quad x^{dw} = 0.816 \tag{2.33}$$

Secondly, cubic smoothing spline method is implemented in this EMS being a useful method for noisy data defined in *Matlab Curve Fitting Toolbox*. Another prediction method could be used in further research. Reserve prices have dependence for DM prices but high variance, and consequently, using linear or polynomial curves to estimate them will have low accuracy, as can be observed in Figure 2.15a, for Spanish 2017 data.

Cubic smoothing splines can address possible non-linearities and high fluctuations. Thus, an interpolating function is defined with smoothness properties, which presents better accuracy. Figure 2.15b shows the expected prices for these two approaches for a given day. Spline method has more accuracy than linear approximation. After the optimization process, hourly FRR market bids are optimized for each RES plant. During the operation, the real-time AGC power signal is required for each plant and it is unknown at the time of the auction.

Figure 2.16 displays two FRR schedule bidding for wind and solar respectively for a given day. Hourly energy use data ($AGC^{+}_{r,h}$ and $AGC^{-}_{r,h}$) are uncertain data at the time of the FRR schedule bidding, only hourly assigned capacity ($P^{up}_{r,h}$, $P^{dw}_{r,h}$) are calculated in the optimization process.

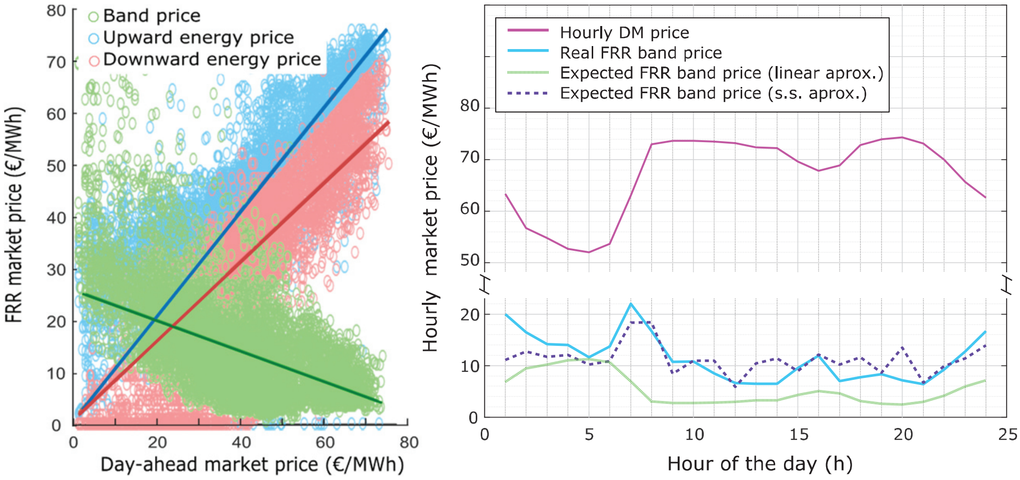


Figure 2.15 – a) Real FRR prices VS DM price, b) Expected band prices.

Thus, $AGC^{+}_{r,h}$ and $AGC^{-}_{r,h}$ values are neither used as known information to calculate FRR schedule bidding nor influence the optimization process. They are only used to model the intra-hour AGC power signal.

In order to model the $AGC_{r,k}$ power signal applied in RT operation, eq. (2.29) is applied from historical energy data ($AGC^{+}_{r,h}$ and $AGC^{-}_{r,h}$). That is, $AGC_{r,k}$ power signal is calculated based on hourly $AGC^{+}_{r,h}$ and $AGC^{-}_{r,h}$, according to the hourly assigned capacity $P^{up}_{r,h}$, $P^{dw}_{r,h}$. $AGC_{r,k}$ power signal is needed for the validation of the EMS in RT operation. $AGC_{r,k}$ for a given day is shown in Figure 2.17, based on energy values of Figure 2.16.

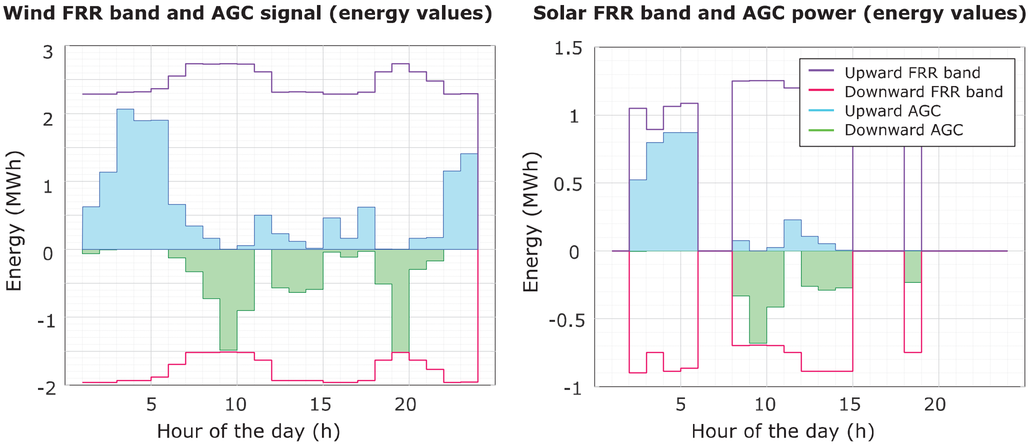


Figure 2.16 – Wind/solar capacity bids and hourly AGC energy of a given day.

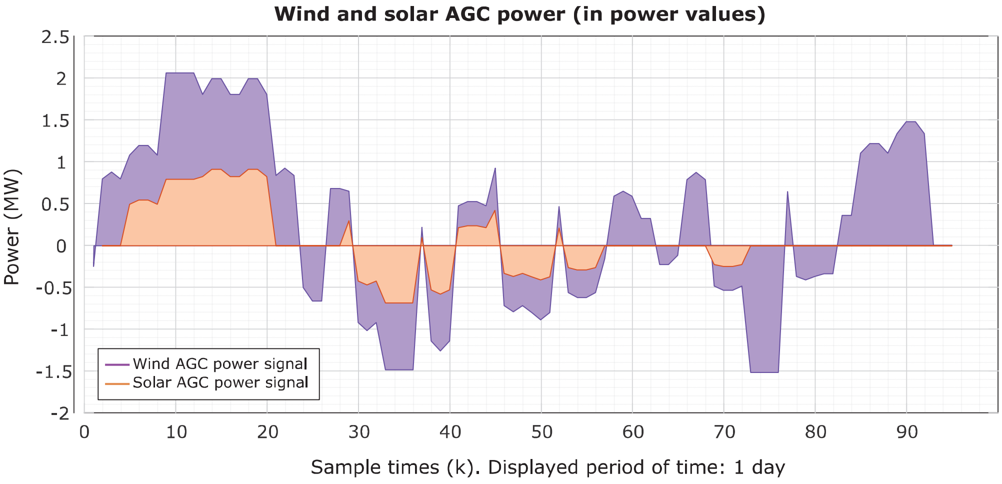


Figure 2.17 – Daily AGC power signal applied in RT operation of a given day.

2.4 ESS aging analysis

To enhance ESS reliability and security, a Battery Management System (BMS) is often required. Its function is to offer accurate State of Charge (SOC) and State of Health (SOH) estimation [207],[208]. Both parameters are essential in the ESS state determination, which indicate the available energy and the available capability at a given time.

The SOC is relative to the stored charge that is available. Section 2.4.1 summarizes the methods proposed in the literature to estimate the SOC and later, the applied SOC estimation method is explained.

The SOH reflects the current capability of a battery to store and supply energy/power relative to that at the beginning of its life, calculated as the ratio of the actual cell capacity/resistance and its initial value [209],[210].

Figure 2.18 represents the procedure for a proper ESS aging prediction analysis, in which the ESS lifetime is estimated, according to calendar and cycling aging models, which will be explained below in Section 2.4.2. Consequently, an accurate estimation of SOC and SOH is necessary.

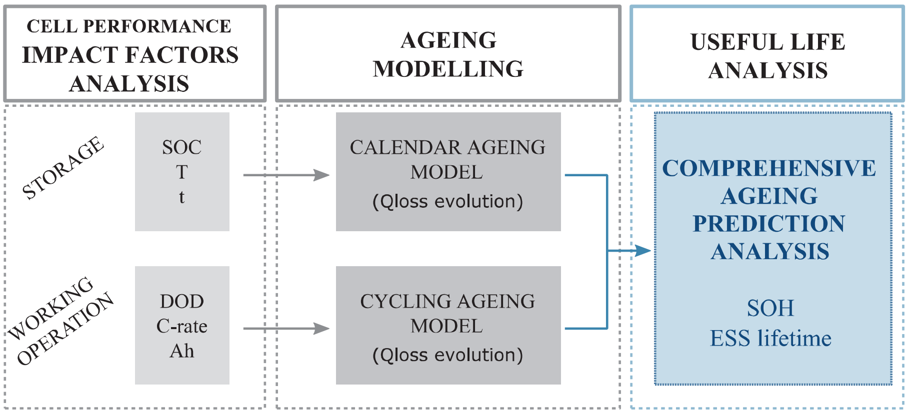


Figure 2.18 – ESS aging prediction analysis procedure. Adapted from: [210].

2.4.1 ESS state of charge estimation

As the battery SOC is an important parameter, which represents the amount of available capacity in the ESS at a given time. It reflects the ESS performance, so accurate estimation of SOC cannot only protect ESS, prevent overcharge or discharge, and improve the ESS lifetime, but also SOC is useful for control strategies and optimization process described in Section 2.3. However, batteries are electro-chemical energy storage systems, and this chemical energy cannot be directly measured [211].

Several methods to estimate SOC are presented in the literature [211] summarized in Table 2.2. SOC estimation methods can be classified in: direct measure methods (such as Open Circuit Voltage, OCV method), book-keeping estimation methods (such as Coulomb counting method), adaptative methods (such as Kalman filters or neural networks) and hybrid methods which combine two or more previous methods.

In this PhD thesis, there is not possible to use direct measure methods due to the lack of physical battery modelling (voltage, impedance or current in real or experimental operation). Therefore, a modified Coulomb counting method is applied according to the next procedure.

The Coulomb counting method measures the discharging current of a battery and integrates the discharging current over time in order to estimate SOC [20]. The current SOC value ($SOC_{r,k}$) is estimated from the

Table 2.2 – Classification of SOC estimating methods.

Categories	Mathematical methods
Direct measure	OCV method / Terminal voltage method Impedance method / Impedance spectroscopy method
Book-keeping estimation	Coulomb counting method Modified Coulomb counting method
Adaptative systems	Kalman filter / Support vector machine Neural network / Fuzzy neural networks

previously estimated SOC value ($SOC_{r,k-1}$) and the discharging current ($I_{r,k}, A$) divided by the current ESS capacity (Q_t^{ESS}, Ah), following eq. (2.34). The general SOC equation is particularized for the given application for the ESS associated of a RES plant (r) and the sample (k).

$$SOC_{r,k} = SOC_{r,k-\Delta k} + \frac{\Delta t \cdot I_{r,k}}{Q_{r,k}^{ESS}} \tag{2.34}$$

The ESS is modelled in energy and power-related terms along the optimization process (energy flow model, defined in eq. (2.6)), instead of through current and voltage variables. Consequently, eq. (2.34) can be also expressed in energetic terms [Wh] instead of [Ah], as in eq. (2.35), assuming that the ESS operates at nominal (or average) voltage. The power output ($P_{r,k}^{ESSin}$, in W) includes the ESS efficiency and the current ESS capacity ($C_{r,k}^{ESS}$, in Wh) includes the SOH of the battery.

$$SOC_{r,k}^{ESS} = SOC_{r,k-\Delta k}^{ESS} + \frac{\Delta t \cdot P_{r,k}^{ESSin}}{C_{r,k}^{ESS}} \cdot 100 \tag{2.35}$$

The closed circuit voltage (CCV) and Open Circuit Voltage (OCV) can be observed in Figure 2.19 for an NMC Li-ion battery [212],[213]. As can be seen, the Li-ion battery does not have a linear relationship [211], but it can be assumed almost constant inside the safe operating SOC range.

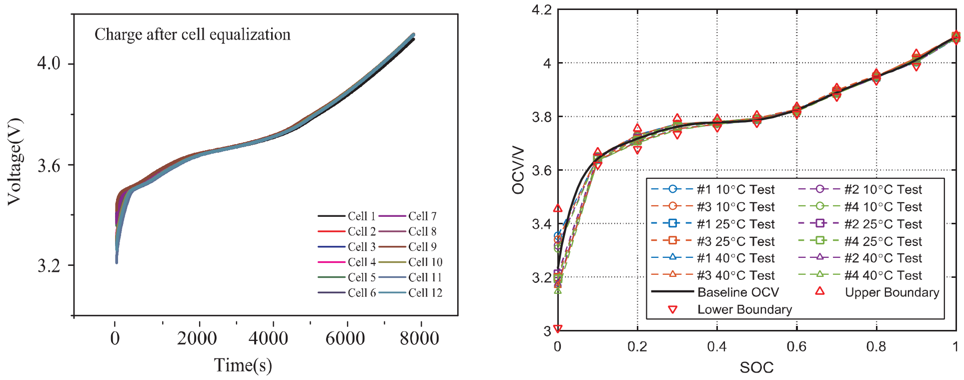


Figure 2.19 – a) CCV-charging time for an NMC cell. Source: [212] b) OCV-SOC test results for an NMC cell. Source: [213].

2.4.2 ESS aging modelling and ESS lifetime prediction

The ESS lifetime is typically shorter than the lifespan of power electronic systems or renewable generators, and usually shorter than the investment period of a certain application. Besides, ESS operating, maintenance and replacement costs still suppose a significant percentage of the initial investment, because depending on the ESS sizing and the operational performance, ESS replacements will be required.

Thereby, the ESS lifetime prediction is one of the limiting factors when evaluating their economic feasibility, directly influenced by the ESS initial sizing and operation. Therefore, the lack of considering their lifespan estimation in a long-term economic analysis will result in inaccurate or sub-estimation of all above costs.

On the one hand, with the aim of reducing the ESS investment costs, ESS could be undersized. Due to a high demanding operation and huge depth-of-discharge cycles, it could lead to early-degradations on the ESS and an increase on the operating costs and number of replacements that finally have to be assumed by the facility owner.

On the other hand, a larger ESS sizing allows a more reliable and profitable real-time operation, increasing the potential services provided by the ESS. An oversized ESS will allow RES plant to increase energy arbitrage, reduce energy imbalances, or provide more ancillary services. The operating conditions with larger ESS capacity are less aggressive, resulting in a longer ESS lifetime. However, its high acquisition and replacement costs could not be compensated by additional market profits.

Thus, the ESS degradation associated to their operation (cycling aging) and their storage (calendar aging) should be estimated to achieve a trade-off between the economic benefits from a profitable and reliable market participation and operation, and the overall ESS costs, associated to their investment, operation, degradation and replacement issues.

Despite its economic relevance, most publications in the literature rarely emphasize on aging modeling together with the ESS sizing. The authors in [179] suggest to consider safe operating limits for ESS to prevent fast degradation or damage, or in [176] a limitation of the variations of the battery power exchange is developed, to reduce the number of cycles. There are few studies that estimate the ESS degradation costs expressed as a function of battery cycles and Depth-Of-Discharge (DOD) as in [184]–[188], without calendar issues. Finally, the research in [144] estimates the ESS usage costs with semi-empirical calendar and cycling models.

It can be pointed out that any ESS aging model for SOH estimation and ESS lifetime prediction can be included in the developed EMS. However, more accurate techno-economic results are obtained when experimental and/or customized ESS cycling and calendar models are applied to estimate more precisely ESS lifetime and their ESS costs.

Selection of ESS lifetime prediction method

According to the ESS lifetime prediction methods, they can be divided in several categories [214][215], summarized in Table 2.3: physical/chemical-based models, mathematical-based models, and fatigue-based models.

Table 2.3 – Classification of ESS lifetime prediction methods.

Categories	**Methods**
Physical/chemical-based models	Electro-chemical models Equivalent circuit model Empirical models Semi-empirical models
Mathematical-based models	Artificial Neural network (ANN) Autoregressive Integrated Moving Average (ARIMA) Fuzzy logic method Support Vector Regression (SVR)
Fatigue-based models	Wöhler method Weighted Ah-model

A short description of each model is given below:

Starting with the physical/chemical-based models, a detailed ***chemical and physical model*** of the aging processes of the electrochemical ESS system can be used. It must provide detailed information on local conditions such as temperature, current, SOC, electrolyte concentration, etc. which are the result of the operating conditions.

It is also possible to model the behavior of a cell, in response to a specific operation through its ***Equivalent Circuit Model*** (ECM). ECM consists in an equivalent electrical circuit composed by various electrical components (resistors, capacitors, etc.) [214]. Each component of the EMS can be also linked to internal or external parameters, such as temperature, current, or state of charge in order to assess ESS aging degradation.

Empirical models rely on experimental aging tests. Empirical models are an easy technique in which aging tests are used to extrapolate results. It can be used as a first approach for approximate lifetime estimation. These empirical models can be expressed as polynomial, exponential or logarithmic equations [216], depending on the ESS cell or modelling.

Semi-empirical models combine theoretical ESS aging mechanism (for example from physicochemical models) with experimental observations (analytical models with mathematical empirical data fitting) [210],[217]. Developing these kind of aging models generally consists on capturing the relations between battery's Health Indicators, e.g. capacity or internal resistance, the operating time, temperature, SOC, Ah-throughput, C-rate, DOD and the average SOC (high, middle, or low). Overall, in order to develop accurate models, extensive laboratory tests must be carried out.

Mathematical models use numerical resolution methods to assess the ESS aging or lifetime prediction. The numerical methods that can be applied are: artificial neural network models, fuzzy neural network, fuzzy logic model, or autoregressive Integrated Moving Average, among others.

Fatigue-based models is a heuristic approach, because the model does not really represent ESS aging effects on a physical or chemical basis. Firstly, ***Wöhler method*** estimates the incremental loss of ESS lifetime caused by several events [214]. The impact of these "events" on lifetime can either be determined experimentally (empirical models) or mathematically [215]. This approach is frequently used for planning purposes and for designing and estimating the lifetime of components prediction in many areas of engineering. Wöhler method has also been extensively applied to battery life assessment [184]–[188]. This algorithm is used extensively in materials fatigue stress analysis to count cycles and quantify their depths.

Finally, ***weighted-Ah model*** assumes that the impact of a given Ah-throughput on the lifetime depends on the operating conditions. It is also a fatigue model since it is based on a damage addition hypothesis. Here, lifetime is reduced, in function of the charge (Ah) throughput during use and not in function of number of cycles. ESS cycle lifetime is simply determined by discharging the battery with a constant current to a certain depth of discharge and a subsequent full charge with a given charging regime [215]. Regarding the existing methods, for some general applications, ESS lifetime data can be found on the ESS manufacturers' datasheets usually by weighted-Ah models. However, these commercial datasheets are mainly uncompleted or avoid results in some specific performance conditions. Thus, they could not be enough to model and assess suitably the ESS degradation for this specific application.

Due to the lack of physical ESS parameters or experimental testing, chemical and physical model and purely empirical models are not be considered in the proposed EMS.

As exposed above, Wöhler method has also been extensively applied to ESS life assessment in the literature. However, each Wöhler curve is only suitable for a particular cell technology tested by specific performance and operating conditions for a given application or ESS operation.

Consequently, the use of experimental Wöhler curve-based aging models from a laboratory testing are more accurate and personalized for the considered application. In contrast, these laboratory testing are time-consuming and costly when more operating parameters want to be addressed and evaluated by means of several Wöhler curves.

That is, the extraction of all needed relevant aging data for Li-ion aging model development becomes more time and cost-demanding. A solution to minimize the required testing efforts in order to develop an accurate aging model is the development of self-adaptive aging models [216]. In future researches, self-adaptive aging models can be included when the EMS is implemented and validated under real experimental testing.

However, in the EMS developed in this PhD thesis, additional laboratory testing could not be performed for the given application. Therefore, previous suitable testing has been used for Wöhler-curve method. Consequently, a Wöhler method with experimental data is proposed using a Kokam's NMC-based Li-ion cell under 1C-rate charging condition.

Regarding calendar lifetime, an approximated semi-empirical model reported in [218] is applied under known temperature and SOC conditions, for the same NMC-based Lithium ion cell.

Cycling aging model

In relation to cycling degradation, cycling aging models aims to estimate the ESS degradation due to the operating cycles.

In order to implement a Wöhler-curve method, the Rainflow cycle counting algorithm [185]–[187], [219] counts the number of charging and discharging cycles at certain DOD from a certain SOC profile. Figure 2.20 represents the procedure to match each charging cycle at a given DOD with a discharging cycle with the same DOD.

Depth of Discharge (DoD) represents the absolute difference between the starting and ending SOC for each charge or discharge applied to the battery, following the eq. (2.36), between two sample times (from a to b).

$$DOD = \left|SOC_b^{ESS} = SOC_a^{ESS}\right| \tag{2.36}$$

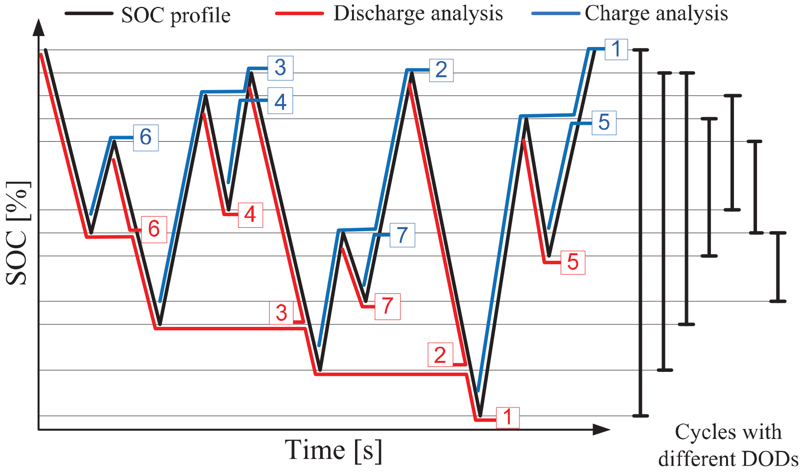


Figure 2.20 – Rainflow cycle counting algorithm. Source: [108],[110].

Once the charging and discharging cycles matching is obtained, each pair of cycles is usually matched to the ESS lifetime data. Under this cycle aging model, each “event” (that is, each of charge-discharge cycle) causes independent stress, and the loss of battery life is the accumulation of degradation from all cycles. That is, the Wöhler curve-based aging model evaluates the effect of each “event” upon the ESS degradation.

To be precise, the counted cycles are grouped in 1%-basis and the obtained cycles are matched to the experimental datasheet to calculate their associated degradation. Figure 2.21 depicts the Wöhler curve experimentally obtained for Kokam’s NMC cells considered in the framework of this dissertation. Wöhler curve [117] was obtained from experimental testing in the smart-storage laboratory of IKERLAN.

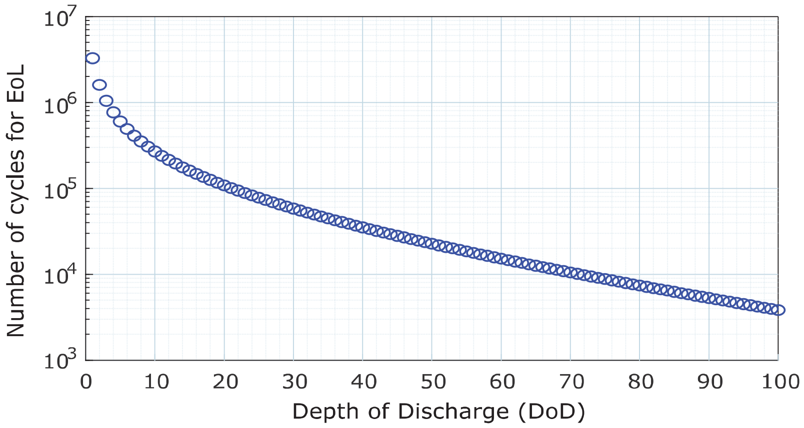


Figure 2.21 – Example of Wöhler curve for Kokam's NMC cells.

Calendar aging model

Besides cycling degradation, the ESS calendar degradation should be taken into consideration. The calendar aging is the capacity loss that occurs as a function of time passed, independent of its utilization. Advanced calendar model calculates the calendar aging based on the average SOC and battery temperature. Generally, the calendar lifespan is reduced with high average SOC and high operating temperatures [220].

The capacity fade model for storage period takes into account the storage time, cell temperature and the average SOC at which the cell is stored. The capacity loss due to calendar life can be modelled as mathematical equations, following eq. (2.37) reported in [210],[217] for LFP-based technology and (2.38) reported in [218] for NMC-based technology, from experimental testing made at IKERLAN's laboratories.

$$Q_{T,SOC,t}^{loss_{cal}} = \alpha_1 \cdot e^{\beta_1 \cdot T^{-1}} \cdot \alpha_2 \cdot e^{\beta_2 \cdot SOC^{avg}} \cdot t_{st}^{0.5} \tag{2.37}$$

$$Q_{T,SOC,t}^{loss_{cal}} = (e^{p_1 \cdot T^{-1}} \cdot e^{p_2 \cdot SOC^{avg}} \cdot e^{p_3} + p_4) \cdot t_{st}^{b} \tag{2.38}$$

where T (K) is the ambient temperature, SOC (%) is the average state of charge at which the cell is stored, t_{st} (days) is the time elapsed on storage, and $\alpha_1, \alpha_2, \beta_1, \beta_2,\ p_1, p_2, p_3, p_4$ are constant fitting coefficients.

In this PhD thesis calendar aging model described in [218] is applied. The ESS capacity loss increases at higher SOC and higher ambient *T*. In Figure 2.22 the calendar capacity loss (%) is shown at middle-SOC (or 50%, common in grid-connected application) and several ambient *T*.

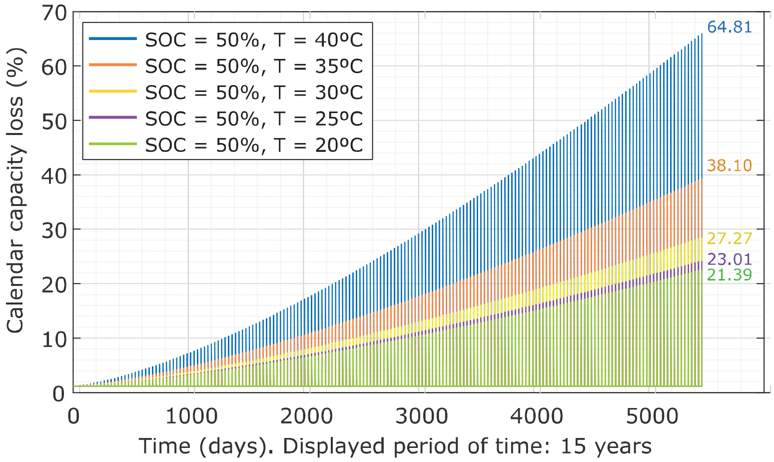


Figure 2.22 – Calendar capacity loss (%) for NMC cells at middle-SOC.

The point when the battery fails to meet the energy or power requirement for its application is commonly defined as the end of life (EOL). Typically, batteries are considered at EOL when their capacities drop below 80% of the initial values (and therefore needed to be replace, as it could lead to sudden cell performance failure), or when total capacity loss reaches 20%.

There is a lack of operating temperatures or online experimental testing for the given application in this EMS. Thus, ambient temperature conditions is assumed to be controlled [187] (normally for stationary applications) around 20ºC with an effective cooling system and at middle-SOC (parameter validated through the PhD results). At these operating conditions, the calendar life could reach 15 years, following the common criteria for defining the End-of-Life (EOL) at 20% of capacity loss.

Therefore, an approximation for calendar loss curve through linear regression is applied considering constant conditions (20ºC and middle-SOC), which limit the calendar life ($\Psi^{cal,ESS}$) up to 15 years.

2.4.3 ESS lifetime prediction analysis

This ESS lifetime prediction analysis is carried out during the RT operation and optimization process to update the actual State of Health ($SOH_{r,k}$), the current ESS capacity ($C_{r,k}^{ESS}$) and the expected ESS lifetime (Ψ^{ESS}), according to the given evaluation period (n_{eval}). According to the Ψ^{ESS}, the associated ESS costs are calculated for eq. (2.4).

In this ESS lifetime prediction analysis, the approach outlined for ESS aging analysis combines calendar and cycling aging effects. Eq. (2.39) calculates the cycling capacity fade ($\Delta SOH_{r,k}^{cy}$) for a period of time. This cycling model applies Wöhler method, in which the effect of each cycle ($n_d^{completed}$) or half cycles (n_d^{ch}, n_d^{dch}) leads to a ESS capacity fade. Eq. (2.40) calculates the capacity fade due to calendar effect ($\Delta SOH_{r,k}^{cal}$) (in MWh for a certain period of time) applying linear regression of eq. (2.38) according to T=20ºC and middle-SOC. This capacity fade corresponds to the evaluation period ($n_{eval} = d^{eval}/d^{y}$, being d^{eval}=1 for one-day or d^{eval}=d^{y} for one-year). Eq. (2.41) estimates the expected ESS lifetime from both aging effects. Finally, eq. (2.42) updates the current ESS ($C_{r,k}^{ESS}$) according to the total capacity fade until that time, composed by current cycling and calendar capacity fade and accumulated capacity fade from previous evaluation periods (ΔSOH_r^{acc}), calculated as in eq. (2.43).

$$\Delta SOH_{r,k}^{cy} = \sum_{d=1}^{100} \frac{(n_d^{completed} + n_d^{ch}/2 + n_d^{dch}/2)}{Wöhler\ curve\ aging_d} \cdot \left(1 - SOH^{min}\right) \cdot C_{r,k}^{ESS} \tag{2.39}$$

$$\Delta SOH_{r,k}^{cal} = \frac{\left(1 - SOH^{min}\right)}{n_{eval} \cdot \Psi^{cal,ESS}} \cdot\ C_r^{nom} \tag{2.40}$$

$$\Psi_{r,k}^{ESS} = \frac{(1 - SOH^{min})}{n_{eval} \cdot \left(\Delta SOH_{r,k}^{cy} + \Delta SOH_{r,k}^{cal}\right)} \cdot C_{r,k}^{ESS} \tag{2.41}$$

$$C_{r,k}^{ESS} = \left(1 - \frac{\Delta SOH_{r,k}^{cy}}{C_{r,k}^{ESS}} - \frac{\Delta SOH_{r,k}^{cal}}{C_r^{nom}} - \Delta SOH_r^{acc}\right) \cdot C_{\mathrm{r}}^{nom} = SOH_{r,k}\ \cdot C_{\mathrm{r}}^{nom} \tag{2.42}$$

$$\Delta SOH_r^{acc} = \frac{\Delta SOH_{r,k}^{cy}}{C_{r,k}^{ESS}} + \frac{\Delta SOH_{r,k}^{cal}}{C_r^{nom}} + \Delta SOH_r^{acc} \tag{2.43}$$

This ESS aging and lifetime prediction analysis is carried out at certain stages during the optimization process and RT operation:

- The ESS aging analysis is repeated iteratively when CIM+FRR bids are jointly optimized in order to achieve a trade-off between an intensive ESS operation and a reduction of ESS degradation costs due to an extended ESS lifetime. The iterative procedure is made to calculate the ESS lifetime from cycling and calendar models, applying from eq. (2.39) to (2.41). The process is repeated until convergence in which the value of lifetime (Ψ_{r}^{ESS}) has the same value of the previous iteration. The initial condition for ESS lifetime is 15 yr. Finally, Ψ_r^{ESS} is updated in the objective function.
- Moreover, this ESS aging analysis is also carried out during the RT operation to calculate and update Ψ_r^{ESS}, $SOH_{r,k}$, $C_{r,k}^{ESS}$ values:
    - During the operating day, the ESS capacity loss is linearly estimated from linear calendar and cycling coefficient to reduce the computational time for intra-day operation. This model is reported in [117], applying similar equations as eq. (2.18)-(2.19).
    - At the end of each day, a complete ESS aging analysis is carried out applying eq. (2.39)-(2.43). The ESS capacity fades ($\Delta SOH_{r,k}^{cy}$, $\Delta SOH_{r,k}^{cal}$) and Ψ_r^{ESS} are predicted. Finally, the current ESS capacity ($C_{r,k}^{ESS}$) and current $SOH_{r,k}$ are updated in the EMS, taking into account previous or accumulated capacity losses. The resultant ESS capacity influences the optimization results and the RT operation, because it has been reduced.
    - At the end of a longer evaluation period (for example, one-year evaluation period), a complete ESS degradation analysis is carried out from eq. (2.39) to (2.42), with the entire annual ESS operation profile (the results of the annual ESS aging analysis will be exposed in the techno-economic analysis of Chapter 3 and 4).

2.5 Lower level control: real-time operation

After the market scheduling process, the lower level control is applied, in which real-time operation is carried out applying the optimal values calculated in the upper control. The aim of the RT operation is to fulfil grid power set-points composed by the most recent DM+CIM schedule and current AGC signal according to the instantaneous RES generation and the energy stored in the ESS(s).

However, any energy deviation due to RES forecast errors or other uncertain RT parameters during RT operation have negative influence on the optimal energy market schedule and ESS energy optimal profiles. These uncertain parameters in RT operation change the energy stored in the ESS in order to fulfill the grid power set-points. And consequently, DM+CIM schedule needs to be updated in following CIM auctions along the day in order to manage the operation. The main challenge of the RES operation is to avoid large energy imbalances caused by unpredicted forecast errors and to provide a high technical market compliance. These RT controls may be implemented in a plant controller to make quick decisions and control instantaneously RES generation and ESS.

This lower level control for RT operation is configurable for different scenarios, as can be observed in Figure 2.23: an individual RES+ESS plant (with decentralized control) and for a RES+ESS portfolio (several RT control can be applied). After the calculation of final grid power delivery ($P_{r,k}^{grid}$), an ESS aging analysis is carried out following the procedure exposed in Section 2.4 (ESS degradation analysis).

There are several stages defined in the lower level control: i) calculation of instantaneous RES generation (real generation or through equalization techniques), ii) calculation of the ESS output power and final grid power delivery, iii) cooperation of AGC signal requirements in case of non-compliance, and iv) analysis for the ESS degradation in operation.

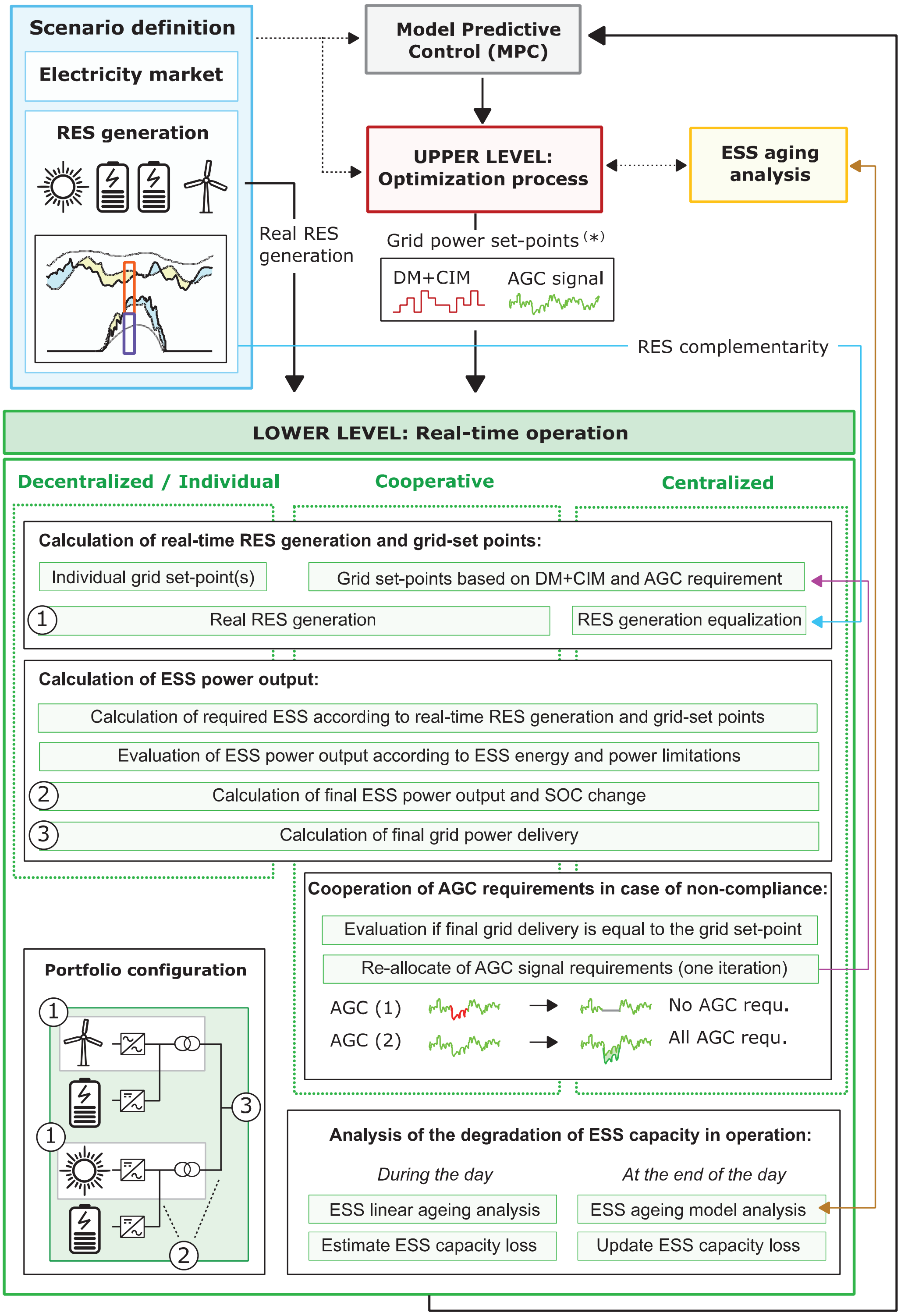


Figure 2.23 – Lower level control (Real-time operation) block in detail.

2.5.1 Individual RES+ESS operation

The RES+ESS plant is controlled in RT operation to fulfil the grid power set-point ($P_{r,k}^{grid*}$) according to instantaneous RES production ($P_{r,k}^{real}$). The $P_{r,k}^{grid*}$ is composed by the DM+CIM scheduling, AGC power signal and energy imbalances when needed. These RT values modify the ESS operation from the optimal profile calculated in the upper control ($E_{r,k}^{ESS}$).

$P_{r,k}^{AGC}$ produces an additional SOC variation, in addition to the SOC variation due to forecast errors. $P_{r,k}^{AGC}$ signal could be positive or negative. An upward reserve power has a positive value (which discharges the ESS) and a downward reserve power has a negative value (which charges it).

Accordingly, the ESS power applied to the ESS (P_{k}^{ESSin}), next state of charge ($SOC_{r,k}^{ESS}$) and final grid output ($P_{r,k}^{grid}$) are calculated, by following eq. (2.44)-(2.47), under normal operation. These values may be constrained by ESS power and energy limits.

After each day, a complete ESS aging analysis is carried out from Wöhler curve and calendar aging models and applying ESS aging model. The ESS lifetime (Ψ^{ESS}) and current ESS capacity ($C_{r,k}^{ESS}$)are updated considering an *EoL* of 20% of C_{r}^{nom}. Finally, the current $SOH_{r,k}^{ESS}$ and consequently, ESS capacity ($C_{r,k}^{ESS}$) are updated (2.48) in other blocks of the EMS.

$$P_{r,k}^{grid*} = P_{r,k}^{DM+CIM} + P_{r,k}^{imb+} - P_{r,k}^{imb-} + P_{r,k}^{AGC} \tag{2.44}$$

$$P_{r,k}^{ESSin} = \left(P_{r,k}^{real} - P_{r,k}^{grid*}\right) \cdot (u_{r,k} \cdot \eta^{ch} + \frac{1 - u_{r,k}}{\eta^{dch}}) \tag{2.45}$$

$$SOC_{r,k}^{ESS} = SOC_{r,k-\Delta k}^{ESS} + \frac{\left(\Delta t \cdot P_{r,k}^{ESSin}\right)}{C_{r,k}^{ESS}} \cdot 100 \tag{2.46}$$

$$P_{r,k}^{grid} = P_{r,k}^{real} - P_{r,k}^{ESSin} \cdot \left(u_{r,k}/\eta^{ch} + \left(1 - u_{r,k}\right) \cdot \eta^{dch}\right) \tag{2.47}$$

$$C_{r,k}^{ESS} = SOH_{r,k}^{ESS} \cdot C_{r,k}^{nom} \tag{2.48}$$

The ESS efficiency (η^{ch}, η^{dch}) are included. The variable (u_k) is 1 when charging and 0 when discharging. These equations are constrained by an optimal SOC range and a maximum ESS power ($\overline{P_r^{conv}}$).

2.5.2 Portfolio RES+ESS operation

Equal to individual RES+ESS, the main challenge of the RES operation lies in avoiding large energy imbalances caused by unpredicted forecast errors and providing a high technical compliance in FRR market. In order to reach this objective, advanced controls should be implemented in real-time operation, which try to follow the optimal market scheduling and grid power set-points with the available RES generation ($P_{r,k}^{real}$) and current SOC of the ESSs. Three portfolio supervisory controls were implemented in this EMS for the renewable portfolio: decentralized, cooperative and centralized. This lower level control for RT operation is configurable for these different scenarios,

While individual RES+ESS plants must be operated independently, renewable portfolio with distributed ESS can be also operated and controlled in a centralized way to provide all the grid power set-points according to the total available RES generation and ESSs' stored energy, with the objective of minimizing SOC changes, reducing ESS usage, and extending their lifetimes.

In this lower level, a decision-making process is applied according to the portfolio supervisory control selected. These supervisory control decides the degree of cooperation, interconnection and operation among RES plants and associated ESSs.

The lowest level of cooperation of the portfolio results in the decentralized control (Dctr). The final portfolio market schedule and RT operation is the aggregate of the decisions and controls of each individual plant. Thus, they operate as separated plants, which could result usually in suboptimal decisions and/or faulty on extreme RT operation conditions. The results of this control are shown and discussed in Section III, where each individual renewable plant with storage is controlled by its own. RES plants are independently operated following pseudo-code lines 2, 4, 10-24.

In accordance with Spanish rules for FRR market [221], the provision of AGC power signal can be provided by all plants gathered in a Regulation Zone (RZ). Each RZ is composed by one or more generation units authorized for FRR. In RT operation, the RZ controller decides and allocates the AGC set-points to their own generation units (depending on their availability) as long as the total AGC signal is fully provided.

Following this assumption, the AGC signal could be provided by each RES plant independently (Dctr) or could be shared by all RES in case of non-compliance or failure of one of them. This control is defined as cooperative control (Coop), in which they are supported in the provision of the AGC signal in case of ESS fully (dis)charged including equations of the pseudo-code from line 25 to 31.

Finally, the concept Virtual Power Plant (VPP) has turned up in order to manage and operate more efficiently distributed energy resources, which allows them to participate in both energy and reserve markets, through a virtual grid connection. Therefore, two purpose are established for Centr control: i) reduce ESS usage at each time step (minimize SOC changes) to increase ESS lifetimes sharing grid power set-points, and ii) collaborate in AGC signal provision if FRR non-compliance happens.

Moreover, there is clear evidence that the diversification of RES plants presents complementary generation profiles as reported in [156]–[158]. However, there is no research which integrates and analyzes the complementary effect on the portfolio market operation, as [222] claims. In this present PhD dissertation, complementarity of RES generation is taken into advantage to reduce SOC fluctuations, and thus, the usage of ESS.

When several ESS must be controlled and operated, distributed ESSs are preferred rather than aggregated ESSs. Moreover, SOC equalization techniques can be used to manage multiple ESSs. In contrast to other SOC equalization [143], [144], [179] described in Section , this RT control provides the total grid power set-points (sum of both RES plants) according to the total available RES generation. This implemented RES equalization technique aims of reducing ESS usage, by minimizing SOC changes. This RT control is implemented from line 2 to 9.

As conclusion, RES generation complementarity, distributed ESSs control and SOC equalization techniques are the main key features to be implemented on an advanced EMS for a VPP market participation. A schematic block diagram can be observed in Figure 2.24 for pseudo-code.

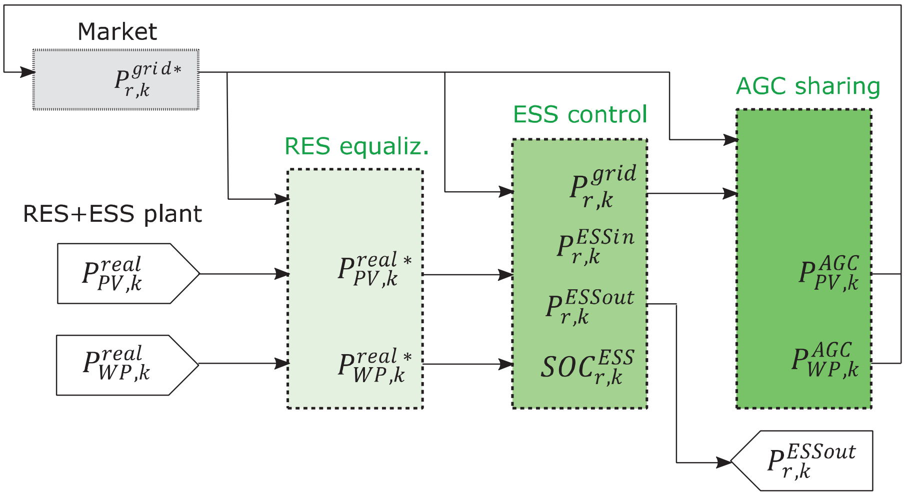


Figure 2.24 – Schematic block diagram for centralized control.

This centralized portfolio supervisory control was included in a patent pending "IKER017. Procedimiento e instalación para la gestión de energía eléctrica", *("Procedure and installation for energy management - centralized control")*, by Amaia González, Andoni Saez de Ibarra, and Haizea Gaztañaga in Sept. 2019.

Pseudo-code: Real-time operation. Centralized supervisory control.

```
1: function F($P_{r,k}^{DM+CIM}, P_{r,k}^{imb+}, P_{r,k}^{imb-}, P_{r,k}^{AGC}, P_{r,k}^{real}, k$)
2:     Calculate grid set-point: $P_{r,k}^{grid*} = P_{r,k}^{DM+CIM} + P_{r,k}^{imb+} - P_{r,k}^{imb-} + P_{r,k}^{AGC}$
3:     Calculate power difference: $\Delta P_r = P_{r,k}^{real} - P_{r,k}^{grid*}$
4:         if Dctr/Coop control then; $P_{PV,k}^{real*} := P_{PV,k}^{real}$ and $P_{WP,k}^{real*} = P_{WP,k}^{real}$
5:         elseif $(\Delta P_{PV}^{+} > -\Delta P_{WP}^{-}) \mid\mid (-\Delta P_{PV}^{-} > \Delta P_{WP}^{+})$ then
6:             $P_{PV,k}^{real*} := P_{PV,k}^{real} + \Delta P_{WP}$ and $P_{WP,k}^{real*} = P_{WP,k}^{real} - \Delta P_{WP}$
7:         elseif $(\Delta P_{PV}^{+} \leq -\Delta P_{WP}^{-}) \mid\mid (-\Delta P_{PV}^{-} \leq \Delta P_{WP}^{+})$ then
8:             $P_{PV,k}^{real*} := P_{PV,k}^{real} - \Delta P_{PV}$ and $P_{WP,k}^{real*} = P_{WP,k}^{real} + \Delta P_{PV}$
9:         end if
10:    for r = PV to WP
11:      Required ESS power: $P_{r,k}^{ESSout*} = P_{r,k}^{real*} - P_{r,k}^{grid*}$
12:        if ESS need to be charged: $u_k := 1$
13:        if ESS need to be discharged: $u_k := 0$
14:        end if
15:            case normal ESS charging or discharging
16:              $P_{r,k}^{ESSin} := P_{r,k}^{ESSout*}\left(u_k \cdot \eta^{ch} + \frac{1-u_k}{\eta^{dch}}\right)$
17:            case not enough ESS energy that is needed
18:              $P_{r,k}^{ESSin} := C_{r,k}^{ESS}\left(\frac{u_k \cdot \eta^{ch} \cdot (\overline{SOC} - SOC_{r,k})}{\Delta t \cdot 100} + \frac{(1-u_k) \cdot (\underline{SOC} - SOC_{r,k})}{\eta^{dch} \cdot \Delta t \cdot 100}\right)$
29:            case not enough ESS power that is needed
20:              $P_{r,k}^{ESSin} := \overline{P_r^{conv}}\left(u_k \cdot \eta^{ch} + \frac{1-u_k}{\eta^{dch}}\right)$
21:    end for
22:    Solve final ESS power output: $P_{r,k}^{ESSout} := P_{r,k}^{ESSin}\left(\frac{u_k}{\eta^{ch}} + (1-u_k) \cdot \eta^{dch}\right)$
23:    Solve final SOC: $SOC_{r,k}^{ESS} := SOC_{r,k-\Delta k}^{ESS} + (\Delta t \cdot P_{r,k}^{ESSin}) / (C_{r,k}^{ESS}) \cdot 100$
24:    Solve final grid power delivery: $P_{r,k}^{grid} := P_{r,k}^{real*} - P_{r,k}^{ESSout}$
25:    Evaluate grid power $P_{r,k}^{grid} == P_{r,k}^{grid*}$ to share AGC signal ($P_{r,k}^{AGC}$)
26:    if Dctr control OR $P_{r,k}^{grid} == P_{r,k}^{grid*}$ then do nothing
27:    elseif $(P_{PV,k}^{grid} \neq P_{PV,k}^{grid*})$ && $[(P_{WP,k}^{grid} == P_{WP,k}^{grid*}) \mid\mid (P_{r,k}^{AGC} > 0\ (up)$
           && $\underline{SOC} \geq SOC_{PV,k}) \mid\mid (P_{r,k}^{AGC} < 0\ (dw)$ && $\overline{SOC} \leq SOC_{PV,k})]$ then
28:                $P_{WP,k}^{AGC} := P_{PV,k}^{AGC} + P_{WP,k}^{AGC}$ and $P_{PV,k}^{AGC} := 0$
             Repeat RT operation from line 2 to 24 with AGC signal sharing
29:    elseif $(P_{WP,k}^{grid} \neq P_{WP,k}^{grid*})$ && $[(P_{PV,k}^{grid} == P_{PV,k}^{grid*}) \mid\mid (P_{r,k}^{AGC} > 0\ (up)$
           && $\underline{SOC} \geq SOC_{WP,k}) \mid\mid (P_{r,k}^{AGC} < 0\ (dw)$ && $\overline{SOC} \leq SOC_{WP,k})]$ then
30:                $P_{PV,k}^{AGC} := P_{PV,k}^{AGC} + P_{WP,k}^{AGC}$ and $P_{WP,k}^{AGC} := 0$
           Repeat RT operation from line 2 to 24 with AGC signal sharing
31:    end if
```

2.6 Model predictive control

The general objective of MPC, as can be observed in Figure 2.25, is to follow the reference (or optimal) trajectory of the system (calculated in the upper level control). However, the system conditions change during the time due to unexpected or uncertain parameters and the measured past output is different from the reference trajectory. Therefore, another optimization (from upper control) should be carried out to calculate the future control actions with the aim of modifying the future trajectory to reach the final set-point. This new future trajectory is known as predicted future output based on the current control inputs and future actions.

Focusing on other studies of VPP [166]–[173], they are more focused on the market scheduling optimization stage, instead on the validation in operation. Controllable plants are always taken into account in the literature, reducing the unpredictable RES nature and hugely restrictive technical constraints for RT operation. Due to this fact, they do not require to implement, to a great extent, RT techniques which enable to make quick decisions according to instantaneous system conditions.

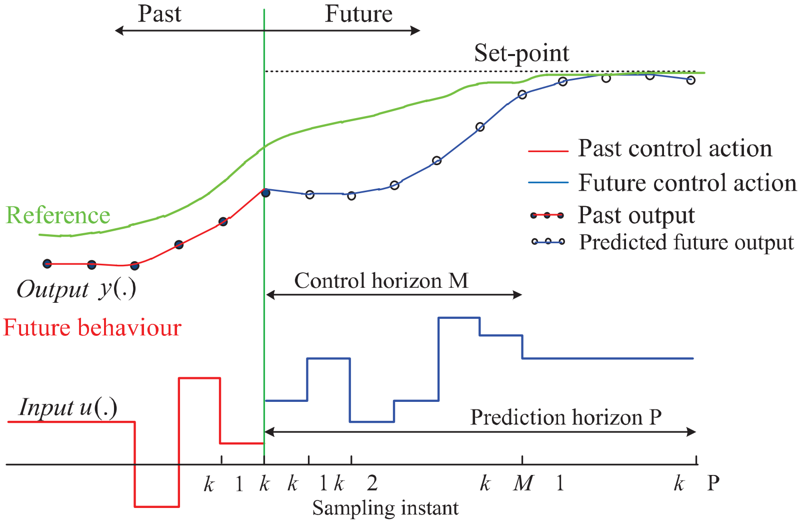


Figure 2.25 – General concept for MPC [223].

In contrast, other researches are more focused on RT control strategies for VPP. MPC is widely used as RT control in order to adapt the pre-defined RES operation according to instantaneous system measurements and conditions, and to perform corrective actions when uncertainties or unexpected events appear in RT operation.

For analogy, one reference trajectory could be the optimal SOC profile which maximizes the market revenues and finishes at middle SOC. The past trajectory is the real SOC profile up to a given time, which differs from the optimal SOC profile. One future control action could be a modified ESS power output, while one predicted control inputs could be RES generation forecasts. Therefore, the predicted future output can be a new expected ESS SOC profile which reaches the set-point.

Therefore, MPC enables to optimize previous energy market bidding schedule through CIM offers during the day in case of large RT deviations from the optimal operational performance considered the day before (at DM auction). MPC is applied as a closed-loop control, in which only the first grid power set-points are requested in RT operation. The implementation of MPC in the EMS can be observed in Figure 2.26.

A sample time step ($\varDelta k$) is defined in this EMS which corresponds to a real-time period ($\varDelta t$) of 1/4h (that is, 15 minutes), because of the resolution of RES generation profiles. This time period less than 1 hour enables to model intra-hour behavior of the AGC signal and operate suitably the ESS in a more realistic scenario.

In each loop, RES forecast, current ESS and system operating conditions are updated, and the horizon window shifts $k+\varDelta k$ in order to optimize market schedule along the optimization horizon (K_H) when current k matches with any market gate closure (k_{DM}, k_{CIMx} or k_{FRR}), or otherwise, RES+ESS plants follow the grid-set points until next market re-schedule.

After that, ESS power output and next SOC, among other parameters, are calculated in the lower level control in operation according to power requirements and previous state of the ESS. These values are updated in the next iteration, where $k{=}k{+}\Delta k$.

MPC enables to optimize the market bidding and re-schedule CIM offers during the day. Thus, MPC reduces negative impacts of RES generation and AGC signal uncertainty, enhances ESS operation, reduces RES energy imbalances and improves the level of compliance of DM, CIM and FRR market requirements.

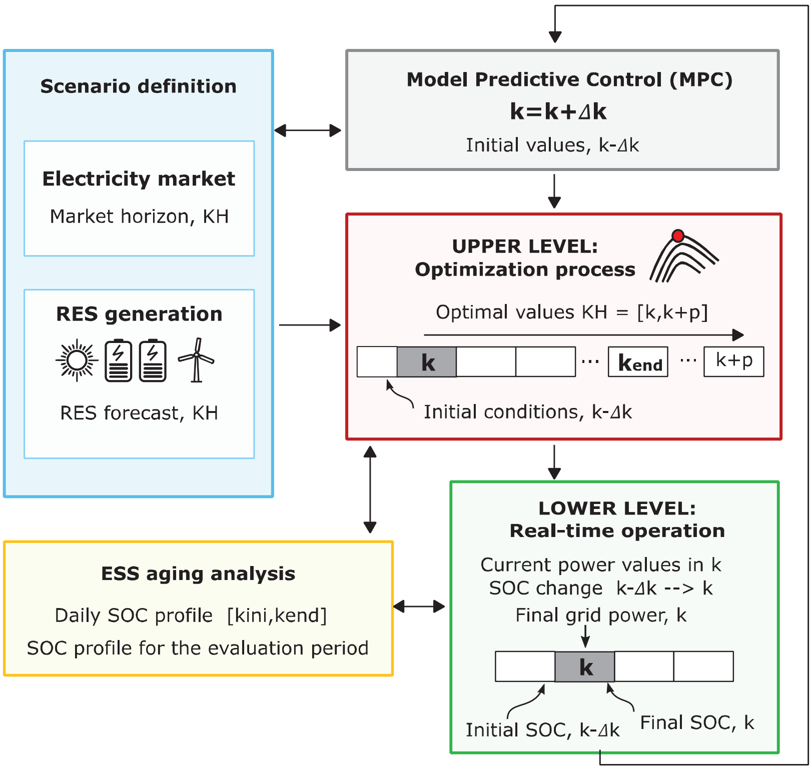


Figure 2.26 – Implementation of MPC in the proposed EMS.

Chapter 3 EMS oriented to individual RES plants

This chapter addresses the individual (or decentralized) operation of RES plants. The EMS methodology presented in Chapter 2 is simulated and validated by means of two case studies: PV+ESS and WP+ESS with the objective of evaluating the profitable participation of each renewable energy technology plus storage in multiple markets from an economic and technical point of view.

The development of an advanced EMS enables maximizing market revenues and minimizing overall ESS costs associated to acquisition and degradation costs, including ESS aging analysis. Firstly, the MILP optimization is applied to calculate the optimal daily joint market bidding in energy markets and reserve markets for one individual renewable plant with storage, while it avoids expected energy imbalances and penalties. In that way, the RES+ESS plant contributes to the system frequency stability.

At lower level control, RT operation with decentralized (individual) control is applied to each RES technology. ESS energy fluctuations which come from renewable forecast errors and real-time FRR market requirements are managed by the stored energy of the ESS through MPC approach. Large ESS deviations are counteracted afterward through the Continuous Intraday Market (CIM) re-scheduling. Consequently, the RT control enables a high compliance of frequency reserve requirements and a huge reduction of energy imbalances in real-time operation, as will be demonstrated along the technical results of Chapter 3.

Additionally, several ESS capacities are selected in order to evaluate the cost-effectiveness of the ESS operation for utility-scale PV or WP application in the Spanish market. Future scenarios of market prices or investment costs are also considered in order to assess the current and/or future profitability of ESS integration in a renewable facility.

3.1 Techno-economic analysis for PV+ESS

In this section, the techno-economic analysis for the market participation and operation of a PV plant with ESS will be exposed, following the proposed EMS from Figure 3.1. The PV+ESS is independently operated and controlled as an individual plant, following decentralized control described in Section 2.5.1.

3.1.1 Scenario definition for PV+ESS case study

The PV+ESS EMS is applied for an annual solar generation profile extracted from TSO database from [224], composed by public historical annual data of day-ahead, intraday forecasts and real generation on a 15-minutes basis. PV forecast profiles ($P_{r,k}^{pred}$) are used in the optimization, while real generation ($P_{r,k}^{real}$) is applied in RT operation. These profiles are scaled for a PV plant with an installed capacity of 30 MW. Moreover, as the annual solar irradiance of central Europe is less than in south Europe (in particular Spain in this study), spring and summer seasons are selected and doubled which result in 1485 annual Equivalent Full-Load Hours (FLH), similar to the Spanish solar irradiance. Additionally, this annual profile has a sunny period with more irradiance and a cloudy period with less irradiance which corresponds to typical winter and autumn periods.

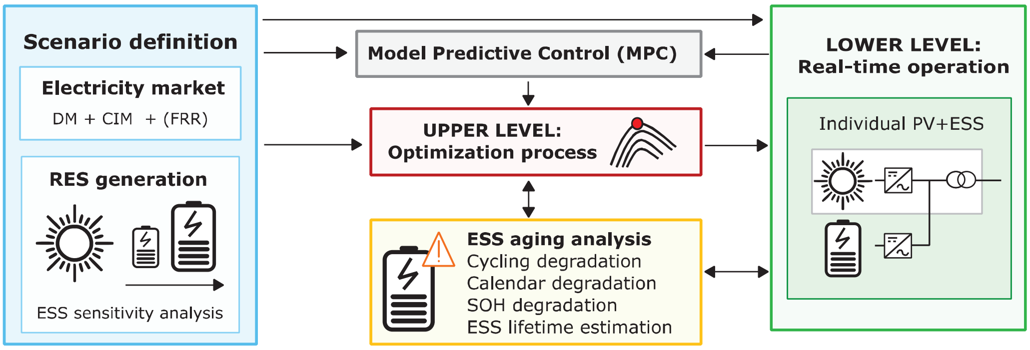


Figure 3.1– Proposed PV+ESS Energy Management Strategy.

The solar generation distribution percentiles (PCTL) can be shown in Figure 3.2 as shaded bands around the central median line. As can be deduced, the daily peak power varies from 4 MW to 25 MW for extreme irradiance days. The median peak is around 17 MW, resulting in an absolute error of -13MW and 8MW for extreme days. In contrast, the maximum error between the real generation and the most recent forecast is 7.9 MW (26.4%) considering PCTL-100, and 4.1 MW (13.8%) with PCTL-90. Thus, this EMS considers the day-ahead and most recent forecasts from [224], as inputs for the upper level control (optimization process). The Programable Logic Controller (PLC) can load these generation data and applied them on the EMS accordingly.

Several ESS sizing are selected in order to evaluate the cost-effectiveness of the ESS for this application. The ESS nominal capacity (C_r^{nom}) is selected from 6.5 MWh to 16.25 MWh values (around 21-54% $\mathrm{MWh_{ESS}}$ per MW of PV installed, or $\mathrm{MWh_{ESS}/MW_{PV}}$), based on a previous ESS sizing of 13 MWh (around 43% $\mathrm{MWh_{ESS}/\ MW_{PV}}$) resultant from another PhD dissertation for 30MW-PV smoothing and arbitrage purposes [117].

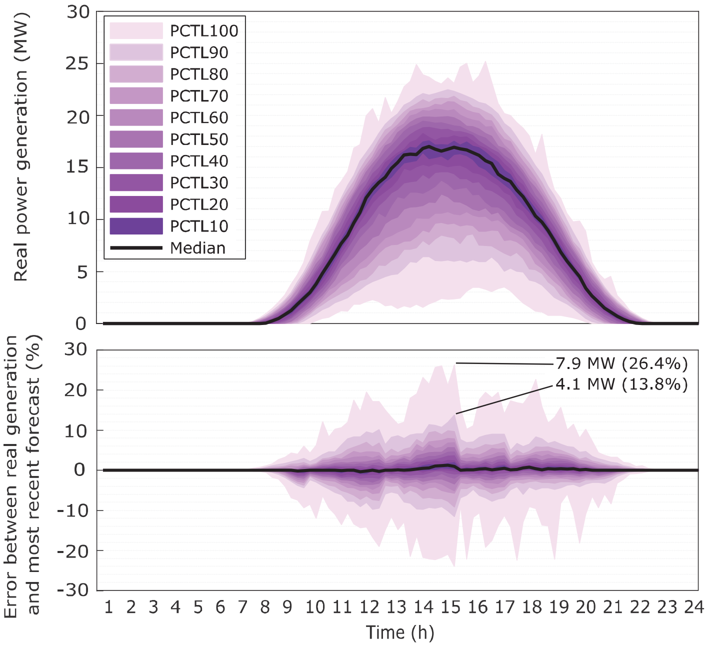


Figure 3.2 – Solar power generation.

Table 3.1 summarizes other design variables, mainly defined in the scenario definition. Moreover, one-year simulation period has been selected to evaluate the proposed EMS. In particular, a static Techno-Economic Assessment (TEA) is conducted and validated according to Spanish market rules [221], real market prices and FRR energy needs of 2017, extracted from Spanish TSO data [189], without any interest rate.

On the one hand, annual market benefits (B) are calculated as in eq. (3.1). They are composed by the revenues from DM and CIM markets, cost or revenues from negative and positive imbalances, revenues from FRR band availability and real upward energy provided (E_k^{uw}) and costs from real downward energy required at RT operation (E_k^{dw}). Finally, when the plant does not provide the AGC signal (P_{rk}^{AGC}), a FRR penalty cost is added (last term in eq. (3.1)). It can be pointed out that the downward AGC energy is used to charge to ESS and sold this energy later as a more valuable energy, thus increasing the CIM market bid. On the other hand, the upward AGC energy is sold by an hourly price (λ_k^{uw}) generally higher than the energy market price (DM and CIM), and consequently, the following CIM market bids are reduced.

Table 3.1 – Scenario definition of individual RES+ESS plant.

Variable	Unit	Value
ESS nominal capacity	C_r^{nom}	0 & 6.5 - 16.25 MWh
ESS maximum power	P_r^{conv}	13MW
ESS efficiency	$\eta^{ch/dch}$	90%
SOC limits for safe operation	$\underline{SOC}^{opt}$, $\overline{SOC}^{opt}$	10% / 90%
SOC limits for FRR participation	$\underline{SOC}^{FRR}$, $\overline{SOC}^{FRR}$	15% / 85%
SOC limits for RT operation	$\underline{SOC}^{rt}$, $\overline{SOC}^{rt}$	5% / 95%
SOC range at the end of the day	$\underline{SOC}^{end}$, $\overline{SOC}^{end}$	30% / 50%
Expected converter and RES lifetime	ψ^{conv}, ψ^{PV}, ψ^{WP}	25 years
ESS cycling aging model	Wöhler curve method (Kokam's NMC)	
ESS calendar aging model	Linear regression for math. model from [218]	
Market participation	DM + CIM and DM + CIM + FRR	

$$B = \sum_{k=1}^{keval} \begin{bmatrix} \Delta t \cdot \Sigma_k \, [\lambda_k^{DM} \cdot P_k^{DM} + \lambda_k^{CIM} \cdot P_k^{CIM} \\ +\lambda_k^{imb\pm} \cdot \left(P_k^{grid} - P_k^{DM+CIM} - \left(E_k^{uw} - E_k^{dw}\right)\right)^{\pm} \\ +\lambda_k^{band} \cdot P_k^{band} + \lambda_k^{uw} \cdot E_k^{uw} - \lambda_k^{dw} \cdot E_k^{dw} \\ -1.5 \cdot \lambda_k^{band} \cdot \left|P_k^{grid} - P_k^{DM+CIM} - P_k^{band}\right| \,] \end{bmatrix} \tag{3.1}$$

On the other hand, current and future PV+ESS costs are defined. The Base Case (BC) corresponds to current PV+ESS costs and Spanish market prices from 2017 [189]. Another two Future Scenarios (FS1 and FS2) are included, based on a reduction of investment PV+ESS costs, and an increase on market prices. The detailed values for these three scenarios (BC, FS1 and FS2) are summarized in Table 3.2. Investment costs of the PV are considered in €/MW from 1 million of euros (M€) per 1 MW installed capacity. A reduction of system costs in future scenarios are settled from 20-25% to 40-50% and a change of market prices around ± 5, 10 and 20% according to future market trends reported in [47],[225].

Table 3.2 – PV+ESS costs and market prices for the techno-economic analysis.

Variable, unit		**Base Case & Future Scenarios (1 -2)**		
		BC	**FS1**	**FS2**
PV costs, M€/MW	c^{PV}	1	0.8 (-20%)	0.6 (-40%)
ESS power costs, M€/MW	c^{MW}	0.5	0.4 (-20%)	0.3 (-40%)
ESS energy costs, M€/MWh	c^{MWh}	0.4	0.3 (-25%)	0.2 (-50%)
ESS repl. costs	c^{MWh}	$c^{MWh} \cdot \text{⍰}_{r=1}^{n}[1 - \left(0.8 \cdot e^{-0.11 \cdot yr(r)} + 0.13 \cdot e^{0.017 \cdot yr(r)}\right)]$		
DM price, €/MWh	λ_h^{DM}	2017	+ 5 %	+ 10 %
CIM price, €/MWh	λ_h^{IM1}	2017	+ 5 %	+ 10 %
Energy imb. price, €/MWh	$\lambda_h^{imb\pm}$	2017	± 10 %	± 20 %
Band price, €/MW	λ_h^{band}	2017	+ 5 %	+ 10 %
Upward price, €/MWh	λ_h^{uw}	2017	+ 10 %	+ 20 %
Downward price, €/MWh	λ_h^{dw}	2017	– 10 %	– 20 %

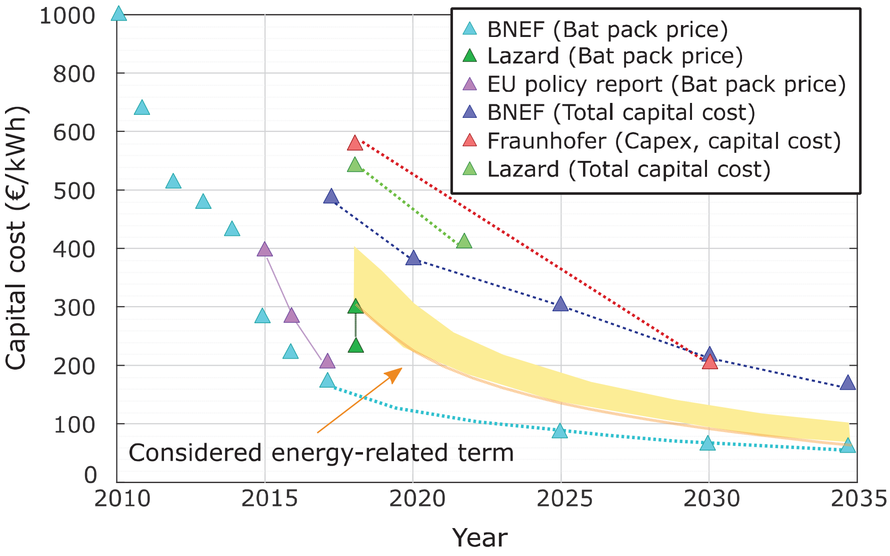


Figure 3.3 – ESS costs tendency. Sources: [89], [105], [226]–[229].

Investment costs of the ESS [51], [226], [230] are composed by energy and power terms according to EPRI convention, as well as replacement energy terms according to the number of replacements needed (n) during the lifetime of the renewable asset (RES lifetime *(Y)* is considered 25 years).

Regarding ESS battery-pack costs, at the end of 2017, the cost of a lithium-ion battery pack fell to \$209/kWh, assuming a cycle life of 10-15 years. BNEF predicts that lithium-ion batteries will cost less than 100 \$/kWh by 2025. Otherwise, including all installed ESS costs, the total ESS costs reaches around 600-400\$/kWh from other sources. In contrast, EPRI suggests a total installed costs expressed in \$/kW from 500\$/kW by 2017 and from 350\$/kW by 2020 [226], [230]. A summary of all these investment ESS costs are reported in Figure 3.3, divided by battery-pack costs and total capital costs.

Therefore, ESS capital costs are divided following the EPRI convention, considered in power and energy-related terms from: 0.3-0.5 M€/MW (c^{MW}) and 0.2-0.4 M€/MWh (c^{MWh}) (without including yet financing costs). The energy-related term considers the investment from battery pack capacity, their installation costs or other energy-associated costs, while power-related costs are investments associated to the converter power, auxiliary equipment and devices, and civil works. Evaluating the investment costs of the battery in terms of capacity and power enables to evaluate and assess the impact of ESS sizing.

Moreover, ESS replacement costs ($R_{r,y}^{ESS}$) are calculated from a reduction cost curve according to the expected ESS replacements (n), according to Figure 3.4, which follows eq. (3.2). To estimate the operating and replacements ESS costs, the expected ESS lifetime is calculated through the ESS degradation analysis for the annual complete ESS operation.

$$R_{r,y}^{ESS} = C_r^{nom} \cdot c^{MWh} \cdot \Sigma_{x=1}^{n}[1 - (0.8 \cdot e^{-0.11 \cdot y_x} + 0.13 \cdot e^{0.017 \cdot y_x})] \qquad (3.2)$$

where y_x corresponds to the year in which each ESS replacement (x) is made, including the ESS costs reduction curve up to next 20 years.

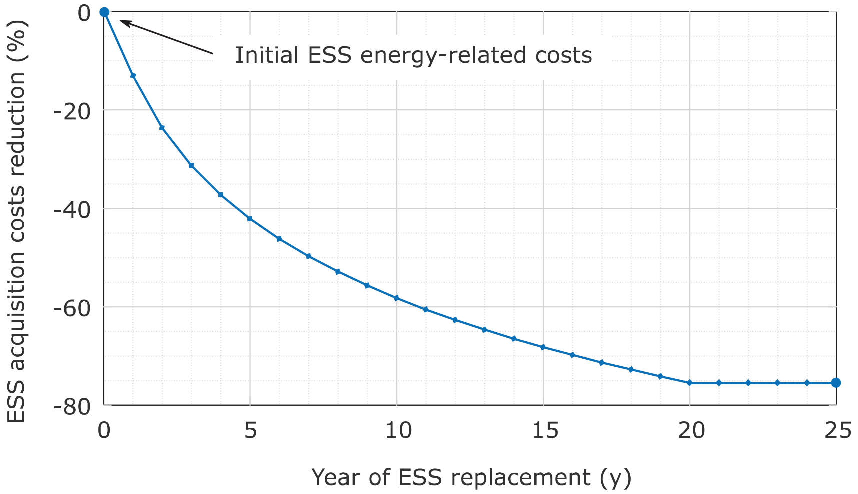


Figure 3.4 –ESS acquisition costs for ESS replacements.

Sources: [89], [105], [226]–[229].

3.1.2 PV+ESS participation and real-time operation

The joint operation of a single day is shown in Figure 3.5. As can be observed, the ESS can control the grid output power, manage the PV forecast errors and follow the DM+CIM market schedule and the current AGC signal in real-time operation. The AGC power signal was modelled following Section 2.3.3 based on the FRR availability band calculated in the upper level control at FRR auction-time. The AGC power signal was calculated based on the hourly upward and downward FRR energy requirements of 2017 available in the Spanish TSO website [182].

Analyzing the Figure 3.5, it can be observed that the DM schedule calculated at DM auction time (12:00 of the day "D-1") follows the DM forecast (green line). Afterward, the FRR availability band is calculated at FRR auction time (17:30 of the day "D-1") thanks to the MILP optimization to maximize both market schedule revenues but minimizing the expected energy imbalances and FRR penalties and controlling the SOC at the end of the day at 50%. As a result, the expected SOC profile

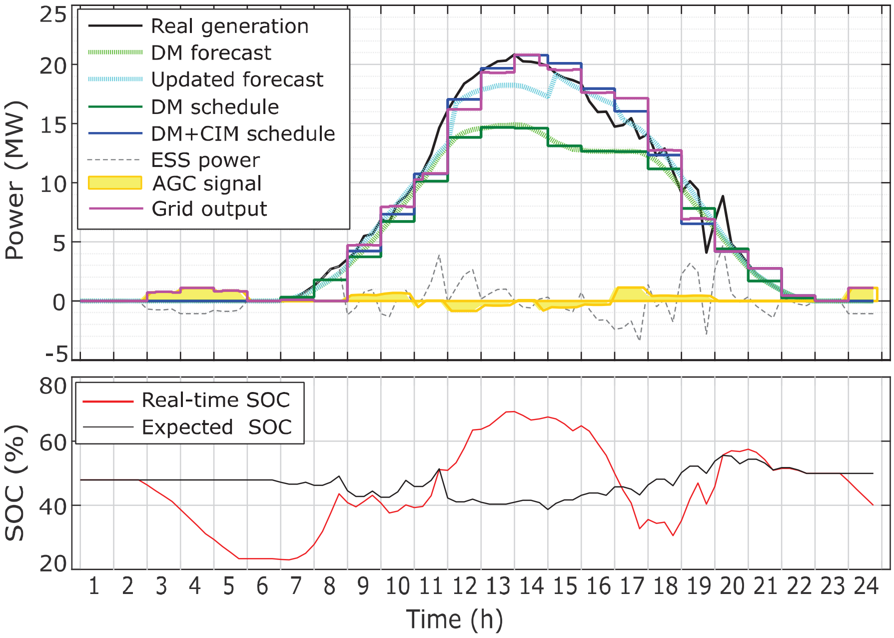


Figure 3.5 – Example of one daily real-time PV operation.

(in black line) at that time, before the optimization day “D”, has not huge fluctuations and it is maintained around 50% SOC. That is because the expected FRR revenues are higher than making arbitrage in energy markets. Therefore, SOC should be maintained around 50% in order to maximize the possible SOC increment or decrement to follow the AGC signal according to hourly FRR availability bands.

After DM and FRR market auctions, CIM re-schedule is made due to:

- Difference of the starting SOC value at each day from 50%.
- Influence of FRR prices and CIM prices, estimated from DM prices.
- Updates on renewable forecast generation profile (most recent information available, known as updated forecast for 4 hour-ahead).
- SOC deviations due to RES generation forecast errors.
- SOC deviations due to uncertain AGC signal from FRR requirements.

All these factors will be analyzed below. The first CIM market auction is cleared at 23:00. In this CIM auction, CIM re-schedule bid can be optimized according to approximated hourly daily CIM market prices because they can be predicted from DM market prices (see Section 2.3.3), as can be observed in Figure 3.6. The upper level control will modify the CIM schedule in order to maximize the objective function, shifting some amount of energy from off-peak price hours to on-peak price hours. As can be observed the monthly traded energy in Spanish CIM is increasing, reducing its illiquidity, but taking into account FRR band constraints.

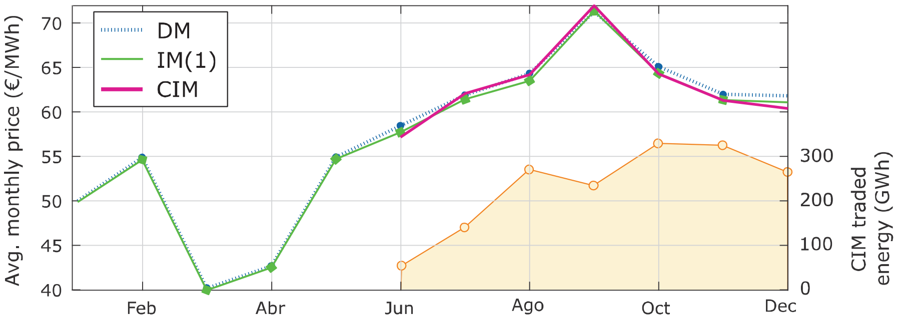


Figure 3.6 – Relationship between DM, CIM (continuous), and IM (by auction) prices. (CIM data only available from June-December 2018).

Another reason for sending a CIM market re-schedule is in case of final SOC at “D-1” is expected to be far from 50% SOC. One hour later, the same calculation is made known the expected final SOC at the end of the day “D-1”. For example, if the SOC is 30%, the PV+ESS plant will send a CIM schedule for this optimization day “D”, knowing that less energy to sell is required, sending a negative CIM offer, to charge the ESS. The upper level control will reduce the CIM schedule in order to maximize the objective function, that could be in the less expensive hour. Otherwise, if the final SOC excesses 50%, the PV+ESS plant will send a positive CIM re-scheduling, which leads to an increase of delivery energy at DM+CIM.

During the day, CIM market re-schedule bids are more influenced by the most updated PV forecast generation profile, with the objective of smoothing the PV generation and reducing sharp SOC changes. Moreover, large AGC requirements also lead to opposite CIM re-schedule bids. For instance, a large upward AGC signal provokes a decrease of energy available in the ESS and therefore a negative CIM offer is sent for following hours. In contrast, a large downward AGC signal provokes an increase of energy available in the ESS and therefore a positive CIM offer is sent for next hours in order to reduce the SOC around the middle value (50%) and be able to provide future AGC needs in both directions.

This operation can be appreciated in Figure 3.5. The CIM at sunrise is reduced in order to charge the ESS. After, the downward energy required between 11:00 and 13:00 (h=12-13) is high, therefore the SOC increases up to 70%. Consequently, the upper level control tries to reduce DM+CIM schedule. Therefore, DM+CIM schedule between 13:00 and 14:00 increase considerably from the most recent PV forecast (to counteract h=12) with the purpose of reducing SOC. Without PV forecast errors, the SOC will be reduce almost the same amount as the energy stored from downward FRR requirements. However, SOC is maintained due to positive PV forecast errors. After several hours following the same approach and taking into account AGC signal and PV forecast errors, SOC is reduced around 16:00, and these uncertain RT variables are counteracted.

3.1.3 Annual PV+ESS economic results

Firstly, the profitability of different PV+ESS plants will be analyzed under current Base Case scenario (BC). Annualized net profits (N) are calculated based on annualized market benefits (B) and annualized system costs (C). The Base Line (BL, 100%) is referred to the net profits (N) obtained by a PV plant without ESS for the BC, defined in Table 3.2.

Figure 3.7. shows the annualized market profits and net profits for a PV+ESS considering different ESS capacities, market operation and cost scenarios. In Figure 3.7.a, annual market profits increase with a larger ESS sizing as can be observed from dotted lines. The blue dotted line represents the annual market profits considering the participation in DM and CIM markets. In contrast, the green dotted line represents the annual market profits considering the participation in DM, CIM and FRR markets. As it can be deduced, the participation in reserve markets increase the annual market revenues, and this difference is higher with larger ESS. This fact is because a larger ESS can send higher FRR availability bands (increasing FRR market revenues in comparison with smaller ESS sizing), in addition to an improvement in smoothing PV variability and intermittency and reducing PV energy imbalances.

In contrast, the blue dotted line is almost plain because the objective function gives priority to reduce energy imbalances (mostly produced by the PV forecast errors) instead of making arbitrage between higher and lower CIM prices. If only energy arbitrage is considered, the SOC of the ESS will be maintained in 90% or 10%, charging and discharging continuously when local maximum and local minimum prices appear. Therefore, with this main objective ESS is not able to control the PV generation. This ESS operation can be observed in previous works shown in Figure 1.18 and Figure A.5.

It can worth noting that the annual market revenues without ESS are slightly fewer than market revenues with ESS. It was not surprising because energy imbalance prices is the same than DM prices in most hours with two-price settlement system, according to Table 1.1. The Spanish energy imbalances and DM prices difference can be seen in Figure A.8. Thus, this market design does not encourage RES plants to provide their own DM+CIM schedule, because energy imbalance prices do not really penalize this operation. Consequently, it is expected that future energy imbalance prices will reflect the real costs of energy imbalances when more RES plants are installed. Extreme scenario of energy imbalance penalties was simulated in Section A.5.

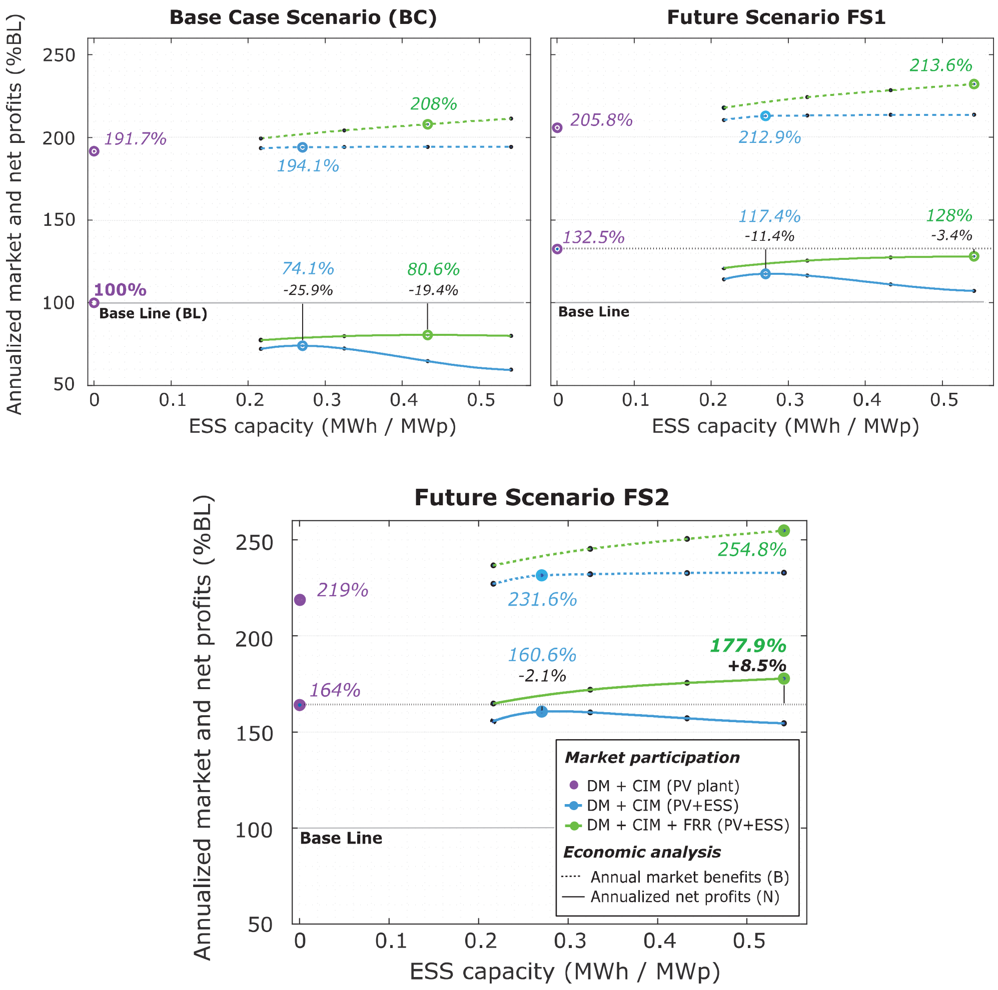


Figure 3.7 – Annualized market benefits and net profits for the considered PV plant with different ESS capacities, market operation and cost scenarios: a) Results for BC, b) Results for FS1, and c) Results for FS2 scenario.

Afterward, it is important to analyze the annualized net profits, considering the ESS acquisition, operational and replacement costs. Consequently, this ESS costs are so high that a PV plant without ESS is the most profitable option in the BC scenario.

Considering a light reduction of PV+ESS costs (around 20%) and a light increase of market prices (around 5%) according to Table 3.2 for future scenario FS1, the market and net profits increase compared to the Base Line as expected. In FS1, the annualized net profits for a PV with a ESS of 54% MWh/MWp participating in DM+CIM+FRR (green line) is almost the same than a PV without ESS (purple point), in Figure 3.7.b.

Under future scenario FS2 in Figure 3.7.c, the most profitable option under this case study could be the PV+ESS participating in all markets (DM+CIM+FRR). Net profits increase 8.5% compared to the operation of a single PV without ESS.

Focused on all economic terms that compose net profits (N), market benefits (B) and system costs (C) are analyzed in Figure 3.8, for the best three options extracted from the BC of Figure 3.7. As it can be observed, positive and negative energy imbalances without ESS (purple bars) reach almost ±10% of net revenues (however, both terms are themselves counteracted), in addition to the favorable market design of energy imbalances prices (called as future scenarios, FS). Nevertheless, it can be concluded that with the ESS installation, energy imbalances are reduced hugely (less than 1% with 0.28 MWh/MWp and less than 0.03% with 0.43 MWh/MWp). However, ESS acquisition costs increase regarding the ESS size and power, which could result in a better performance and more market revenues, but not always a more profitable asset.

In case of FRR participation (green bars) for the considered PV+ESS plants, the net profits increase in 17% and 9% for FRR band availability and upward energy, they decrease in 3.3% for downward energy and 0.016% for AGC penalty. In contrast, net profits decrease in 15.3% for

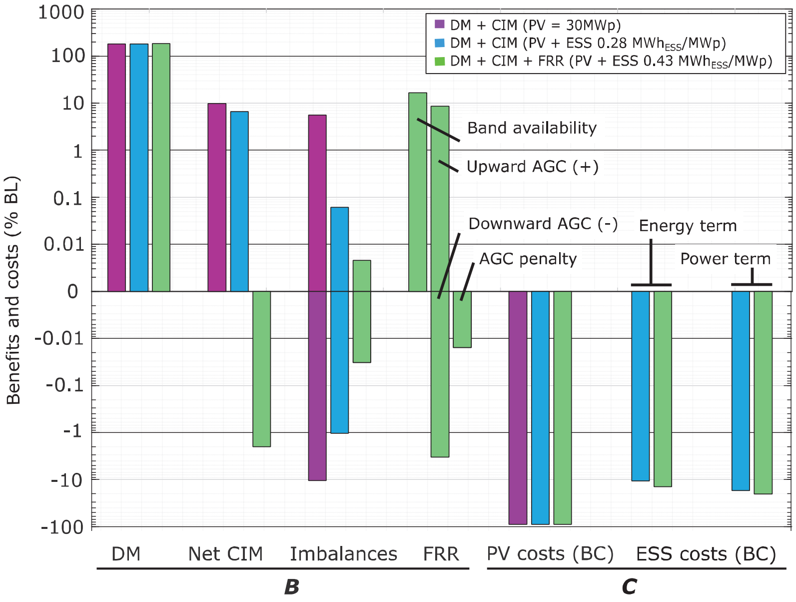


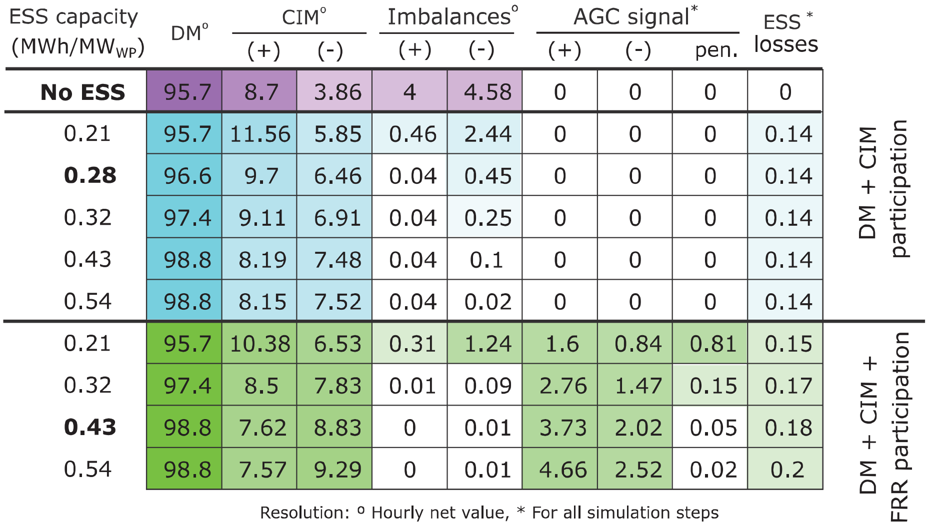
Figure 3.8 – Annual market benefits (B) and PV+ESS costs (C) at BC.

energy-related ESS costs and 20.4% for power-related ESS costs, resulting in a less profitable PV+ESS installation than without ESS.

3.1.4 Annual PV+ESS technical results

Annual results can be evaluated from an energetic point of view, as in Figure 3.9. It can be concluded that energy traded in CIM with FRR participation increases in order to manage hourly imbalances and AGC signal. For that reason, it is important to increase the liquidity of CIM, which allows shifting energy for upcoming hours without incurring in energy deviations from the involved BRPs. In addition, the most significant improvement in energy markets is the reduction of energy imbalances, as it has been exposed previously in economic terms

Moreover, the FRR availability band could be considered relatively substantial compared to the ESS capacity size, knowing that the annual AGC energy is less than 30% of the FRR bands. The PV+ESS participate mostly with an hourly FRR band around 20% of the ESS capacity (the maximum value for hourly FRR band) in sunshine hours.



ESS capacity (MWh/MW_{WP})	DM°	CIM°		Imbalances°		AGC signal*			ESS* losses	
		(+)	(-)	(+)	(-)	(+)	(-)	pen.		
No ESS	95.7	8.7	3.86	4	4.58	0	0	0	0	
0.21	95.7	11.56	5.85	0.46	2.44	0	0	0	0.14	DM + CIM participation
0.28	96.6	9.7	6.46	0.04	0.45	0	0	0	0.14	
0.32	97.4	9.11	6.91	0.04	0.25	0	0	0	0.14	
0.43	98.8	8.19	7.48	0.04	0.1	0	0	0	0.14	
0.54	98.8	8.15	7.52	0.04	0.02	0	0	0	0.14	
0.21	95.7	10.38	6.53	0.31	1.24	1.6	0.84	0.81	0.15	DM + CIM + FRR participation
0.32	97.4	8.5	7.83	0.01	0.09	2.76	1.47	0.15	0.17	
0.43	98.8	7.62	8.83	0	0.01	3.73	2.02	0.05	0.18	
0.54	98.8	7.57	9.29	0	0.01	4.66	2.52	0.02	0.2	

Resolution: ° Hourly net value, * For all simulation steps

Figure 3.9 – Traded energy respect to the annual solar generation (%).

Other technical factors mostly related to the ESS operation are evaluated here. As it can be observed in Figure 3.10.a, the ESS output power ($P_{r,k}^{ESSout}$) gives information about the maximum ESS converter power (P_r^{conv}) needed and their associated ESS power-related costs. The maximum absolute values, settled between 11 and 13.9 MW, determine the required P_r^{conv} for different ESS sizes. However, 5th and 95th percentiles are settled between -2.33 and 2.60 MW. Therefore, the required P_r^{conv} will be reduced hugely (and thus the power-related costs) in case of not considering ±5% percentile data. In contrast, along this time, ESS will be restricted by converter power limitation.

Furthermore, $SOC_{r,k}^{ESS}$ profile and annual FECs are shown in Figure 3.10.b and Figure 3.11.a, respectively. FRR participation increases the utilization of the ESS capacity, in terms of SOC dispersion and number of FECs. On the contrary, larger ESS capacity (C_r^{nom}) results in less extreme SOC values and fewer FECs, which increase the cycling lifetime around 41% compared to smaller C_r^{nom}, according to ESS aging analysis.

Finally, the FRR compliance level and annual participation hours are compared in Figure 3.11.b Both factors increase with more C_r^{nom} considered. With 0.54MWh/MWp, the level of FRR compliance is more than 99.95% and the PV+ESS plant participates 60.2% hours of the year, mostly during the sunshine hours, in which more control of ESS can be made thanks to re-schedule solar generation through CIM offers. Although the technical performance and market revenues are improved with more ESS capacity, it can be kept in mind that the PV+ESS profitability depends finally on system costs, as exposed in Section 3.1.3.

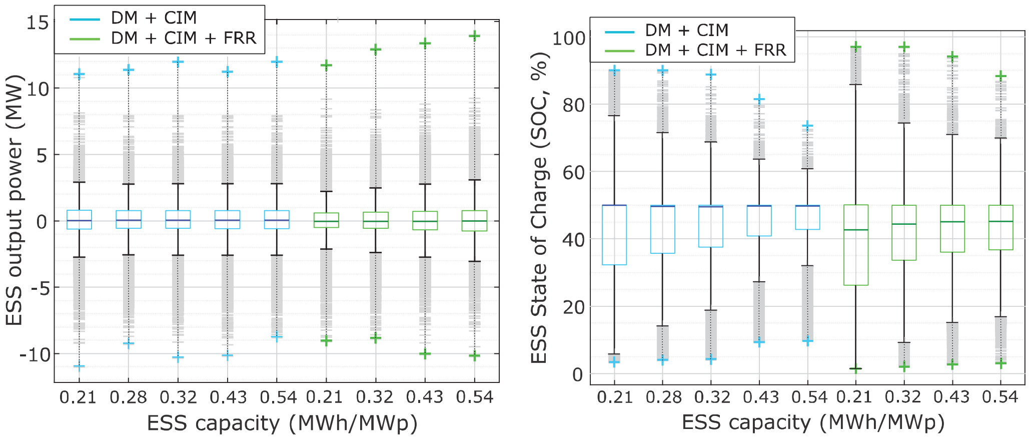


Figure 3.10 – a) ESS power output (MW), b) ESS State of Charge (%).

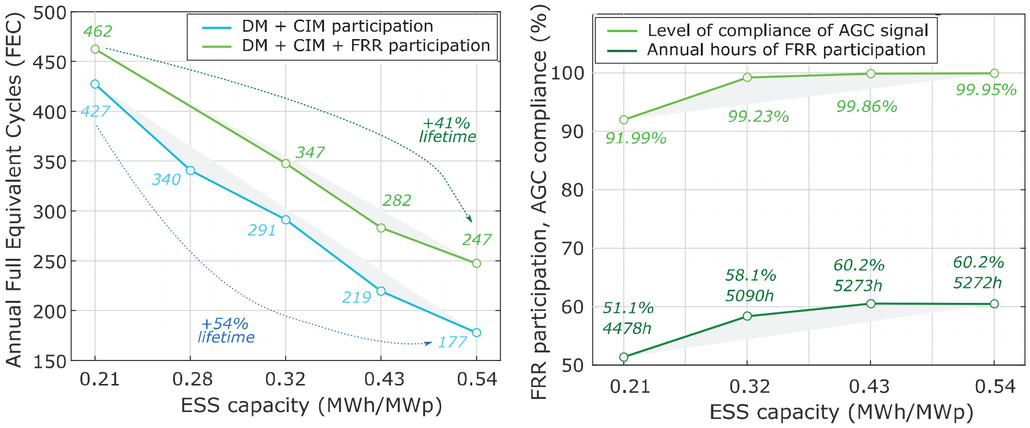


Figure 3.11 – a) Annual Full Equivalent Cycles (FEC), b) Level of compliance of AGC signal (%) and annual hours of FRR participation (%, hours).

3.2 Techno-economic analysis for a WP+ESS

In this section, the techno-economic analysis for the market participation and operation of a WP plant with ESS is exposed, following the proposed EMS from Figure 3.12. The WP+ESS is independently operated and controlled as an individual plant, following decentralized control described in Section 2.5.1. The results achieved in this techno-economic analysis for a WP+ESS plant can be compared with the results shown in Section 3.1 for the market participation and operation of a PV+ESS.

3.2.1 Scenario definition for WP+ESS case study

In Figure 3.13, the wind generation distribution percentiles (PCTL) can be shown as shaded bands around the central median line. As can be deduced, the maximum and minimum power for PCTL100 varies from 0 MW to 25.9 MW for periods of time with extreme or low wind velocity. The median generation is around 5.85 MW, resulting in an absolute error up to 20 MW for periods with high wind forecast errors. However, the maximum error between the real generation and the most recent forecast is 10.42 MW (34.72%) considering pctl-100, and 2.7 MW (9%) with pctl-90. Thus, the consideration of most recent forecast profiles as input data for CIM optimization reduces energy errors, instead of the implementation of a stochastic optimization with RES forecast scenario tree.

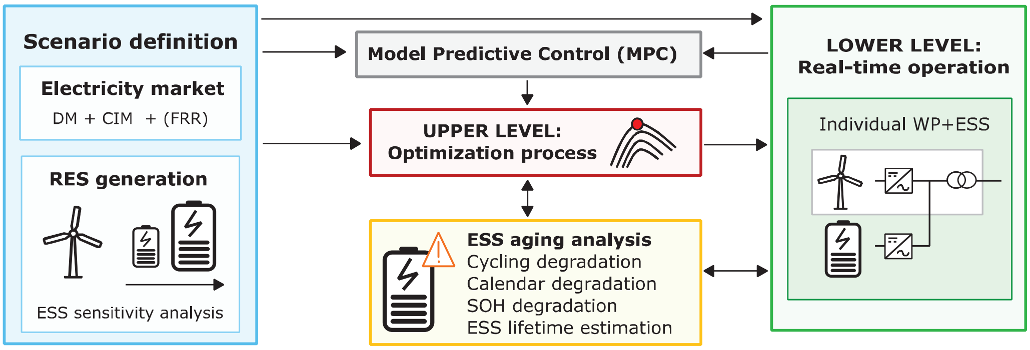


Figure 3.12– Proposed WP+ESS Energy Management Strategy.

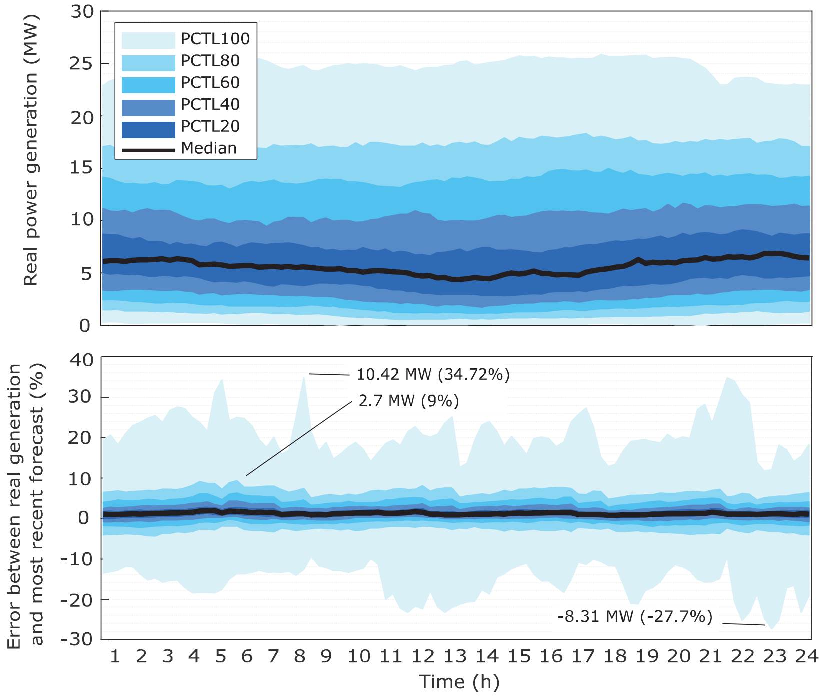


Figure 3.13 – Wind power generation.

In line with the case study for PV+ESS, several ESS sizing are also selected in order to evaluate the cost-effectiveness of the ESS for this particular application. An ESS sizing between 0.21 and 0.54 $\mathrm{MWh_{ESS}}$ per MW installed (expressed as $\mathrm{MWh_{ESS}/MW_{WP}}$), from 6.5 MW to 16.25 MW is considered for the ESS sizing sensitivity analysis. ESS aging model and market participation are the same ones considered in Table 3.1.

The proposed EMS of WP+ESS plant is analyzed and validated for a one-year simulation period. For that evaluation, a static TEA is conducted according to Spanish market rules [221], real market prices and FRR energy needs of 2017, extracted from Spanish TSO website [189]. On the one hand, annual market profits are calculated as in eq. (3.1). This equation includes revenues from DM, CIM, FRR band availability, upward energy provided and positive energy imbalances; and costs from negative imbalances, downward energy provided and FRR penalties in case of non-compliance.

On the other hand, different WP+ESS cost scenarios are defined, summarized in Table 3.3. Current investment costs of WP are considered 1.25 M€/MW reported in [225] (where *M=million*), and future Cost Reductions (CR) of 20% and 40%. Investment costs of the ESS [51], [226], [230] are considered based on energy and power terms: investment energy-related term (in M€/MWh), investment power-related term (M€/MW) and replacement energy term according to the number of replacements needed (n) during the lifetime of the WP (Y=25), whose replacement costs are reduced, according to the ESS reduction cost curve from Figure 3.4. In WP case study, market prices are maintained constant (from 2017) for other CR scenarios, in order to assess more directly the influence that the investment and replacements costs have on WP+ESS profitability.

The EMS is applied for an annual wind generation profile based on [224]. These generation profile data from the Belgian TSO (Elia) are composed by day-ahead forecast, (intra-day) updated forecast and real wind generation on a 15-minutes basis. In this case, the annual profile was scaled for a WP of 30 MW resulting in 2230 Equivalent Full-Load Hours which match properly with a great windy location in Spain.

Table 3.3 – WP+ESS costs and market prices for the techno-economic analysis

Variable, unit		**Base Case & Cost Reduction scenarios**		
		BC	**CR1**	**CR2**
WP costs, M€/MW	c^{WP}	1.25	1 (-20%)	0.75 (-40%)
ESS power costs, M€/MW	c^{MW}	0.5	0.4 (-20%)	0.3 (-40%)
ESS energy costs, M€/MWh	c^{MWh}	0.4	0.3 (-25%)	0.2 (-50%)
ESS repl. costs	c^{MWh}	$c^{MWh} \cdot \boxed{?}_{\mathrm{r=1}}^{\mathrm{n}}[1-(0.8 \cdot \mathrm{e}^{-0.11 \cdot \mathrm{yr(r)}} + 0.13 \cdot \mathrm{e}^{0.017 \cdot \mathrm{yr(r)}})]$		
DM price, €/MWh	λ_h^{DM}	2017	2017	2017
CIM price, €/MWh	λ_h^{IM1}	2017	2017	2017
Energy imb. price, €/MWh	$\lambda_h^{imb\pm}$	2017	2017	2017
Band price, €/MW	λ_h^{band}	2017	2017	2017
Upward price, €/MWh	λ_h^{uw}	2017	2017	2017
Downward price, €/MWh	λ_h^{dw}	2017	2017	2017

3.2.2 WP+ESS participation and real-time operation

The joint operation of a single day is shown in Figure 3.14. As it can be observed, DM schedule is calculated based on the DM forecast at midday. Later, a joint optimization for FRR and DM+CIM re-schedule is calculated. This CIM bid can be saved or updated later before the first CIM gate closure at 23:00. The resultant SOC profile is shown in Figure 3.14 as "reference SOC". This expected SOC profile (in black line) at that time, before the optimization day "D", has not huge fluctuations and it is maintaining around 50% SOC in order to maximize the possible SOC increments or decrements to follow the AGC signal according to hourly FRR availability bands.

Before starting the optimization day "D", an evaluation and update is made regarding the current SOC, most recent forecast profile and

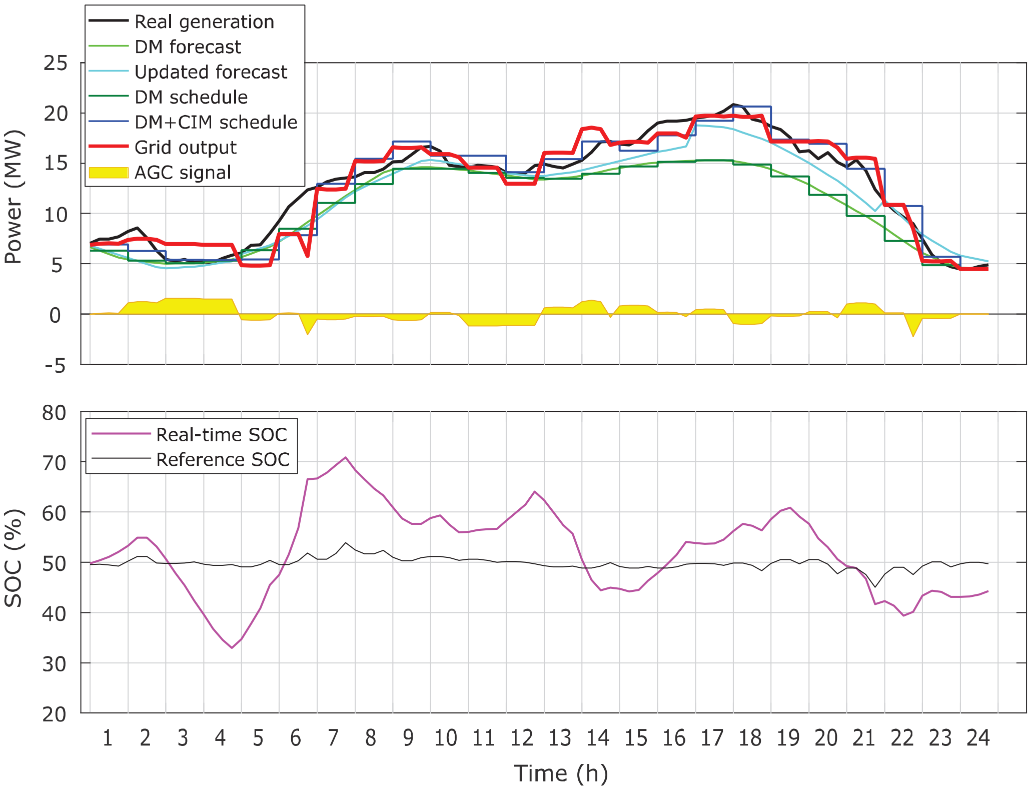


Figure 3.14 – Example of one daily real-time WP operation.

expected CIM prices. Based on this real-time information, the MILP optimization re-calculates the optimal DM+CIM scheduling for current conditions according to the objective function of eq. (2.4) for one individual plant with ESS. During the day, CIM market re-schedule bids are more influenced by the most updated WP forecast generation profile, previous WP forecast errors and large AGC needs. CIM bids are sent in successive market auction to modify the DM schedule, resulting in a final DM+CIM scheduling, with the objective of controlling the available energy of ESS and providing the grid-set points without penalties.

For this particular day, the ESS is not fully charged and discharged and it is able to control the grid output at all times. This is the main objective of the upper level control. Consequently, ESS deep discharges or charges happens only a few sample times. In most cases, the grid power set-point ($P_{r,k}^{grid*}$) corresponds to the final DM+CIM schedule plus the required AGC signal for FRR markets without energy imbalances. And this grid power set-point is equal to the final grid output ($P_{r,k}^{grid}$), according to the instantaneous RES production ($P_{r,k}^{real}$) and the final ESS power output ($P_{r,k}^{ESSout}$), as in eq. (3.3), following eq. (2.44) - (2.48).

$$\left[\ P_{r,k}^{grid*} = P_{r,k}^{DM+CIM} + P_{r,k}^{AGC}\ \right] == \left[\ P_{r,k}^{grid} = P_{r,k}^{real} - P_{r,k}^{ESSout}\ \right] \qquad (3.3)$$

3.2.3 Annual WP+ESS economic results

In order to evaluate the profitability of the WP+ESS, different ESS capacities were selected from 6.5 MW to 16.25 MW (defined in the scenario definition, Section 3.2.1) to compare the annual WP+ESS market benefits and annualized net profits (market benefits minus the annualized WP+ESS costs according to Table 3.3).

Figure 3.15 summarizes all these economic results, in which the Base Point (BP, 100%) corresponds to annualized net profits of a WP without

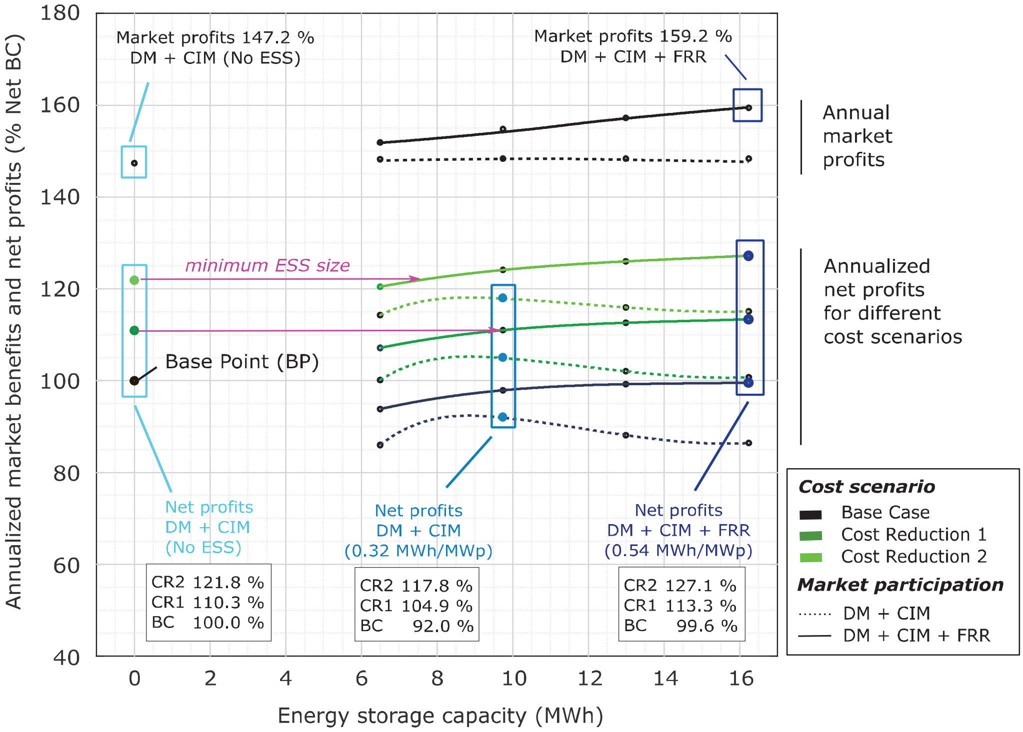


Figure 3.15 – Annualized market profits and net profits (%) for a WP of 30 MW, considering different ESS capacities (without ESS and 0.21-0.54 MWh/MW), considering 2 market participations (DM+CIM and DM+CIM+FRR) and 2 cost reduction scenarios (CR).

ESS participating in DM+CIM market. Therefore, all net profits of a WP+ESS plant are compared to the BP.

On the one hand, the profitability of the WP+ESS under Base Case (black lines, with current system costs) is analyzed. Compared to the Base Point (100%), in case of DM+CIM participation (black dotted curve), additional costs of ESS are higher than the increment due to market benefits obtained thanks to the reduction of annual energy imbalances costs. For this DM+CIM participation and considering the optimal ESS sizing in which net profits are maximized (0.32 MWh/MW, 9.75 MWh), it can be observed that annualized net profits have been reduced 8% with respect to the BP without ESS. Therefore, it can be concluded that the installation of ESS together with a WP is not profitable only with the purpose of smoothing wind generation, participating in energy (DM+CIM) markets, following the grid set-point and reducing the energy imbalances committed. Additional high-value services should be included in ESS operation in order to increase the achieved annual market profits.

Consequently, in case of DM+CIM+FRR participation, the optimal ESS capacity increases up to 0.54 MWh/MW (16.25 MWh). Net profits with this ESS sizing (99.6%) reach nearly the BC without ESS (100%), because annual market profits increase by 12% from the smaller ESS size thanks to the proportional increment of maximum FRR capacity reservation at $25\% \cdot C_r^{ESS}$ (P_r^{bmax}), defined in the upper level control following eq. (2.23).

However, the Spanish WPs nowadays participate mainly in IM auctions every 4/6 hours, and therefore, their energy imbalances costs are quite higher than the ones considered in this analysis for the BL. Thus, these annualized net profits for common WP operation could be less than net profits achieved with DM+CIM+FRR participation.

On the other hand, if several reductions of WP and ESS costs are considered (green curves, CR1 and CR2), the economic results show that the joint operation of a WP+ESS will be more profitable than a WP without ESS when FRR is contemplated.

In order to assure a more valuable option of a WP+ESS than without ESS in CR1 and CR2 scenarios, the minimum ESS sizing that should be installed is 9.75 MWh in case of CR1 scenario and 7.5 MWh in case of CR2 scenario. The future trends reveal that the best ESS capacity would be 16.25 MWh or even higher.

Focusing on all terms that composed net profits, they could be divided into benefits and/or costs related to: DM, CIM, imbalances, FRR band availability, upward AGC signal, downward AGC signal, AGC penalty, WP investment, ESS energy-related term (battery-pack investment and replacements) and ESS power-related term.

The optimal choices drawn from Figure 3.15 for Base Case for each market participation are compared in Figure 3.16 in detail:

- WP without ESS under DM+CIM participation.
- WP with optimal ESS (9.75 MWh) under DM+CIM.
- WP with optimal ESS (16.25 MWh) under DM+CIM+FRR.

As can be concluded from Figure 3.16, the usage of CIM increases when ESS is installed, because wind forecast errors are absorbed by the ESS, and then, this energy is shifted in the coming hours through higher CIM bids. Even more, FRR participation increases net CIM offers in negative sign to counteract net FRR energy required in RT (more positive than negative). Additionally, positive and negative imbalances terms are hugely reduced. Specially, energy imbalances are practically zero for DM+CIM+FRR participation with a high ESS capacity (16.25 MWh).

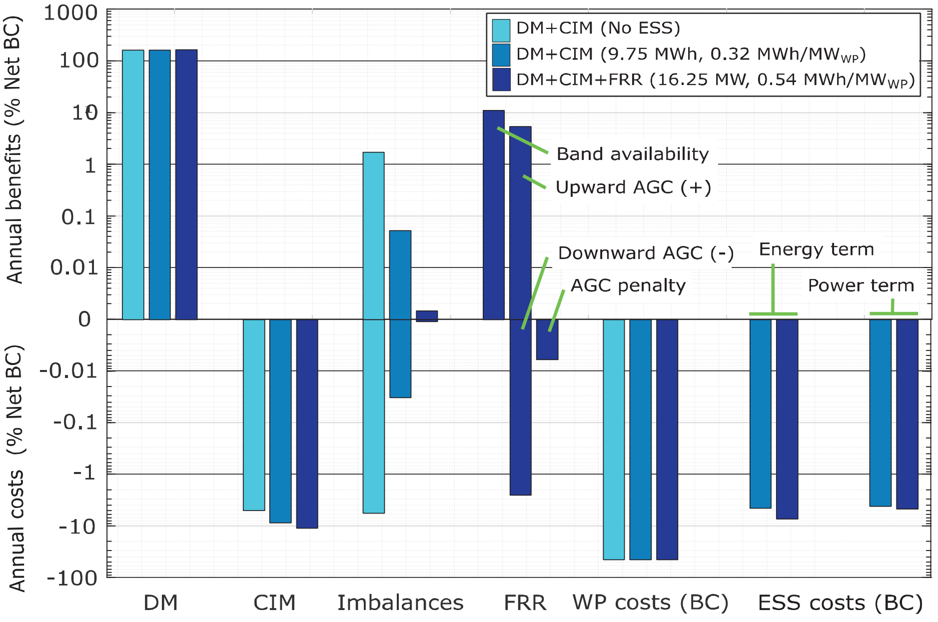


Figure 3.16 – Annual benefits and costs of the three optimal plants under the Base Case: 1) DM+CIM without ESS, 2) DM+CIM with 0.32 MWh/MW (9.75 MWh), 3) DM+CIM+FRR with 0.54 MWh/MW (16.25 MWh).

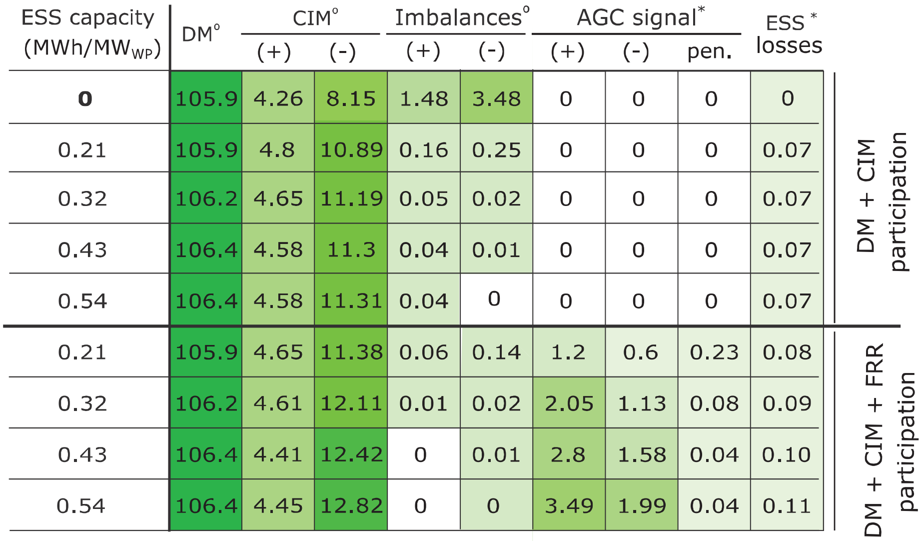
Moreover, the FRR participation increases benefits by 10.65% for band availability, 5.22% for upward AGC signal, -2.66% for downward AGC signal and -0.006% for AGC penalty. On the contrary, ESS investment and replacement costs increase the annualized costs by 7.57% for energy terms plus 4.88% for power terms, according to the third WP+ESS plant (darker bar) in Figure 3.16.

3.2.4 Annual WP+ESS technical results

Annual energy traded with respect to the annual wind generation is analyzed in Figure 3.17, with similar conclusions drawn from Figure 3.16. As can be observed, the energy traded in DM corresponds mostly to the DM generation forecast. Furthermore, the CIM participation increases or decreases in order to manage hourly energy imbalances from forecast errors and real-time AGC power signal. Regarding energy imbalances, they are reduced significantly as the ESS sizing increases. Concerning FRR service, the hourly available FRR band and the energy delivered through the AGC signal increase proportionally to the ESS capacity, because the maximum hourly band is limited up to 20% of the C^{ESS}. As can be observed, AGC penalties are also reduced in energy terms when more ESS capacity is installed. The total energy which comes from energy imbalances or AGC penalties are really trivial compared to the annual generation and the energy traded in DM, CIM and FRR markets.

Finally, ESS losses are calculated based on the ESS power profile applying the overall ESS efficiency considering all the conversion stages related to the energy storage system (95%). It can be observed that these values are relatively low compared to the annual market delivery, while the ESS helps to smooth wind generation and control their operation.

Other technical aspects that should be discussed are related to the ESS operation and the level of compliance of FRR service. Figure 3.18.a analyzes technical results regarding annual Full Equivalent Cycles. It can be observed that FECs are reduced when ESS size is larger. In case of



ESS capacity (MWh/MW$_{WP}$)	DM°	CIM°		Imbalances°		AGC signal*			ESS * losses	
		(+)	(-)	(+)	(-)	(+)	(-)	pen.		
0	105.9	4.26	8.15	1.48	3.48	0	0	0	0	DM + CIM participation
0.21	105.9	4.8	10.89	0.16	0.25	0	0	0	0.07	
0.32	106.2	4.65	11.19	0.05	0.02	0	0	0	0.07	
0.43	106.4	4.58	11.3	0.04	0.01	0	0	0	0.07	
0.54	106.4	4.58	11.31	0.04	0	0	0	0	0.07	
0.21	105.9	4.65	11.38	0.06	0.14	1.2	0.6	0.23	0.08	DM + CIM + FRR participation
0.32	106.2	4.61	12.11	0.01	0.02	2.05	1.13	0.08	0.09	
0.43	106.4	4.41	12.42	0	0.01	2.8	1.58	0.04	0.10	
0.54	106.4	4.45	12.82	0	0	3.49	1.99	0.04	0.11	

Resolution: ° Hourly net value, * For all simulation steps

Figure 3.17 – Traded energy with respect to the annual wind generation (%).

FRR participation, annual FECs increase due to a more demanding operation in order to follow AGC signal in real-time operation. Thus, annual FECs result from 501 FECs (0.21 MWh/MW) to 281 FECs (0.54 MWh/MW). According to these annual FECs, the lifetime of the ESS could be estimated between 8.6 years -181 FECs- and 13.3 years -501 FECs-, by applying Wöhler curve method and limiting the calendar lifetime up to 15 years. This means that one or two ESS replacements will be made during the WP lifetime depending of the ESS sizing.

Finally, the technical reliability of FRR participation is worth analyzing. Other studies are not focused on this parameter, while other ones address it [146]–[148] but not to the point that the power quality standards need. The developed EMS enables a huge reduction of energy imbalances and achieves a high technical reliability of upward and downward FRR needs (from 97.9 % up to 99.9%), as can be observed in Figure 3.18.b.

Moreover, the daily number of hours of FRR participation increases with the ESS size, taking into account that an hourly minimum band must be 1 MW and a maximum band is limited up to 20% of the ESS capacity. Moreover, the WP+ESS plant participates daily a maximum of 23 hours,

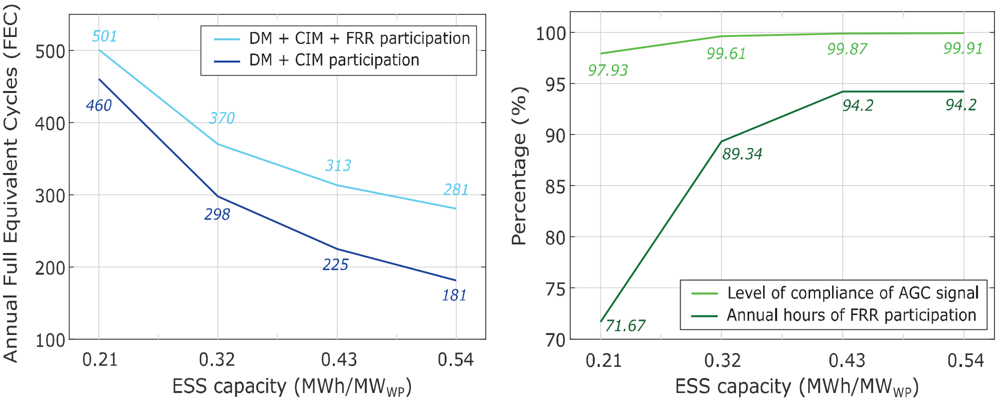


Figure 3.18 – a) Annual Full Equivalent Cycles for each market participation and ESS capacity and b) Level of compliance of AGC signal and annual hours of FRR participation.

because the last hour is destined by design to manage the final daily SOC at the middle value. Thus, the mean daily hours increase from 17.2 h (with 6.5 MWh) to 22.6 h (with 13.25 MWh).

The research presented in Section 3.2 was published in [231] by Amaia González-Garrido, Igor Villarreal, Haizea Gaztañaga, Andoni Saez de Ibarra, and Pablo Eguia “Optimized Energy Management Strategy for Wind Plants with Storage in Energy and Reserve Markets” *Journal of Physics: Conference Series, vol. 1222 (2019).* Presented at *WindEurope Conference and Exhibition*, Bilbao, April 2019.

3.3 Discussion and conclusion

As it can be concluded from above results, the joint operation of RES+ESS in multiple markets improves their economic revenues as well as the annual real-time operation. In this chapter, decentralized EMS are applied to addresses the RES integration challenge to a great extent in the grid and in the electricity market.

Through the application of the proposed EMS, the daily DM+CIM schedule and hourly bands for FRR service are calculated in order to maximize the overall market benefits, considering also the overall ESS costs which are calculated by means of the expected ESS lifetime (including cycling and calendar ageing models) regarding the ESS operation. These obtained economic results were obtained based on Spanish market framework and market prices of 2017, with the aim of evaluating the cost-effectiveness of the ESS for PV and WP applications.

Regarding PV+ESS operation, the proposed EMS enables controlling the SOC profile, avoiding energy imbalances and achieving a high level of compliance of AGC signal (up to 99.95%) for this case study with the installation of an ESS of 0.54 MWh/MWp. However, the installation of ESS does not increase the profitability of the PV facility, due to the low penalization of current energy imbalances. Under a considerable reduction of cost and an increase on market prices, the installation of an ESS of 0.54 MWh/MWp would be more profitable than no ESS integration.

In case of WP+ESS, the implementation of the EMS enables the avoidance of annual energy imbalances and achieves a high technical reliability of FRR needs (up to 99.91%) with an ESS sizing of 0.54MWh per MW of wind power capacity installed for the study case, and an expected ESS lifetime of years. Under a light reduction of these ESS costs (around -25%), the joint operation of a WP+ESS plant could be more profitable than a WP without ESS.

Focusing on technical results, it can be observed than there is a hugely reduction of energy imbalances, and light FRR non-compliance. The introduction of a larger ESS improves more RT operation performance and it is expected to require one replacement, while two replacements are required with smaller ESS. Thanks to the economic analysis, the most profitable ESS sizing is assessed according to market benefits and overall systems costs which include acquisition, operation and replacement costs.

Chapter 4 EMS oriented to a RES+ESS portfolio

Further development on the coordination of a RES+ESS portfolio can be considered to improve the techno-economic results. As a result, a global EMS for the asset management is applied to improve the profitability. Chapter 4 evaluates the application of the proposed EMS for a portfolio composed entirely by RES with ESS in multiple markets to increase the value of RES energy.

The main objective is to maximize the portfolio profitability, finding a trade-off between market revenues, overall storage costs and a reliable operation. This proposed EMS strategy is based on two-level architecture. In the upper level, the optimization process described in Section 2.3 is applied for both RES+ESS. MILP optimization is applied to calculate the optimal daily joint market bidding in energy markets and reserve markets, while it avoids expected energy imbalances and penalties. These optimal market schedules are calculated and updated during the day considering renewable forecast, market design and requirements and constraints related to the limited storage capacity.

While in the lower level, a decision-making process, explained in Section 2.5.2, is applied in RT operation according to three different portfolio controls: decentralized (or individual), cooperative and centralized. While an individual RES+ESS plant must be operated decentralized, RES+ESS portfolio with distributed ESS can be also operated in a cooperative or centralized way to provide the both grid power set-points according to the total available RES generation and ESSs' stored energy, with the objective of minimizing SOC changes, reducing ESS usage, and extending their lifetimes, taking into account RES complementarity, SOC equalization techniques and sharing AGC signal in case of non-compliance.

Firstly, a preliminary TEA is carried out to evaluate and compare these portfolio supervisory controls with fixed ESS capacities (from optimal ESS sizing for Chapter 3). Finally, a Levelized Cost of Energy (LCOE) analysis is carried out in which several ESS capacities and market participation strategies are selected in order to evaluate the cost-effectiveness of the ESS operation with RES portfolio.

4.1 Scenario definition for a RES+ESS portfolio

Chapter 4 presents the main techno-economic results of the developed EMS for a renewable portfolio for the optimal joint participation in energy and reserve markets. The main objective is to maximize the portfolio profitability, finding a trade-off between market revenues, overall storage costs and a reliable operation.

This proposed EMS is based on two-level architecture, described in Chapter 2. Particularly, in the lower level control, a decision-making process is applied in real-time operation, where three different portfolio supervisory controls are described and compared (decentralized, cooperative and centralized), which include RES complementarity and SOC equalization techniques in a novel approach. The methodology developed in RT operation is described in Section 2.5.2.

The case study is focused on a RES portfolio composed by a PV plant, a WP plant and their associated ESSs. The installed renewable capacity is 30 MW per technology according to the average size of Spanish RES facilities. Moreover, initial 13MWh and 17MWh ESS capacities are defined for PV and WP respectively in accordance with conclusive results

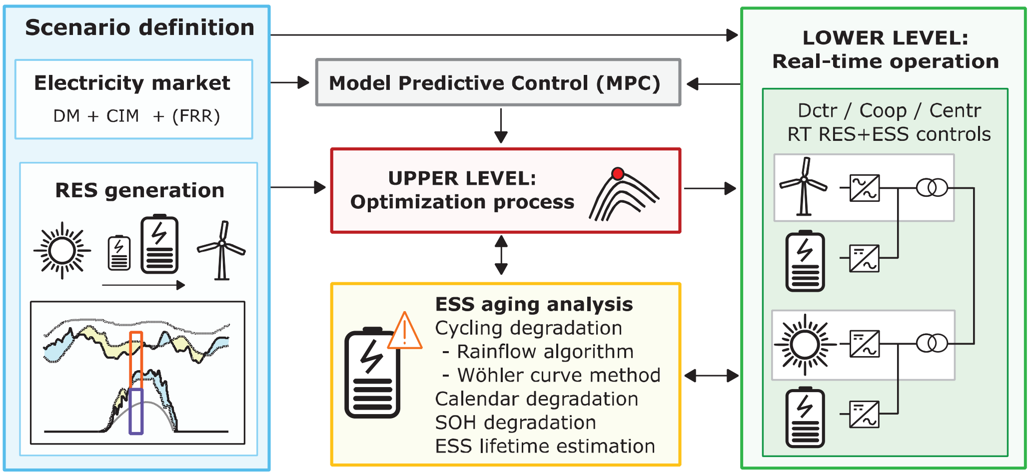


Figure 4.1 – Proposed RES+ESS portfolio Energy Management Strategy.

exposed in previous Chapter 3, applying decentralized or individual RT control. Annual RES generation is extracted from [224], and adjusted to Spanish Full-Load Hours (FLH) per MW installed of 1560.8 FLH for PV (with a Capacity Factor of 17.8%) and 2230.6 FLH for WP (with a Capacity Factor of 25.4%). The RES generation data are the same profiles in previous Chapter 3 for decentralized EMS for individual RES+ESS. Table 4.1 summarizes the selection of ESS capacity for each RES plant. Table 3.1 summarizes other design ESS variables defined previously.

A techno-economic assessment is conducted according to Spanish market rules and real prices of 2017, as reported [189],[192]. One-year simulation period has been selected to compare the RT technical performance of each portfolio control, in terms of the annual traded energy in each market, hourly FRR capacity band, annual FECs, the ESS degradation, State of Health and lifetime. The LCOE is calculated by levelized portfolio investment and replacement costs and the levelized energy generated.

Moreover, a static cost benefit assessment is presented according to annualized portfolio market profits and overall RES+ESS costs. Finally, the portfolio market revenues per MWh are compared to several Levelized Costs of Energy (LCOE). LCOE is calculated by levelized portfolio investment and replacement costs and the levelized energy generated. LCOE [232] evaluates the minimum market price at which RES production can be sold in order to achieve a profitable asset exploitation, according to eq (4.1) and (4.2).

Table 4.1 – Scenario definition of RES+ESS portfolio.

Scenario	Unit	Fixed value	ESS sizing
ESS nominal capacity for PV	C_r^{nom}	C_r^{ini} =13 MWh (optimal ratio: 0.43)	0 MWh, C_r^{ini}, - 50% $\cdot C_r^{ini}$, - 25% $\cdot C_r^{ini}$ + 25% $\cdot C_r^{ini}$
ESS nominal capacity for WP	C_r^{nom}	C_r^{ini} =17 MWh (optimal ratio: 0.54)	
Market participation	DM, DM + CIM and DM + CIM + FRR		

$$LCOE = \frac{\Sigma_{y=1}^{Y}\left[\dfrac{I_O \cdot CRF + (OV_y + OF_y) \cdot (1 + CPI)^y + R_y^{ESS})}{(1 + d)^{-y}}\right]}{\Sigma_{y=1}^{\mathrm{Y}}\left[\dfrac{G_y}{(1 + d)^{-y}}\right]} \quad (4.1)$$

$$CRF = \frac{i \cdot (1 + i)^{\mathrm{Y}}}{(1 + i)^{\mathrm{Y}} - 1} \quad (4.2)$$

RES investment costs (*Io*) [225],[233] of 1.25 M€/MW for WP and 0.75 M€/MW for PV are considered (without including yet financing costs), as Chapter 3. Moreover, ESS acquisition costs are divided in energy and power-related terms according to EPRI convention [51], [226], [230]: 0.3 M€/MWh and 0.4-0.2 M€/MW.

Moreover, total ESS replacement costs of both plants (R_y^{ESS}) are calculated according to the number of replacements needed (*n*) during the lifetime of the renewable asset (RES lifetime *(Y)* is considered 25 years). These ESS replacement costs are calculated from a reduction cost curve according to the expected ESS replacements from Figure 3.4.

Regarding operations and maintenance (O&M) costs, annual fixed and variable O&M (OF_y, OV_y) costs are also considered according to [233],[232], adding a Consumer Price Index (CPI) of 1.2%: 20.000€/MW for PV OF_y, 25.000€/MW for WP OF_y and 2 €/MWh for WP OV_y, where the CPI is 1.2%. Finally, a reduction of 0.025% per year is included for PV generation (G_y). Annual WP generation is assumed to remain constant.

The Capital Recovery Factor (CRF) expressed as in eq. (4.2) allows annualizing the investment costs (*Io*) considering a discount rate (*d*) and taking into account the lifetime of the whole project, which includes above RES+ESS investment costs. A discount rate is used to calculate the present value of future payments in the LCOE formula. In this case the discount rate (*d*) can be assumed equal to the interest rate (*i*), varying for example from 0% up to 5.5%. Table 4.2. summarizes all costs.

All considered RES+ESS costs are summarized in Table 4.2 below, in which investment and O&M costs are included (where *M=million*).

LCOE enables to compare the levelized costs of the renewable energy generated compared to the achieved revenues for the total energy delivered through the market. Figure 4.2 shows the final market price of 2017, in which 88.2% of the final price (60.55 €/MWh) corresponds to the DM and IM market price (weighted annual value of 53.41 €/MWh).

Table 4.2 – RES+ESS costs for the techno-economic analysis

RES+ESS costs		**Investment (without financing)**	**Fixed O&M**	**Variable O&M**
PV costs, M€/MW	c^{PV}	0.75	20.000€/MW	-
WP costs, M€/MW	c^{WP}	1.25	25.000€/MW	2 €/MWh
ESS power costs, M€/MW	c^{MW}	0.4 (Section 4.2) 0.2 (Section 4.3)	-	-
ESS energy costs, M€/MWh	c^{MWh}	0.3	-	-
ESS repl. costs	c^{MWh}	$c^{MWh}\cdot\sum_{r=1}^{n}[1-\left(0.8\cdot e^{-0.11\cdot yr(r)}+0.13\cdot e^{0.017\cdot yr(r)}\right)]$		

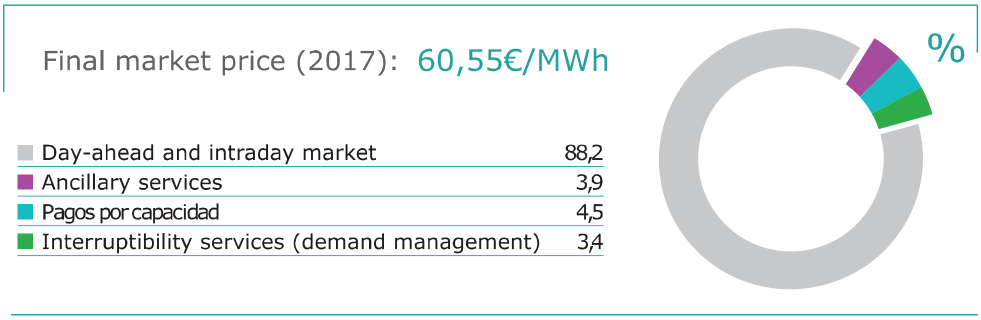


Figure 4.2 – Final price composition (in 2017) according to energy markets, ancillary services, capacity payments and interruptibility services. Source: REE

4.2 Techno-economic results with fixed ESS sizing

This section presents the results of the developed EMS for a renewable portfolio with fixed ESS for their joint participation in multiple markets.

Without FRR participation, Energy Markets (EM = DM+CIM) scheduling tries to follow latest forecast and manage RES intermittency in order to maximize market revenues and minimize energy imbalances, taking into account also expected market prices and ESS degradation costs. Each RES+ESS plant operates according to its optimal schedule with a Dctr control. As can be observed in Figure 4.3, when RES+ESS plants participate in FRR service, they should provide the AGC signal in RT operation (another uncertain RT parameter in addition to RES forecast), and thus, more unexpected energy deviations appear in SOC.

To avoid a complete ESS discharge or charge, successive CIM bids are sent to counteract these large energy deviations. For example, when upward AGC signal is required, SOC may as well be below the optimal value (low SOC). Thus, EM schedule in following hours tends to reduce in order to charge the ESS. However, in some circumstances under extreme RT requirements (like 6th hour), the ESS associated with WP is fully discharged. As can be observed the DM wind generation forecast (grey profile) was really high, and CIM forecast (the most recent forecast) is also high compared to real wind generation for previous hours. After consecutive hours with low wind generation in addition to the high upward AGC required, the ESS associated to the wind farm is fully discharged. Consequently, the PV+ESS provide all portfolio's AGC signal and FRR compliance is achieved (in Coop and Centr controls).

In contrast, FRR penalties are produced at this time with Dctr control. In Dctr control, the PV+ESS does not provide the AGC associated to the WP+ESS, and vice versa, and therefore, FRR penalties are committed when one ESS is fully charged or discharged.

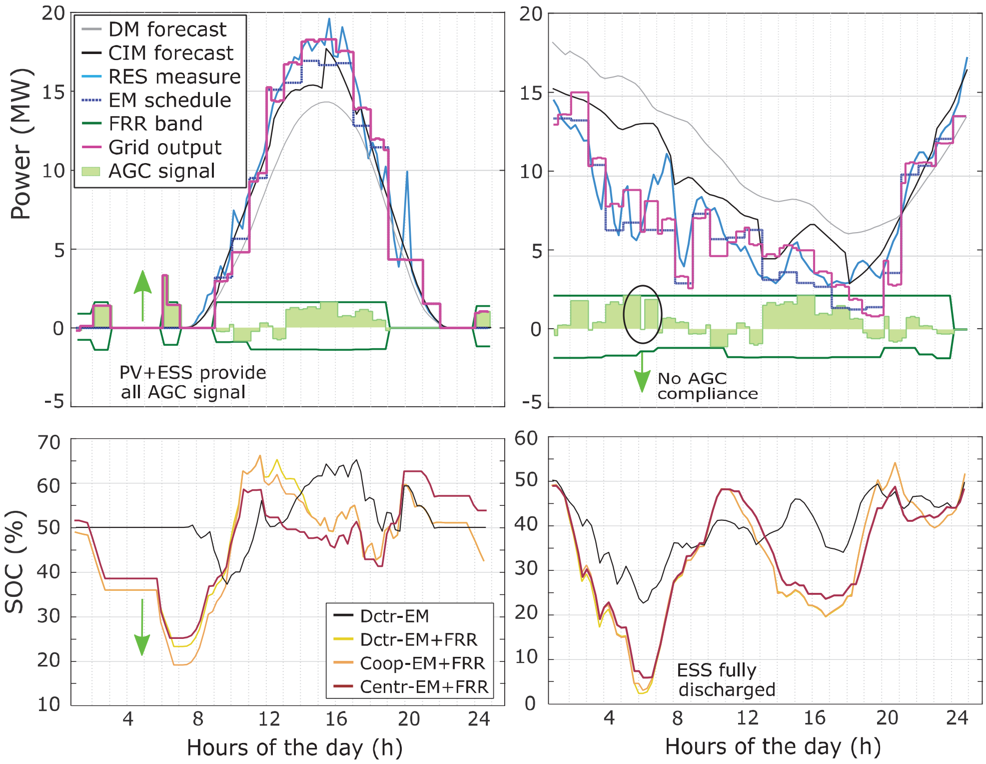


Figure 4.3 – Daily market operation for Centr control and comparison of ESS SOC profile (%) for all RT portfolio supervisory controls.

All RES generation is delivered through several markets. The details for energy traded can be seen in Figure 4.4. Energy is sold in DM according to the expected forecast (104.58% of the real RES generation), CIM (expressed in net daily values), and AGC signal according to FRR bands assigned in auction.

In addition to the energy delivered through EM and FRR markets, some energy imbalances and FRR penalties might be committed, and ESS losses should be taken into consideration. It can be highlighted that FRR penalties are avoided in Coop and Centr, while Dctr penalizes 4.75h (PV) and 3h (WP) out of 12129 h/year (both RES plants participate in FRR around 70% hours per year). These values are extremely low because the selection of ESS capacities (13 MWh and 17 MWh) were optimized to maximize PV+ESS and WP+ESS profitability in which FRR penalties are almost minimized, and also when each plant operates in Dcntr control.

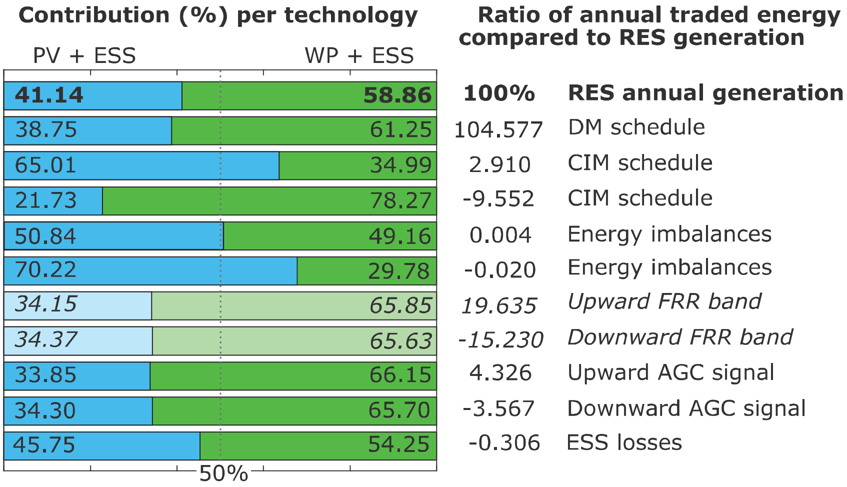


Figure 4.4 – Ratio of annual traded energy compared to annual RES generation (%) and the contribution per technology (%).

Other conclusions that can be drawn from Centr control compared to other controls is that CIM schedule, energy imbalances and ESS losses are also reduced. In particular, ESS losses for Centr control is 0.3% compared to 0.35% for Coop and Dctr. In energy terms, 161 GWh and 191 GWh are lost from each ESS for Coop and Dctr control, compared to 118 GWh and 221 GWh, compared to the annual solar (46.8 TWh) and wind (66.9 TWh) energy generated, respectively. These improvements are the result of an annual RES complementarity of 29% and the centralized control which minimizes the ESS usage in RT operation.

Regarding FRR participation, mean daily hours for PV and WP are 13.6h (56.8%) and 19.6h (81.63%) respectively. The mean, median and hourly percentiles for both RES plants can be observed in Figure 4.5. Some constraints in the optimization model of Section 2.3 limit the hours of participation: in case of PV plant, excessive or consecutive hours during nighttime are limited based on energy capacity limits following eq. (2.24) and (2.25) in the optimization model. In case of WP generation, there is a lower bound for hourly FRR participation which corresponds to 5% of the installed wind capacity. Moreover, the final daily SOC should be

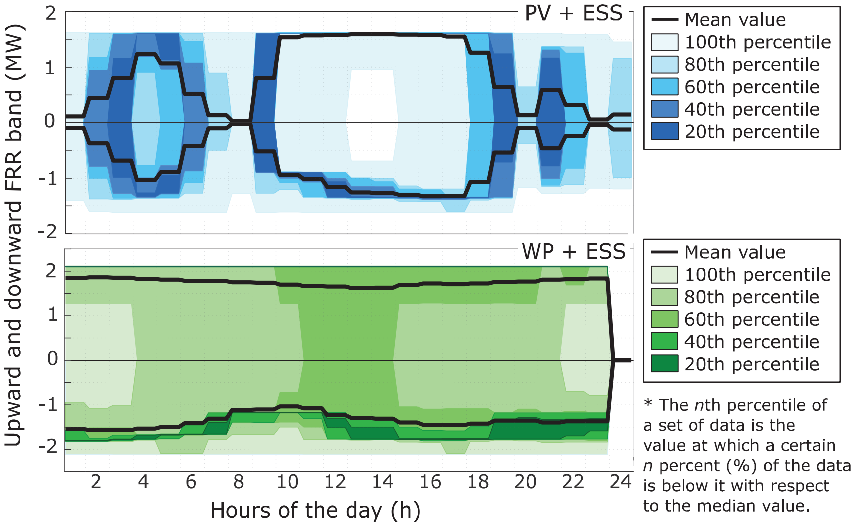


Figure 4.5 – Upward and downward FRR band (MW) for Centr control.

settled at 50% of the last hour of the day as eq. (2.15).Apart from all these energy constraints, ESS power and energy limitation, maximum and minimum hourly FRR band capacity and other constraints from the optimization formulation in Section 2.3 are applied.

Another important issue to analyze in the techno-economic assessment is ESS degradation costs that can be estimated according to cycling and calendar aging models. One of the main indicators to evaluate the ESS aging is the Full Equivalent Cycles (FECs) per year. According to Figure 4.6.a, FECs increase with FRR participation, because the usage of the ESS is higher to fulfill EM and FRR requirements. As can be concluded and demonstrated through an annual portfolio simulation, Centr control reduces FECs compared to the other controls.

This Centr control provides the total grid power set-points (sum of both RES plants) according to the total available RES generation and the initial required ESS power, with the objective of reducing ESS usage, by minimizing SOC changes. For example, if the grid power set-point of the PV plant is less than what PV is generating, its associated ESS will be charged. In contrast, if the grid power set-point of the WP plant is much more than what WP is generating, its associated ESS will be discharged with more energy than the energy that the ESS associated with the PV is charging. In both situations, ESS losses are produced due to the charge and discharge processes.

Therefore, the Centr control decides that instead of charging the ESS associated to the PV and discharge the ESS associated to the WP, the PV+ESS will be on charge of some energy on behalf of the WP+ESS. In this way, the WP apparently will generate more and its ESS will be discharged less. In conclusion, the energy losses associated with the ESS are reduced, and their annual ESS cycles will be reduced, extending their lifetime. This methodology can be found in the definition of RT portfolio supervisory controls in Section 2.5.2. Table 4.3 provides a simple example for a better understanding of Centr control.

Apart from ESS cycles, ESS sizing has also a direct impact on the resultant annual FECs (more ESS sizing, less FECs). Thus, it can be concluded that the ESS associated to the WP is larger, so WP operation is more energy demanding (to manage WP fluctuations and FRR participation). From Figure 4.6.b, it can be noted that the State of Health (SOH) decreases in accordance with the number of FECs. Therefore, the annual ESS expected lifetime is reduced when participating in FRR.

Nevertheless, market revenues in these scenarios are much higher than the incremental ESS aging costs as will be seen later. It is worth noting that, when Centr control is applied, SOH and ESS lifetimes increase compared to other controls. Thus, ESS replacement costs will be reduced.

Table 4.3 – Example of RES equalization for Centralized control.

Grid set-point		Dctr / Coop				Centr				
	$P^{grid*}_{r,k}$	$P^{real}_{r,k}$	$P^{ESSout}_{r,k}$	loss	$P^{ESSin}_{r,k}$	ΔP_r	$P^{real*}_{PV,k}$	$P^{ESSout}_{r,k}$	loss	$P^{ESSin}_{r,k}$
PV	8*	9	-1(dc)	-0.1	-1.1	1	8*	0	0	0
WP	12*	10	2 (ch)	-0.2	1.8	-2	11*	1 (ch)	-0.1	0.9
Total	20*	19	1	-0.3	0.7	x	19	1	-0.1	0.9

Concerning portfolio profitability, a preliminary static cost benefit assessment is carried out in Figure 4.7, without considering interest rate or inflation rate. The highest annual market revenues are achieved with Centr control. However, as the market design does not encourage RES plant to follow their EM schedule (dual pricing system for imbalances [33], [234]) and it does not highly penalize the FRR non-compliance, the increase on market profits for better RES performance is highly limited. When all RES investment and O&M costs are considered, annual net portfolio profits increase by 21% applying the Centr control participating in EM+FRR compared to the Dctr control without FRR market.

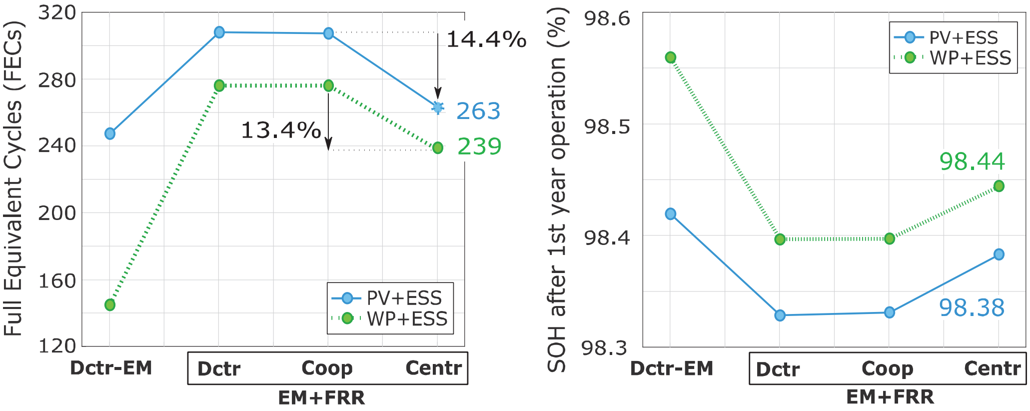


Figure 4.6 – a) Full Equivalent Cycles (FECs) and b) State of Health (SOH).

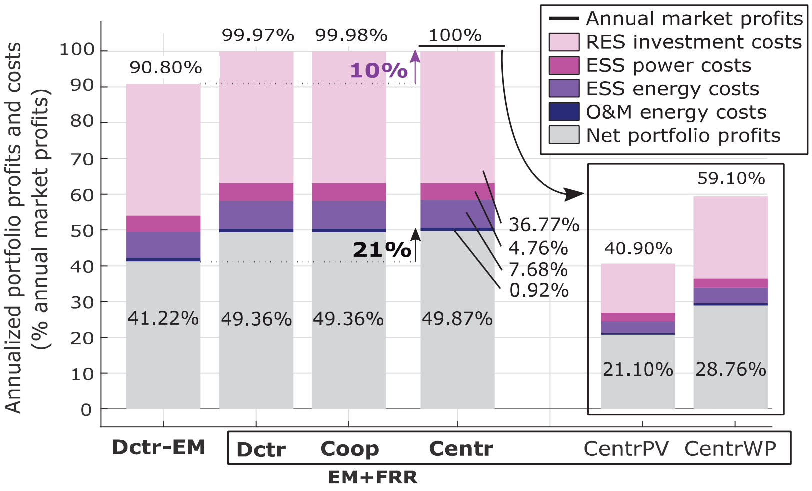


Figure 4.7 – Static cost-benefit assessment for all controls.

As it can be observed in Table 4.4, market revenues per MWh generated (52.02 €/MWh) are similar to the annual DM price (average of 52.24€/MWh and weighted of 53.41€/MWh [189]) when participating only in Dctr/EM case. If EM+FRR participation is carried out, the revenues increase up to 57.38 €/MWh with Centr. Thus, the participation in multiple markets gives more value to the RES portfolio and increases the value of RES generated energy by 5.37 €/MWh (increase of ~10%).

Finally, the LCOE for different controls and interest rates can be discussed. As the interest rate (i) increases, LCOE increases (up to 56.99 €/MWh with i=4% in case of Centr/EM+FRR). RES exploitation may result non-profitable with higher interest rate than 2.95% when it participates only in energy markets (Dctr/EM), whereas participating in EM+FRR, the Internal Rate of Return (IRR) is near to 4%. The IRR is a metric used in capital budgeting to estimate the profitability of potential investments. The IRR is a discount rate that makes the net present value of all cash flows from a particular project equal to zero.

Consequently, the LCOE does not surpasses market revenues per MWh generated when Centr control is applied under an interest rate below 4%. Thus, it could be concluded that the portfolio market operation under the case study is profitable when optimal EMS is applied to participate

Table 4.4 – Revenues per MWh generated (R/MWh), and levelized cost of energy (LCOE) for all portfolio supervisory controls.

RT control and market participation	Revenues (R/MWh)	Levelized cost of energy (LCOE)			
		i = 0%	i = 1.07%	i = 2.5%	i = 4%
Dctr/EM	**52.02**	**40.56**	**44.46**	**50.16**	**56.70**
Dctr/EM+FRR	57.27	40.91	44.87	50.65	57.28
Coop/EM+FRR	57.27	40.92	44.87	50.65	57.28
Centr/EM+FRR	**57.38**	**40.74**	**44.66**	**50.41**	**56.99**
Centr/PV	57.02	39.76	43.55	49.08	55.42
Centr/WP	57.64	41.40	45.42	51.30	58.06

in energy and reserve markets and the most rewarding techno-economic results are reached when Centr control is applied.

On the basis of the above techno-economic assessment, it could be concluded that Centr portfolio supervisory control, which manages all RES resources more efficiently, will enhance the RT operation of the renewable asset, as well as improving the portfolio profitability. On the one hand, Centr control enables to avoid FRR penalties (fully compliance of AGC signal) and reduce energy imbalances and ESS losses. On the other hand, the participation of RES portfolio in high-value services like FRR market increases the revenues per MWh generated up to 57.38 €/MWh. The expected LCOE under most unfavorable scenario (with high interest rates) is expected not to be higher than the expected market revenues per MWh. Thus, these economic results present a profitable RES+ESS exploitation.

This analysis has been carried out with fixed ESS capacities according to Dctr control of PV+ESS and WP+ESS. Therefore, one step forward is to analyze the optimal size of ESS for the portfolio management when Centr control is applied. The cooperation of several RES+ESS would enable to reduce the ESS capacity required while the same reliable standards are maintained in RT operation, such as, energy imbalances or FRR penalties. Furthermore, this analysis will also enable to assess the improvement of Centr control on market performance as function of the ESS capacity. As a result, the portfolio profitability would be increased if the optimal ESS sizing is selected, and combined short-term and long-term EMS are applied, including optimal market bidding and centralized RT controls.

The research presented in Section 4.2. was published in [235] by Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Techno-Economic Assessment of Energy Management Strategies for a Renewable Portfolio with Storage Systems in Energy and Frequency Reserve Markets" *2019 16th International Conference on the European Energy Market (EEM)*, Ljubljana, Sept. 2019. Best paper award

4.3 ESS sizing analysis for a RES+ESS portfolio

In this section, the final techno-economic results are discussed. The developed EMS is evaluated for a renewable portfolio with variable ESS for the optimal joint participation in energy and reserve markets. A sensitivity analysis of the ESS sizing is carried out to show the technical improvements of Centr control on the market performance and reliable provision of FRR requirements in RT operation. Moreover, the optimal ESS capacity can be identified regarding VPP profitability.

The main techno-economic results are presented along this Section 4.3. On the one hand, some technical aspects are analyzed and compared from both considered portfolio supervisory controls in line with previous Section 4.2, such as annual RES forecast errors, FRR capacity band, energy imbalances, FRR penalties, and ESS aging.

On the other hand, Levelized Cost of Energy (LCOE) analysis is carried out in which several ESS capacities and market participation strategies are selected in order to evaluate the cost-effectiveness of the ESS operation with RES portfolio.

As previous researches, the techno-economic assessment is conducted for one-year simulation period according to Spanish market rules and real prices of 2017 in order to compare the performance of each portfolio.

Firstly, renewable VPP without ESSs is simulated under DM and DM+CIM participation to evaluate the influence of forecast information. Secondly, a VPP with total 0.5h of ESSs (initial 100% CESS which corresponds to 13 MWh for 30MW PV and 17 MWh for 30MW WP) -in DM+CIM and under Dctr control- is analyzed in order to show the technical advantages of ESS to support RES market participation and operation. This EMS is the same followed in Chapter 3.

Thirdly, the potential of FRR participation is evaluated under two RT controls: Centralized (Centr) and Decentralized (Dctr). Cooperative control (Coop) is omitted from this final techno-economic analysis, since its RT operation is quite similar to Dctr control, despite the AGC signal is shared at a few times to reduce the FRR non-compliance. Coop control operates equal to Dctr control under normal conditions, and each RES+ESS plant only shares the provision of the AGC signal in case of one ESS is fully (dis)charged, which happens a limited times per year.

As explained in Section 2.5.2, Centr control takes advantage of RES complementarity (when one RES plant produces more than expected, and the other one less than expected). RES generation profiles from [224] have a complementarity of 29% over one year simulation. Due to this fact, as can be observed in Figure 4.8, the joint portfolio forecast errors per total installed RES capacity (60MW) is less than the sum of each RES forecast error independently considered. It can be noticed that portfolio forecast power error does not exceed 6.5% from 60 MW RES installed, with a pctl-80% for one-time step. This maximum forecast power that occurs in a period of time of 15-min may result in a SOC change of 3.25% for one-time step from the ESS capacity of 30 MWh, or 13% if the forecast error is maintained for an hour.

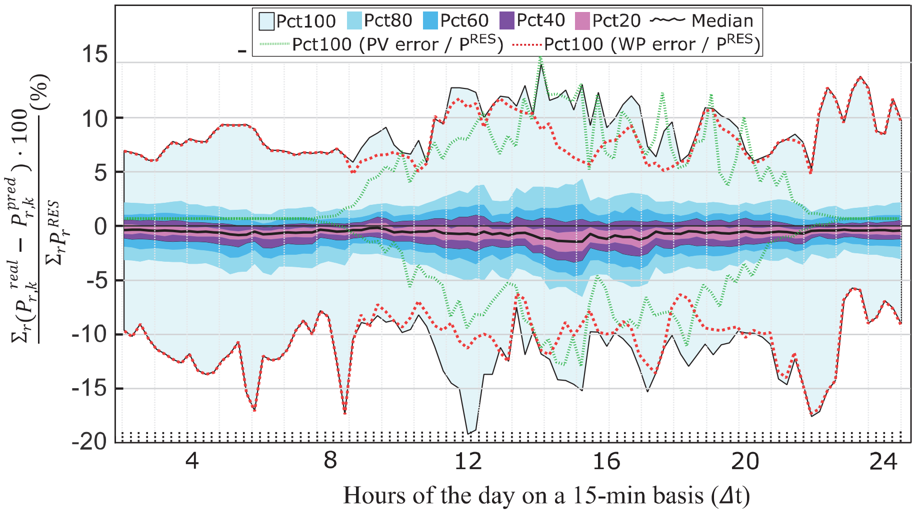


Figure 4.8 – Joint forecast errors (% RES installed)

4.3.1 Comparison of portfolio technical results

Technical results are exposed and discussed firstly, in order to carry out a comparison of different RT controls and assess the improvement of some of them. Analyzing more in detail the annual energy imbalances, it can be noticed from Figure 4.9 that absolute energy imbalances (positive plus negative ones) are around 6.65% with DM participation without ESS, and reduced up to 4.81% with DM+CIM participation (which considers more recent intra-day generation forecasts extracted from [224]). Moreover, it can be concluded that the joint operation in a VPP+ESS reduce annual energy imbalances below 0.2%, due to the forced strategy in eq. (2.4).

Besides RES forecast unpredictability, the provision of AGC signal increases the real-time SOC deviation from the expected SOC profiles. In order to manage both sources of uncertainties and maintain safe SOC limits, a constraint in the hourly maximum FRR capacity reservation (P_r^{bmax}) is defined as $25\% \cdot C_r^{ESS}$ according to eq. (2.22), as can be seen in Figure 4.10. In order to conduct a fair analysis, this limit is maintained proportional for each ESS capacity. As can be observed, PV does not participate in FRR market in the night-time hours and WP in hours with hourly generation less than 5% of wind installed capacity.

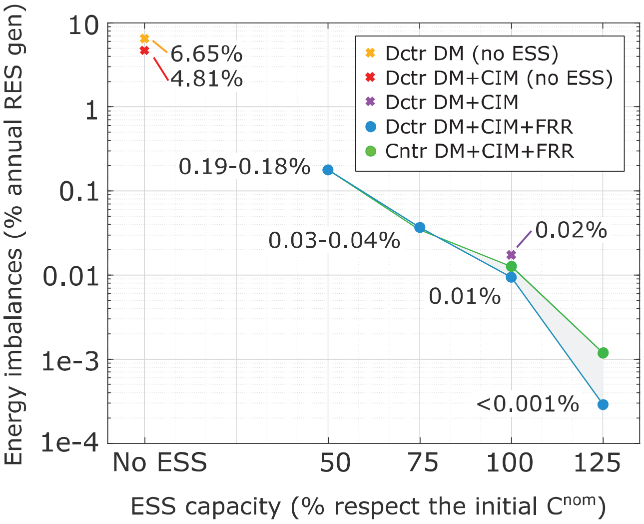


Figure 4.9 – Annual absolute energy imbalances.

Regarding FRR penalties, it can be observed in Figure 4.11 that the smaller ESS capacity is, the more FRR penalties per year are incurred. FRR penalties approach 2.5-1.3% with 50% of initial C_r^{nom}. Afterward, these annual FRR penalties are hugely reduced with Centr control compared to Dctr control. Thus, it can be concluded that a Centr control improve the FRR penalties for any RES technology and any ESS sizing.

Another important factor which influences the VPP profitability is ESS

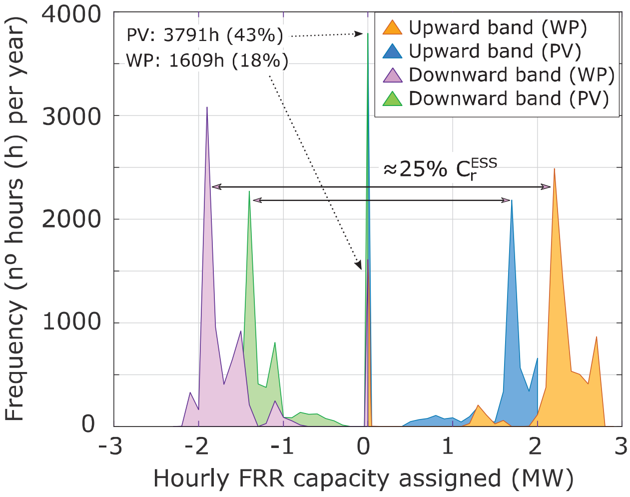


Figure 4.10 – Total band assigned for 100% initial CESS.

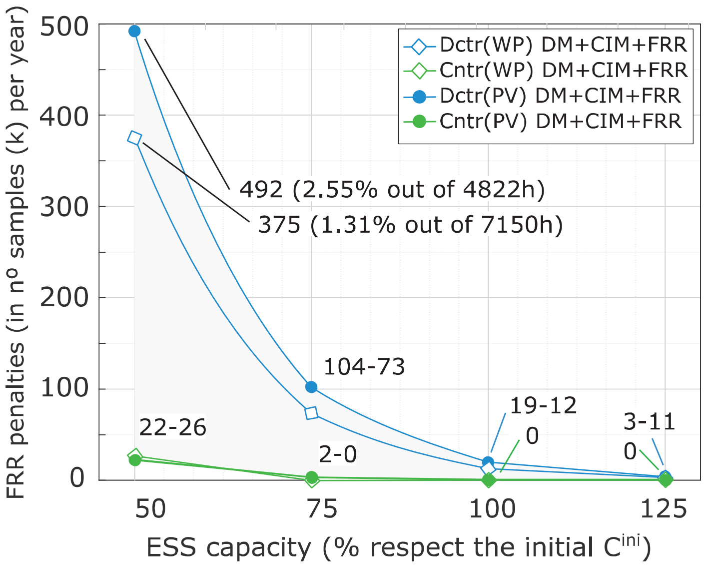


Figure 4.11 – FRR penalties (nº samples k per year).

degradation costs. One of the main indicators to evaluate the ESS aging is the Full Equivalent Cycles (FECs) per year. According to Figure 4.12, FECs increase with FRR participation, because the usage of the ESS is higher to fulfill market schedule and AGC signal. However, thanks to a Centr control the annual FECs are reduced around 15%, reducing the demanding operating conditions. Moreover, it can be observed that the FECs increase with smaller C_r^{nom}, due to the same value of charge or discharge power ($P_{r,k}^{ESSout}$) produces a larger change of SOC

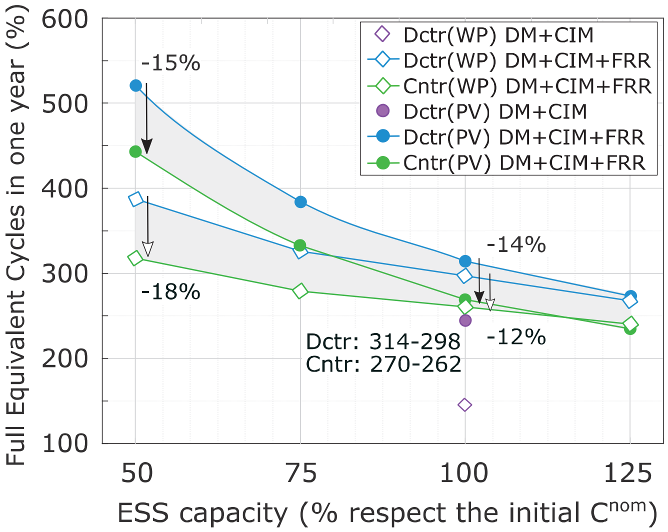


Figure 4.12 – FECs (nº of cycles per year).

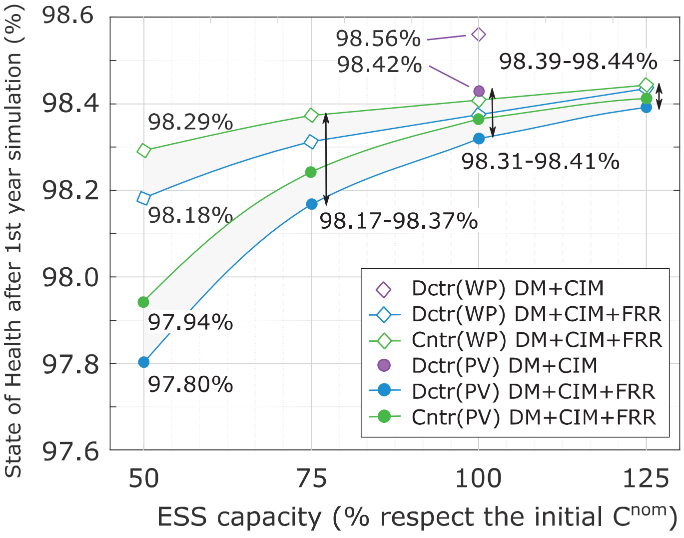


Figure 4.13 – State of Health after one year (SOH, %).

in smaller ESS capacities, while FECs are reduced with higher ESS capacities. Likewise, the State of Health (SOH) after one year is depicted in Figure 4.13. Annual SOH decreases in accordance with the number of FECs, where the smaller ESS undergo a stronger capacity fade. Moreover, the expected ESS lifetimes are reduced when participating in FRR. Nevertheless, it is worth noting that, Centr control enhances SOH and ESS lifetimes compared to Dctr control.

4.3.2 Comparison of portfolio economic results

Finally, a complete techno-economic assessment for different portfolio market participation, ESS sizing, RT supervisory controls and interest rates is carried out. Table 4.5 summarizes the annual market revenues, the market revenues per MWh generated, the LCOE for different interest rates and the net profits.

Annual market revenues are calculated according to Spanish market rules and real prices of 2017. It can be observed that DM+CIM participation is the main source of revenues. It can be concluded that the energy imbalances costs committed are considerable without ESS (relative value from positive and negative energy imbalances economic results), while their costs are reduced to a great extent when CIM participation is considered, and almost avoided with ESS integration.

After the CIM participation, the annual market revenues increase slightly due to the reduction of imbalances costs. Moreover, it may be clarified that the market revenues after the integration of ESS in DM+CIM are slightly reduced (52.02 compared to 52.14€/MWh) due to lower CIM prices and the ESS losses, although imbalances costs are hugely decreased (from 128.8 to 1.8 k€/yr). When DM+CIM+FRR participation is considered, annual market revenues increase more than 5 €/MWh from the initial ESS sizing. And furthermore, annual market revenues increase more in case of centralized control is applied, and even more with larger ESS capacity. Therefore, the market revenues per MWh generated increases in case of considering higher ESS capacities: from 55.08 €/MWh with small ESS to 59.05 €/MWh to largest ESS.

In light of the above results, the LCOE obviously increases in case of considering ESS integration, due to the energy generated is almost maintained in all cases, but the ESS acquisition, operation and degradation costs increase. On the one hand, the LCOE without ESS reaches 38.62 €/MWh. On the other hand, the LCOE with ESS capacities is comprised between 41.50 and 44.33 €/MWh without interest rate i.

However, when the interest rate i increases, the LCOE could reach up to 66.62 €/MWh (with 125% C_r^{nom} and i =5.5%). It can be noted that the interest rate, applied to the investment costs, increases the CRF value, and consequently, the LCOE is increased.

Net annualized profits (in €/MWh) can be used to compared LCOE and market revenues to identify the most profitable VPP configuration. With i less than 2.5%, the integration of ESS could be a profitable decision for the renewable portfolio under current investment costs, considered O&M costs and real market prices. Moreover, ESS contributes to all these technical improvements in the operation, such as, the avoidance of energy imbalances and the participation of FRR to maintain system frequency. In case of higher i, the renewable portfolio without ESS results more profitable in case of DM+CIM participation.

With i more than 4%, renewable portfolio should need any kind of financial or government support, such as reasonable feed-in-tariff (FIT) schemes, some tax exemptions or deductions, incentives for RES investment, additional retribution associated to RES operation or annual generation, definition of suitable market price signals, encouragement of new flexible resources or design of effective electricity markets. Therefore, the cost-effectiveness of the portfolio depends to a large extent on the investment and operating costs and other economic terms considered in the LCOE analysis.

Table 4.5 – Techno-economic assessment for different market participation, ESS sizing, RT controls and interest rates.

Market participation and RT supervisory control	**DM**	**DM+CIM Dctr**		**DM+CIM+FRR participation Decentralized control**				**DM+CIM+FRR participation Centralized control**			
ESS sizing (% initial C^{nom})	0 %	0 %	100 %	50 %	75 %	100 %	125 %	50 %	75 %	100 %	125 %
DM+CIM revenues (k€/yr)	6178.8	6059.4	5919.5	5901.6	5884.8	5863.4	5862.2	5912.2	5896.5	5882.7	5875.5
Imbalances rev/costs (k€/yr)	-308.1	-128.8	-1.83	-7.24	-2.20	-0.36	0.16	-7.30	-2.30	-0.91	-0.22
FRR revenues (k€/yr)	0.0	0.0	0.0	359.4	536.4	709.9	839.4	360.5	537.1	713.0	841.6
FRR penalty costs (€/yr)	0.0	0.0	0.0	-3736.5	-1148.2	-267.1	-217.9	-190.0	-5.6	0.0	0.0
Annual market revenues (k€/yr)	5870.7	5930.6	5916.8	6250.0	6417.8	6571.6	6701.5	6265.2	6431.3	6594.8	6716.9
Market revenues (€/MWh)	**51.61**	**52.14**	**52.02**	**54.95**	**56.42**	**57.77**	**58.92**	**55.08**	**56.54**	**57.98**	**59.05**
LCOE (€/MWh), i = 0 %	**38.62**	**38.62**	**43.24**	**41.50**	**42.37**	**43.39**	**44.26**	**41.50**	**42.44**	**43.39**	**44.33**
LCOE (€/MWh), i = 1.25 %	42.01	42.01	47.43	45.39	46.41	47.59	48.61	45.39	46.49	47.59	48.70
LCOE (€/MWh), i = 2.5 %	45.75	45.75	52.02	49.66	50.84	52.21	53.39	49.66	50.93	52.21	53.49
LCOE (€/MWh), i = 4 %	50.66	50.66	58.05	55.26	56.65	58.27	59.67	55.26	56.77	58.27	59.78
LCOE (€/MWh), i = 5.5 %	56.00	56.00	64.60	61.36	62.98	64.87	66.49	61.36	63.11	64.87	66.62
Net annualized profits (€/MWh) (Revenues – LCOE), i = 0%	13.00	**13.52**	8.78	13.45	14.05	14.39	**14.66**	13.58	14.10	14.59	**14.72**
Net annualized profits, i = 1.25 %	9.60	**10.13**	4.59	9.56	10.02	10.18	**10.30**	9.70	10.05	**10.39**	10.36
Net annualized profits, i = 2.5 %	5.87	**6.39**	0.00	5.29	**5.58**	5.56	5.52	5.43	5.61	**5.77**	5.56
Net annualized profits, i = 4 %	0.96	**1.48**	-6.03	-0.31	**-0.23**	-0.50	-0.75	**-0.18**	-0.23	-0.30	-0.73
Rev – LCOE, i = 5.5 %	-4.39	**-3.86**	-12.58	**-6.41**	-6.56	-7.09	-7.57	**-6.28**	-6.57	-6.89	-7.57

**k=thousand*

4.4 Main conclusion of RES+ESS portfolio

As can be concluded from the above results and discussion, the centralized control for the operation of a RES portfolio with ESS in multiple markets improves their economic revenues compared to a decentralized control of individual RES plants. The proposed EMS addresses the RES+ESS portfolio asset management in the long-term and short-term planning for RES+ESS sizing design, market bidding and real-time operation.

Considering the scope of RES market participation, the main objectives of the proposed EMS ought to maximize the economic opportunities of each electricity market, minimize overall costs and provide a controllable and reliable real-time operation, by smoothing RES variability and volatility, mitigating large forecast errors, and avoiding as much as possible energy imbalances and other market penalties.

Furthermore, how the ESS is managed and controlled during their lifetime operation is essential for the ESS cost-effectiveness. During its lifetime, ESS degradation increases with a high demanding operation (and smaller ESS sizing) or it decreases in case of less demanding operation (and larger ESS sizing). This ESS capacity fade due to calendar and cycling effects influences on the operating and replacement ESS costs. Consequently, the EMS reaches a trade-off between the asset market revenues and their overall costs according to the expected ESS lifetime and operation.

The results exposed that the joint operation of a RES portfolio with ESS in multiple markets improves their economic revenues to be a profitable asset. The techno-economic advantages of the centralized control are proved: i) ***RES energy imbalances*** (and their costs) are almost avoided, from 6.65% absolute energy imbalances with DM participation without ESS up to less than 0.2% with ESS integration and CIM participation, ii) ***FRR penalties*** are hugely reduced or even eliminated with a ESS sizing selection more than 0.43 and 0.54 MWh per MW installed of PV and WP respectively, iii) ***FECs*** increase with FRR participation due to more demanding operating conditions, because the usage of the ESS is higher in order to fulfill EM and FRR requirements. In contrast, thanks to a Centr control the annual FECs are reduced around 15% compared to Dctr control due to RES equalization technique, and iv) ***expected ESS lifetimes*** are reduced when participating in FRR (in line with FECs results). Nevertheless, it is worth highlighting that Centr control enhances SOH and ESS lifetimes compared to Dctr control. Moreover, this fact results in a reduction of ESS replacement costs.

Moreover, the integration of ESS and their participation in FRR markets gives more value to the RES portfolio and increases the annual market revenues up to 7 €/MWh (increase of ~13%) with large ESS. According to LCOE analysis, final economic results present a profitable RES+ESS exploitation under different ESS sizing and several financial conditions.

Thus, Centr portfolio supervisory control, which manages all RES resources more efficiently, enhances the RT operation performance of the renewable asset, as well as improving their overall profitability.

Apart from above specific case studies, the proposed EMS methodology is a useful tool to design, sizing and invest on a RES+ESS portfolio which maximizes expected returns. In the design stage, the selection of ESS capacity plays an important role in assuring a more reliable and profitable operation which leads to increase the market revenues. The simulation of different RES+ESS configuration could be useful to make decision about a new RES+ESS asset or to consider ESS in existing RES plant(s).

After all, it should be highlighted that this EMS enables a high replicability to evaluate the ESS cost-effectiveness under different scenarios, generation profiles, ESS degradation models according to other technologies, considered market framework, desired objective or functionality, market prices and system costs. That is, according to the input data or design scenario given to the EMS, the methodology enables to evaluate the proper ESS capacity for any given application.

Chapter 5 General conclusion and future research lines

In this final chapter, the main conclusions of the present work are collected.

The main contribution of the PhD thesis in the field of the development of optimal sizing and energy management strategies for storage system to support renewable market participation are pointed out.

Lastly, some future research lines are suggested.

5.1 Main contribution and overall conclusion

Throughout the present document some major conclusions were presented related to the state-of-art review, the implementation of the proposed EMS for RES+ESS, its validation for several case studies, and finally its techno-economic results.

In this PhD thesis, the topic of the optimal sizing and energy management of ESS for grid-connected applications was studied. Specifically, the scope of this PhD thesis was focused on the market participation and real-time operation for solar, wind and storage systems considering electrical, technical, market, regulatory, economic and financial issues.

However, the main problem found out in the current literature is the relevant lack of a global EMS for the proper sizing and operation of a renewable plant or a RES asset with ESS, which should take into account: 1) the consideration of a short-term and long-term EMS in which a reliable and profitable market participation and operation is achieved for each day, but also this EMS comprises long-term variables and parameters, which influence this short-term performance, in view of increasing the RES+ESS asset profitability for considered scenarios; 2) the implementation of an upper level control in which market schedule optimization is carried out, and a lower control level in which these grid power set-points are applied in real-time operation. This two-level structure enables applying the market schedule and assess realistically the technical results of each scenario according to the final RT operation; 3) for that purpose, an electricity market framework should be modelled in the most realistic and precise way possible, in which real-time parameters with large degree of uncertainty from reserve markets are considered and applied accurately. Reserve market is characterized of being high-value services and highly rewarded, and a new market opportunity for renewable and storage plants. The technical response to real-time uncertain parameters should be managed immediately in the short-term horizon at RT operation, but the proper RES+ESS sizing and configuration is evaluated after a long-term simulation; and 4) the importance of a customized and detailed ESS aging method to estimate successfully the ESS lifetime, and therefore, its operating costs. When expected ESS lifetime is estimated more properly, long-term economic impact of ESS aging analysis on the selected scenarios is more accurate, so the possible deviation from the expected operating costs are reduced.

With the objective of considering suitably all aspect exposed above, there is a need of developing a global EMS which contemplates both time-frame horizons, in order to maximize the profitability of the considered scenarios, and evaluate and validate also the technical performance and market compliance of the RT operation, when some variables with large degree of uncertainty (market, forecast, etc.) are included.

Consequently, the combined short-term and long-term EMS, for the proper sizing and operation of a renewable asset with ESS, assesses the long-term planning and short-term operation in multiple markets (energy and reserve markets), giving a broader, more detailed, thorough and suitable framework to evaluate the cost-effectiveness of ESS integration for RES grid-connected applications. As exposed above, this global EMS considers, implements and evaluates accurately several main issues which have impact on the overall RES+ESS asset profitability, among others: the expected ESS lifetime and the ESS sizing selection in the ESS acquisition and degradation costs, the level of compliance of reserve market in economic market penalties, and the generation forecast error in the amount of energy imbalances. Thus, this global EMS should consider all these technical and economic variables which have influence in the asset profitability in the long and/or short term.

For this purpose, the adoption of short-term and long-term EMS is developed to achieve a controllable and reliable operation of RES+ESS which leads to a profitable exploitation through the joint participation in electricity markets. Among all the literature analyzed in this field, the influence of ESS sizing, operation and degradation issues in multiple markets supporting RES has not been yet assessed.

In that way, the *Development of Optimal Energy Management and Sizing Strategies for Large-Scale Electrical Storage Systems supporting Renewable Energy Sources* are proposed as the main contribution of this PhD thesis. Thus, two main scenarios have been addressed: an individual RES+ESS plant (solar or wind) and the RES+ESS portfolio.

Focusing on the main results achieved for individual RES+ESS plants, the implementation of a global short-term and long-term EMS, which consider real-time operation, a closed-loop MPC approach, FRR participation and a CIM re-schedule optimization, has demonstrated managing RES generation and controlling the SOC profile inside their safe limits in order to provide market set-points, avoid hugely energy imbalances and achieve a high level of compliance of reserve markets.

Moreover, several interesting correlations related to the ESS sizing selection have been shown. It has been observed that FECs are reduced when ESS sizing is larger (reducing its annual cycles). Therefore, under a lower demanding operation, a larger ESS will increase its expected ESS lifetime, and reducing their operation and replacement costs, although the initial investment is higher. In case of FRR participation, annual FECs increase due to a more demanding operation in order to follow reserve requirements in RT operation, although more revenues are obtained. Consequently, the ESS sizing, annual RES generation, RT operation, and financial conditions, among other issues, influence the final profitability.

Regarding economic results, the FRR participation increase considerably the annual market revenues, however the integration of an ESS in the renewable plant is compulsory to operate successfully and reliably in this reserve market. However, the RES+ESS profitability cannot be ensured under the considered scenarios (some annual generation profiles, market prices, ESS costs, etc.). It should be pointed out that a reduction of

RES+ESS and/or an increase of market prices is needed to find a more profitable scenario than the consideration of a single RES plant. In particular, WP+ESS plants are expected to require less financial support or less favorable cost reduction scenario than PV+ESS plants.

Finally, analyzing the RES+ESS portfolio scenario, the technical advantages of the centralized control are proved compared to other RT controls: RES energy imbalances (and their costs) are almost or full avoided, FRR penalties are hugely reduced or already eliminated, the real-time operation minimize the ESS cycles, and thus the ESS lifetime is extended (reducing their operating and replacement costs). Moreover, economic results are also improved with Centr control application.

In economic terms, the short-term and long-term EMS is evaluated under an ESS sizing and a LCOE analysis. The comparison between annual market revenues and LCOE enables to identify the most profitable RES+ESS configuration, for any given technical input data or economic parameter. Centr control enhances the RT operation performance of the renewable asset, as well as improving their overall profitability.

5.2 Research future lines

From the work developed in this PhD thesis, the following future research lines have been identified, based on the review of the methodology, as well as future trends on ESS deployment and other case studies or applications.

A step closer to the real performance is the implementation and validation of the proposed EMS in a hardware-in-the-loop (HILP) in a research test-bench which commercial elements are controlled to follow the power set-points from the upper and lower controls from the EMS. Therefore, experimental results and the technical performance different controllable energy resources and their response from to the targets given from the EMS can be validated and compared with the results of this thesis.

With regard to validate further the replicability and adaptability of the proposed EMS, other case studies oriented to utility RES plants can be modelled and simulated. According to the given input data or design scenario, the EMS enables to operate the controllable energy resources efficiently and optimize them according to the desired objectives and to evaluate the proper ESS capacity for any particular application. In some cases, a change in the predetermined design variables (RES generation profiles, ESS degradation models, ESS capacity, participation under the considered electricity markets, market prices or system costs) can be directly simulated and validated with the proposed EMS. In that way, other techno-economic results and conclusions can be obtained. In other cases, an introduction of new market participation not considered in this EMS, or the decision to change the desired objectives or functionalities will have more influence on several blocks of the EMS. For example, additional technical and market restrictions should be included. However, it could be highlighted that this EMS gives a clear framework to include other improvements and variations easily.

In view of European ambition to transform the system into a more consumer-centered, residential solar photovoltaic systems, energy storage batteries (including private electric vehicles) will greatly increase in the next years, also due to the net-zero energy building European targets. Energy storage is also an important way to increase the self-consumption ratio in the residential and commercial sectors, and new approaches should be developed to control the distributed energy resources. These changes will bring considerable benefits from a consumer perspective, from an environmental perspective, and from an economic perspective. Therefore, with the increasing distributed energy resources integrated in the low voltage distribution grids, another interesting application would be to develop EMS to control and operate efficiently all these energy resources integrated in local energy communities. This application will require the implementation of local markets, considering new energy trading schemes, energy contracts and peer-to-peer models.

Appendix A Preliminary rule-based EMS

Appendix A has the objective of describing the rule-based EMS developed during the research activities of this PhD dissertation, as preliminary developments which have been also published in several scientific journal or conference articles. This appendix proposes a rule-based ESS energy management with an advanced and optimized market participation methodology for Day-Ahead Market (DM), Intraday Market (IM) by auctions and reserve markets (FRR), with the aim of defining the trade-off between the profits and the fulfilment of FRR requirements.

The main objective is to demonstrate their potential to participate not only in energy markets, but also in frequency ancillary services in order to contribute to the grid stability, as well as being an additional source of revenues. The suitable market participation and operation strategy ensures an optimized and reliable operation despite the uncertainty of solar generation, the uncertain real-time AGC signal and the limited capacity of the energy storage system. Furthermore, a sensitivity analysis of ESS sizing is proposed, in order to evaluate the influence of the ESS capacity in technical market requirements, market benefits and total profitability of the plant. With this objective, several market scenarios have been defined modifying main design features, such as: ESS capacity, ESS costs, reserve band availability and energy imbalances prices.

Finally, the main weaknesses of the rule-based EMS are explained, and several improvements are included in the proposed EMS of Chapter 2.

A.1 Introduction

This section proposes an advanced market participation and operation of RES plants with ESS in day-ahead, intraday and secondary reserve markets, through a Model Predictive Control (MPC) approach. Particularly, this strategy is applied to a photovoltaic power plant (PV) with electrical energy storage (ESS) in Iberian Market, which analyzes only the participation in DM and auction-based IM, but it only applies a fixed or rule-based participation in Secondary Reserve Market (SRM).

This work takes into consideration the ESS acquisition, operational and degradation costs inside the optimization; renewable generation uncertainty; expected prices for IM and FRR; a more realistic reserve power signal modelling, as well as FRR fulfillments. Finally, a techno-economic analysis and a sensitivity analysis is carried out.

Through a linear programming optimization, an annual optimal trade-off between market profits, battery operating costs and market technical fulfillments is defined, with the objective of achieving an optimal profitable and reliable market participation as well as reducing overall battery costs.

A.2 Rule-based optimization

This section focuses on the market participation of a PV+ESS plant in the energy and reserve markets. In the case of Spain, FRR is also known as Spanish Secondary Reserve Market (SRM). The annual PV generation was extracted from a real PV installation in the south of Spain. An annual techno-economic analysis is carried out with market prices of 2016.

This EMS methodology could be divided into four blocks, as can be observed in Figure A.1, following a similar structure that the EMS methodology presented in Chapter 2:

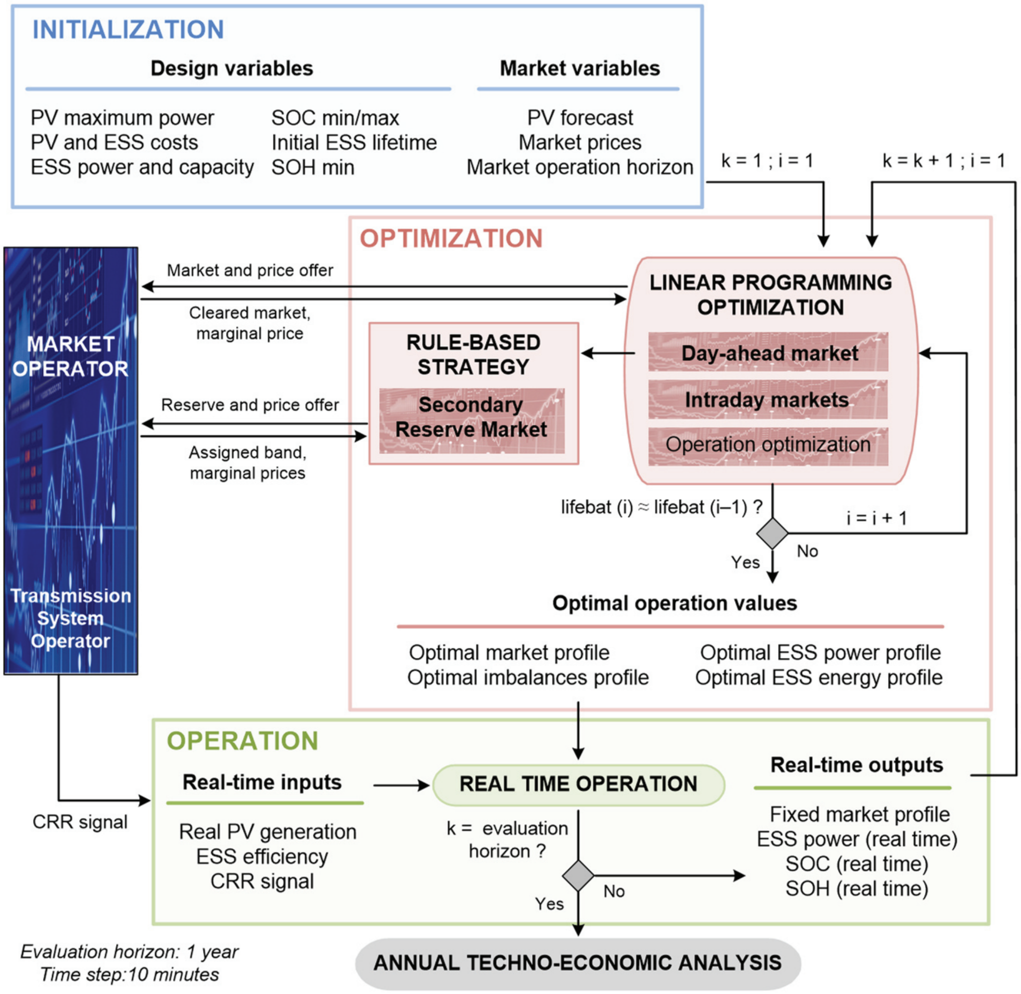


Figure A.1 – Rule-based EMS methodology.

- Initialization
- Market optimization
- Real-time operation
- Annual techno-economic analysis

In the first step, design variables are defined: PV maximum power; ESS capacity; ESS charge and discharge power; minimum and maximum state of charge (SOC); the minimum state of health (SOH), at which the battery must be replaced; the PV plant and ESS investment costs, and the Iberian electricity market schedule from Figure A.2 and historical hourly market prices of the year 2016 (day-ahead, intraday, imbalances and secondary reserve prices).

In order to quantify forecast errors, the mean absolute percentage error (MAPE) is commonly used for solar forecast. MAPE represents the percentage of the variation of predicted values around the measured data. Using artificial neural network and other advanced techniques, the 24h ahead solar forecast MAPE can be reduced below 20%.

Therefore, the PV generation forecast profile (P_k^{pred}) is estimated from the real PV generation (P_k^{real}), adding an hourly random variable ($\sigma_{(h)}$) for a maximum percentage error (ε_{max}) of 20% for DM and 10% for IMs, as expressed in (A.1). The annual PV generation was extracted from a real PV installation in the south of Spain.

$$P_k^{pred} = \sigma_k \cdot \varepsilon_{max} \cdot P_k^{real} \tag{A.1}$$

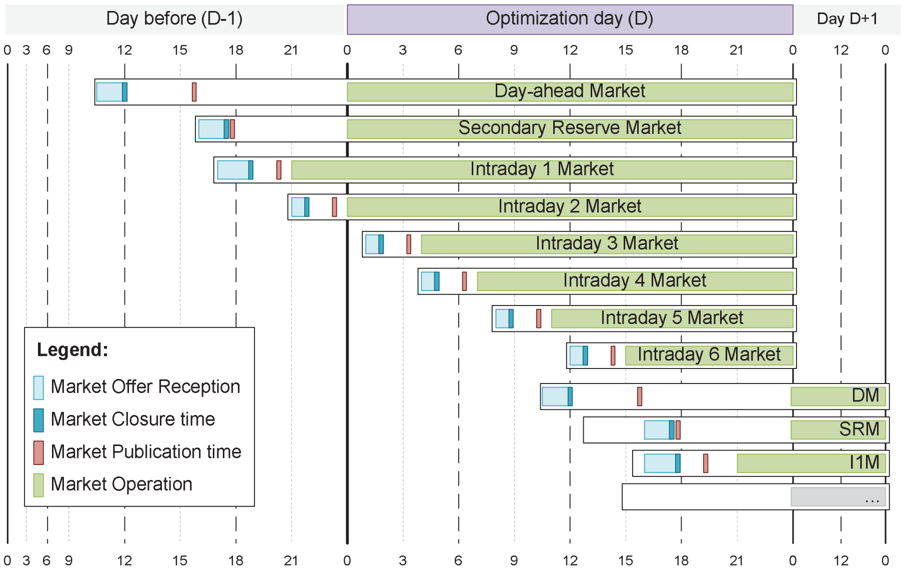


Figure A.2 – Iberian Electricity Market schedule.

The Iberian Electricity market is divided into energy and ancillary services markets cleared sequentially. Regarding energy markets, the Day-ahead market (IM) and six Intraday Markets (IM) are cleared each day. In addition to energy markets, the participation in Secondary Reserve Market (SRM) through daily auctions is also considered. Figure A.2 shows the auction time and operation time of each market.

Thus, the aim is to find the design variables that minimize the cost equation, which is equivalent to maximize the overall profits. Most literature includes the maximization of market benefits, but they do not take into account ESS costs in the optimization. In this work, as explained above, LP optimization is applied to obtain the optimal market bidding power profile (P_k^{MKT}), the assumed positive and negative energy imbalances profiles ($P_k^{imb+/-}$), the optimal battery power profile ($P_{bat(k)}$), and its lifetime (Ψ_r^{ESS} in years. Firstly, P_k^{MKT} corresponds to the DM power profile and later, to the power profile including IMs' bids.

Energy imbalances imply that the PV+ESS plant delivers to the grid more or less energy than the bidding market power (P_k^{MKT}), because this market operation is more profitable than making firming control with the energy storage system, according to the current energy imbalance prices.

$$min\left\{ \sum_{\forall\, k \epsilon K_H} \left[\begin{array}{c} \dfrac{c^{MW} \cdot P_r^{conv}}{\psi^{conv} \cdot d^y} + \dfrac{c^{MWh} \cdot C_r^{nom}}{\Psi_r^{ESS} \cdot d^y} \\ -\Delta t \cdot \left(\lambda_k^{MKT} \cdot P_k^{MKT} + \lambda_k^{imb+} \cdot P_k^{imb+} + \lambda_k^{imb-} \cdot P_k^{imb-} \right) \end{array} \right] \right\} \tag{A.2}$$

The equalities and inequalities included in this model are described in Chapter 2, such as market power balance (2.5), energy flow of the battery without including efficiencies (2.6), energy and power ESS constraint without including FRR reservations (2.7)-(2.10), no-charging during night-time (2.13), final stored energy (2.14)-(2.15), market firming service (2.16) and ESS linear model aging (2.17)-(2.19).

In this model, there is only one variable for ESS power output ($P_{r,k}^{ESS}$), negative when the ESS is discharging and positive when it is charging.

Based on MPC approach, when a market auction is not cleared, the LP optimization recalculates the battery operation profile, taking into account current operating conditions and uncertain parameters, while the current market profile P_k^{MKT} is maintained fixed until the next market auction optimization.

In real-time operation, the real PV generation (P_k^{real}), AGC_k^{PV} power signal and the ESS efficiency are included as input data. These parameters modify the ESS power in RT operation, following Dcntr control from the pseudo-code for RT operation.

After 10 minutes operation (Δt=1/6), a new optimization is carried out with these real-time output values. After having simulated a whole year, an annual techno-economic analysis is carried out analyzing each daily benefits and costs, in accordance with the Spanish market rules and following eq. (3.1).

The daily market profits are the sum of hourly day-ahead market profits, intraday markets profits, positive energy imbalances profits, negative energy imbalances costs (observe that variables with negative superscripts have negative values), secondary reserve band profits, upward reserve energy profits, downward reserve energy costs and secondary reserve market penalty costs.

On the other hand, the daily ESS acquisition cost is calculated. Finally, the annual total profits are calculated as the sum of daily market profits minus the sum of the daily ESS acquisition costs.

A.2.1 FRR market strategy definition

In this section, several rule-based market participation strategies are analyzed, focusing on the most advanced strategy (FRR6), in which a rule-based strategy is applied to FRR participation.

As can be observed in Table A.1, six representative market scenarios are selected, in order to evaluate the knowledge of different optimization inputs (such as the solar generation, market prices and secondary reserve strategy) and compare their techno-economic results. In the first three market scenarios, the PV+ESS plant participates only in day-ahead market and intraday markets. To the contrary, the last three market scenarios include also secondary reserve participation.

The first strategy (EM1) considers a perfect knowledge of solar generation, although mean hourly prices for DM and IMs are applied. Whereas, the second strategy (EM2) considers PV forecast errors (see eq. 6) in order to calculate the market bids. As a result, the battery energy profile in real-time operation will be different than the optimal one.

The third market strategy (EM3) is more realistic in which PV forecast errors are included as well as an expected hourly IM prices. After DM publication, the day-ahead market prices of this specific day are known. Therefore, IM market bids may estimate the IMs' prices and will take advantage of this fact, instead of using hourly mean values as in [22-25, 28-31].

Table A.1 – Optimization inputs for different scenarios.

Scenario	PV power	Hourly market prices	FRR
EM1	PV real	Historical DM and IM	-
EM2	PV pred	Historical DM and IM	-
EM3	PV pred	Historical DM and expected IM	-
FRR4	PV pred	Hist DM, Expected IM and FRR	Fixed (8h)
FRR5	PV pred	Hist DM, Expected IM and FRR	Fixed (10h)
FRR6	PV pred	Hist DM, Expected IM and FRR	Rule-based

On the other hand, three market participation strategies are defined for DM, IM and FRR. In all these cases (FRR4, FRR5 and FRR6), PV forecast errors, historical DM prices and, later, expected IM and FRR prices are included.

According to historical FRR prices in Iberian Market, two fixed secondary market strategies are defined according to the most profitable hours:

- FRR4: $P_h^{band} \geq 1MW \ \forall h \in \{1,2,4,5,7,8,23,24\}$
- FRR5: $P_h^{band} \geq 1MW \ \forall h \in \{1,2,4,5,7,8,16,17,23,24\}$

The last scenario (FRR6) applies a rule-based FRR strategy. After DM publication, assumed energy imbalances, the level of solar generation intermittency and the expected FRR prices are analyzed in order to decide the most profitable and reliable hours to participate (from 10 to 14 hours).

In the optimization day, successive IMs recalculate optimal market bidding power profiles counteracting the deviation of SOC profile from the expected SOC profile, due to PV forecast errors, ESS efficiency and AGC signal. And in each step, the optimal battery operation profile is recalculated in order to maintain the SOC within the operating window.

Finally, the real-time strategy takes into account two considerations: i) give priority to follow the AGC signal from incurring in energy imbalances in that particular hour, and ii) increase SOC operating windows (5-95%) in case AGC signal is required, in order to reduce the FRR non-compliance level.

The general market participation for FRR6 is depicted in detail in Figure A.3, defining the data inputs and the main objectives of the strategy during the daily optimization.

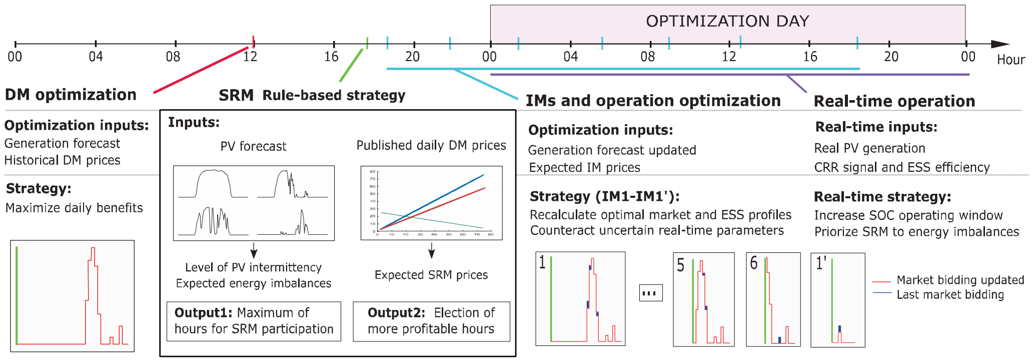


Figure A.3 – Market bidding and operation strategy for FRR6 scenario.

A.3 Market participation results

The market participation of the PV+ESS plant have been simulated and validated for one year (Spanish market prices of 2016) in these 6 different scenarios explained above.

A comparison of annual total market profits is observed in Figure A.4 and Table A.2. The total market profits include: energy markets (DM and IM benefits), energy imbalances (positive imbalances benefits plus negative imbalances costs) and FRR market (including band, upward and downward energy profits and FRR penalty costs).

As can be observed, the total market profits decrease with PV forecast errors (EM2) from the first scenario without PV forecast errors (EM1). The difference is small because the MPC approach and the stored energy in the ESS is able to manage PV errors during the day, and then LP optimization re-schedules the market bidding by changing the market offers in successive intraday markets.

Whereas, when expected IM prices (instead of mean prices as in EM1-EM2) are introduced maintaining PV forecast errors (EM3), the total market profits increase by 0.61% from EM2. This increase in the obtained profits is caused by the changes in IM offers from hours with higher mean historical prices (defined by the DM offer) to expected hours with higher prices (in IM offers).

Regarding FRR participation, all three strategies increase the total profits 4.64% (FRR4), 4.83% (FRR5) and 6.42% (FRR6) from the first scenario EM1. It can be observed that energy market profits (DM and IM) plus energy imbalances are reduced because a portion of annual solar energy is traded in FRR. Moreover, as the AGC signal produces an additional change in the expected optimal SOC profile, some additional energy imbalances are produced. Successive IM offers deal with energy imbalances, reducing them as much as possible.

These large energy deviations from the optimal SOC could change to a great extent the power profile and energy profile of the battery. For this reason, energy imbalances at real-time operation increase from 0.49% (EM3) to 1.09% (FRR4), 1.02% (FRR5) and 1.56% (FRR6). When additional energy imbalances are committed, the battery is not able to manage the PV plant optimally. Although the scenario without ESS is outside the scope of this research, it should be highlighted that energy imbalances without ESS increase up to 17% with perfect forecast.

Regarding FRR penalties, the scenario FRR4 do not participate in daytime hours and therefore, the FRR penalties' percentage is 0%. In all cases, the battery is capable of following the AGC signal. Whilst in the second FRR scenario (FRR5), FRR non-compliance ascends to 11.75%, although its penalty cost is 0.31%, due to afternoon hours' participation. Concerning the optimized market strategy in the scenario FRR6, the FRR penalties are reduced up to 1.49% thanks to giving priority to follow the AGC signal from incurring in energy imbalances and the increment of the SOC operating window in case AGC signal is required. This real-time strategy allows increasing total market profits, reducing the FRR non-compliance level and its associated penalty costs.

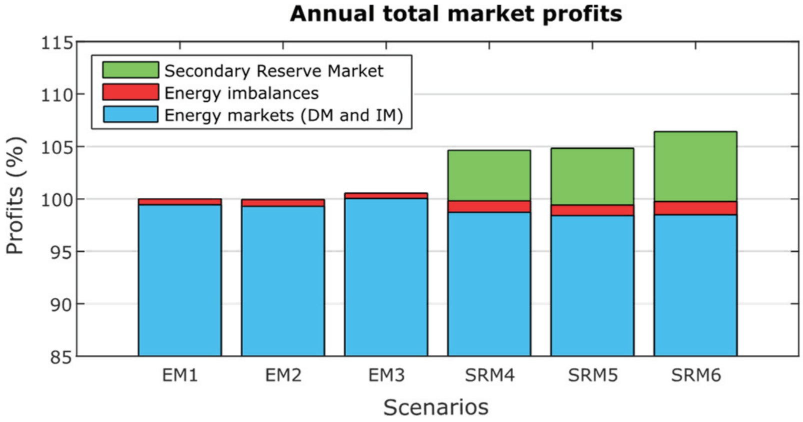


Figure A.4 – Annual total market profits in each scenario (market data 2016).

Table A.2 – Annual market profit in each scenario (%), FRR penalty cost (%), non-fulfilment level (%) and participation (hour per day)

	EM1	**EM2**	**EM3**	**FRR4**	**FRR5**	**FRR6**
Total profit (%)	100	99.93	100.54	104.64	104.83	**106.42**
EM market (%)	99.43	99.28	100.05	98.72	98.41	**98.49**
Energy imbalance (%)	0.57	0.65	0.49	1.09	1.02	**1.26**
FRR market (%)	-	-	-	4.83	5.40	**6.67**
FRR penalty cost (%)	-	-	-	0	-0.31	**-0.05**
FRR non-compliance (%)	-	-	-	0	11.75	**1.49**
FRR participation (h)	-	-	-	8 h	10 h	**11.7 h**

Finally, the SOH at the end of the analyzed year (2016) is 99.02% regarding the cycling aging model. However, ESS battery will be replaced in all scenarios around 15 years, according to the calendar aging, but not for cycling degradation. Consequently, for the same acquisition and replacement costs of PV+ESS plant, the profitability in FRR6 is improved 6.42% from EM1.

A.4 Real-time operation results

This section is focused on analyzing real-time operation. As an example, the real-time operation for one day (January 13, 2016) with FRR6 scenario can be observed in Figure A.5. The DM offer takes into account a PV forecast error of 20% and mean historical DM prices. Then, IM offer adjusts the market profile, updating PV forecast, expecting IM prices and AGC signal. These characteristics are shown in Figure A.3

FRR6 strategy decides to participate for around 12 daily-hours as shown in Table A.2. The AGC signal has been modeled according to the real hourly upward and downward energy reserve use of January 13, 2016 (not mean historical value).

At night hours, ESS follows the AGC signal accurately. IM3 and IM4 counteract this small change in the SOC profile from the optimal SOC value (50%) expected at DM auction time.

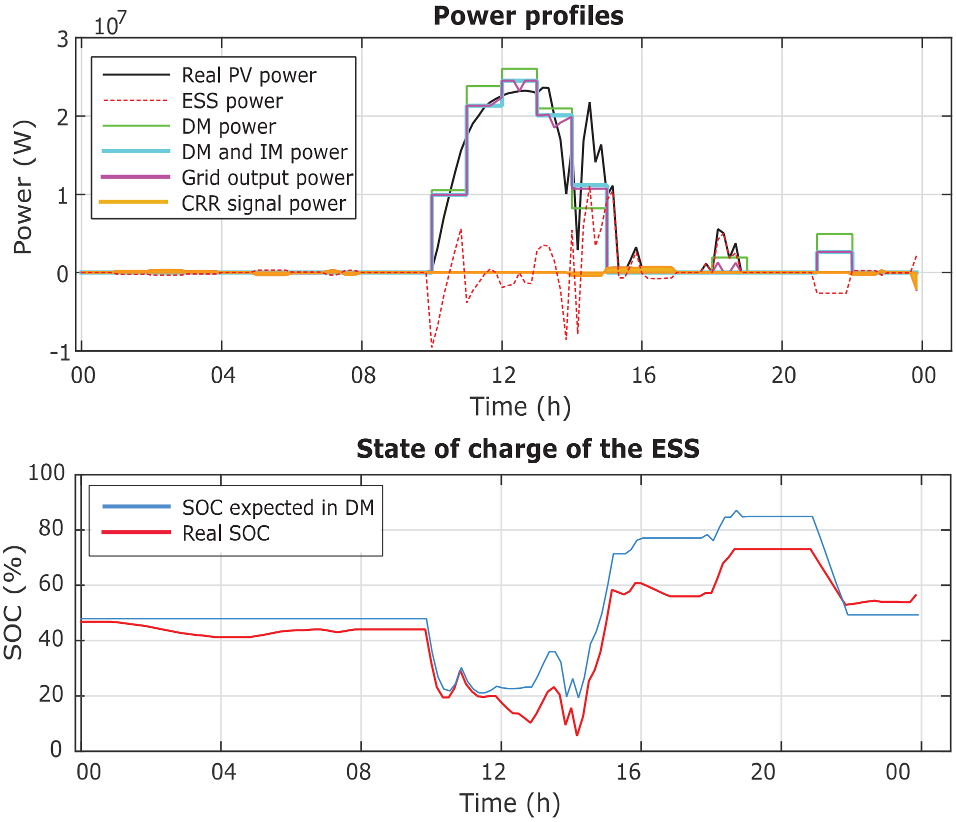


Figure A.5 – Real-time operation for one day (13/01/2016) with FRR6 scenario.

During midday hours, the grid power profile is equal to the bidding market profile (including AGC) plus the assumed energy imbalances. As can be observed in Figure A.5, positive energy imbalance is produced at 11:50 and negative energy imbalances at 12:30 and between 13:30-13:50).

On this particular day, positive energy imbalance has been produced because is profitable from an economic point of view, because positive energy imbalances price is only slightly lower than the day-ahead market price. Whereas, negative energy imbalances have been produced because the battery is not able to be discharged (SOC operating range10%-90%).

In the afternoon hours, the PV+ESS plant participates in FRR from hour 15 to hour 17. In the first hour, the battery is charged with the excess PV solar, while the grid power profile (P_k^{grid}) is equal to the bidding market profile (P_k^{MKT}) plus the AGC signal. In this case, no FRR penalty is assumed. FRR penalties of all days of the year are illustrated in Figure A.6a. Moreover, the battery reduced its normal operating window at 14:20 (4.5%) in order to fulfill with the AGC signal in real time and avoid energy imbalances and FRR penalties. This issue reduces FRR penalties from 2.21% to 1.49%. Figure A.6b illustrates the SOC limits during the year.

According to energy ESS constraints, the SOC at the end of the day is expected to be around 50%. The ESS efficiency and AGC signal after IM1' modify this final value as can be seen in Figure A.6c. The SOC is located between 23.7% and 71.76%, with an annual average value of 53.6%.

The research presented in Section A.2 and A.3 was published in [236] Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Annual Optimized Bidding and Operation Strategy in Energy and Secondary Reserve Markets for Solar Plants with Storage Systems" *IEEE Transactions on Power Systems*, Sept 2018

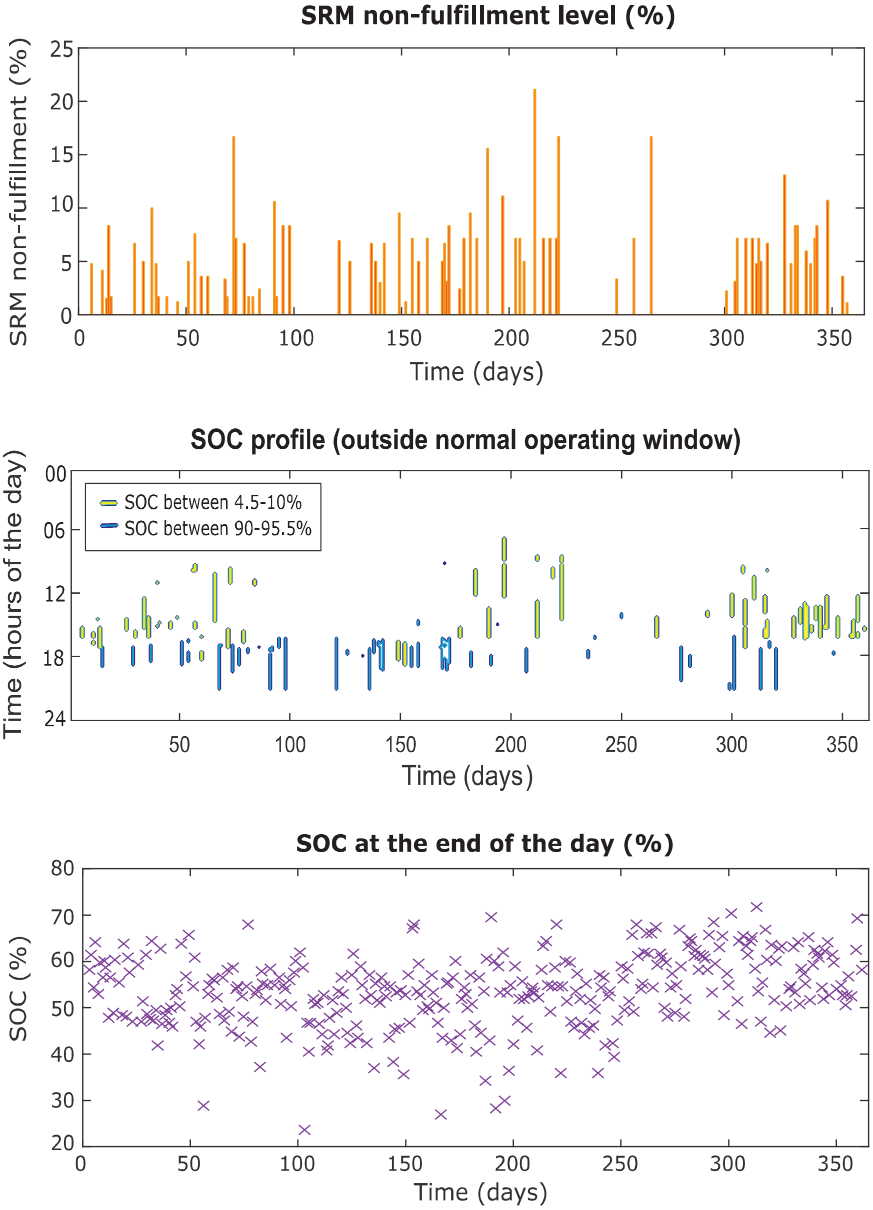


Figure A.6 – a) FRR non-compliance level (annual average value, 1.49%), b) SOC profile (outside normal operating window), c) SOC at the end of the day for FRR6.

A.5 Sensitivity analysis

A sensitivity analysis of the ESS sizing is exposed in this section, in order to evaluate the influence of ESS capacity in energy and reserve market participation. An oversized ESS will allow RES plant to increase energy arbitrage, to reduce energy imbalances, to fulfill real-time FRR requirements and to reduce FRR penalties. However, its high acquisition cost could not be compensated by the increase in market profits.

The sensitivity analysis has been evaluated following the market participation of a PV plant with ESS in the Iberian market, formulated in the previous research [237]. A linear programming is applied to schedule the solar generation in DM and to reschedule in IMs during the day, taking into consideration the ESS efficiency, PV forecast errors, expected market prices, battery lifetime and ESS costs. Moreover, the FRR participation follows a rule-based strategy.

With the objective of analyzing in depth the optimal ESS sizing, several market scenarios have been defined in which FRR band availability, energy imbalances prices and ESS acquisition costs are also modified, in order to find the trade-off between a reliable operation and economic benefits. Thus, this paper is focused on understanding the relative impact of the most relevant market and design variables in the profitability of the power plant under several scenarios. Figure A.7 illustrates a block diagram for the selection of these scenarios.

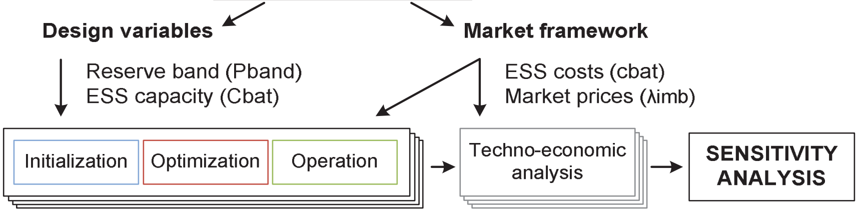


Figure A.7 – Block diagram of scenario selections.

In this section, several variables will be analyzed and modified in order to define different scenarios, such as: the ESS capacity, the reserve band for FRR, ESS acquisition costs and energy imbalances market prices.

Firstly, the ESS nominal capacity (C_r^{nom}) is included in the initialization block and it varies ± 25 % from the value obtained in a previous research carried out by this research group [117]. It should be pointed out that this initial value of 13.85 MWh (C^{prev}) from a previous research [237].

Secondly, the reserve band for FRR (P^{band}) is also modified in order to analyze its impact on market benefits and technical fulfillments. The minimum reserve band in the Iberian Market is 10 MW. Considering a group of 10 PV power plants, this PV plant with ESS should contribute with a minimum band of 1 MW (P^{bmin}). Then, this minimum reserve band will increase in +25 %, +50 % and +75 %. As the reserve band increases, FRR profits are supposed to increase, while the FRR technical fulfillment level could be worsened.

The hours to participate in FRR in this study are fixed regarding the most suitable and profitable hours from [237]: $P_h^{band} \geq 1MW \ \forall h \in \{1,2,4,5,7,8,16,17,23,24\}$

Thirdly, different scenarios are considered according to the market framework, modifying ESS costs and market prices. On one hand, ESS acquisition costs are analyzed regarding their future perspective (from the current battery cell costs of 250 €/kWh to SET plan's targets up to 100 €/kWh in 2030) [51]. For this reason, this sensitivity analysis evaluates the total profits (market profits minus ESS cost) for the current ESS cost and with an ESS cost reduction of 25 % and 50 %.

Moreover, other market scenarios are evaluated regarding energy imbalances prices. Currently, the PV plant is remunerated according to (6) when it produces more energy than the one assigned in DM and IM, and it is penalized as in (7). when it produces less energy than the one assigned in the market. Day-ahead and energy imbalances prices for the year 2016 in the Iberian Market can be observed in Figure A.8.

As a conclusion of Figure A.8a, it can be observed that in mean values, positive imbalances are remunerated in a lower price than the DM price, and negative imbalances are paid by a higher price than the DM price.

However, according to Figure A.8b, energy imbalances are evaluated as the same DM prices the majority of the hours of the year. Thus, producing high energy imbalances could not reduce the market profits to a greater extent. That is, although the plant does not follow the market reference ($P^*_{grid(h)}$), the penalties are not too representative. This fact does not encourage the RES plant to reduce their energy imbalances.

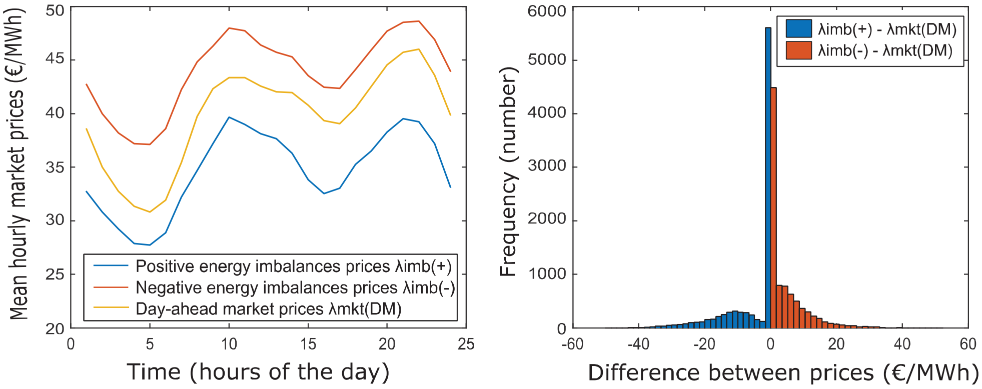


Figure A.8 – a) Mean hourly day-ahead market prices and energy imbalances prices in 2016. b) Difference between imbalances prices and DM prices.

With the increasing penetration of RES, it could be assumed that each RES plant should fulfill its market commitments. Consequently, energy imbalances will be more penalized and thus, energy imbalances prices will differ more from DM prices. For that, two energy imbalances scenarios are applied to evaluate their sensitivity. In the first scenario, energy imbalances are not paid; while in the second one, both energy imbalances are penalized, as exposed in Table A.3.

Table A.3 – Energy imbalances prices in scenario EI1 and EI2

Energy imbalances	**Current price**	**Scenario EI1**	**Scenario EI2**
Positive	λ_k^{imb+}	$0 \cdot \lambda_k^{DM}$ (λ_k^{MKT})	$-1 \cdot \lambda_k^{DM}$
Negative	λ_k^{imb-}	$1 \cdot \lambda_k^{DM}$ (λ_k^{MKT})	$2 \cdot \lambda_k^{DM}$

A sensitivity analysis is carried out in this section. In all scenarios, annual market profits are shown as well as annual total profits in which the ESS cost is taken into account.

This sensitivity analysis is evaluated for three different ESS sizing (75 % / 100 % / 125 % of C^{prev}) and five different FRR participation (without FRR participation (0) and with 100 % / 125 % / 150 % / 175 % of P^{bmin}). P^{bmin} is settled at 1 MW.

Figure A.9 shows the FRR non-compliance level (NFL) in which the PV+ESS plant is not able to follow the AGC signal, because the ESS is totally empty or full, or because energy imbalances are produced during this hour. As can be observed, the NFL (expressed in percentage, %) increases when more FRR reserve band is assigned. This fact is more noticeable if the ESS sizing tends to be smaller.

Regarding economic benefits, different scenarios have been analyzed. The base case (BC) scenario is defined with current ESS cost of 250 €/kWh and current imbalances prices. Moreover, it should be pointed out that all

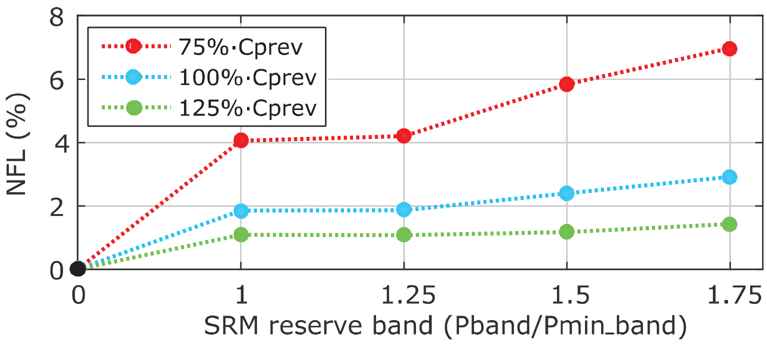


Figure A.9 – FRR non-compliance level (NFL) (%).

the economic values are shown in percentage, not in absolute values. They are referred to the first bar of Figure A.10 (75 % of C^{prev}, no FRR participation and current energy imbalances prices).

As can be seen in Figure A.10 (BC scenario), market profits increase from 5 % (with 100 % of P^{bmin} up to nearly 9 % (with 175 % of P^{bmin}) in case the plant participates in FRR. As supposed, the market benefits are higher with larger ESS sizing, because the uncertainties in real-time operation, such as the AGC signal and PV forecast errors, have less influence on the energy available in the energy storage system. However, the acquisition ESS cost is so high that greater total profits are obtained with smaller ESS sizing. As a conclusion of the BC scenario, additional market profits obtained with larger ESS do not compensate for the increase in acquisition and replacement costs. This first assessment leads to evaluate the impact of ESS costs in market and total profits through a sensitivity analysis.

In Figure A.11 and Figure A.12, the ESS acquisition and replacement costs are modified according to the future perspective defined in [51]. It can be seen that market profits are equal to the BC scenario, due to ESS costs are not included in market profits. In these scenarios at which the

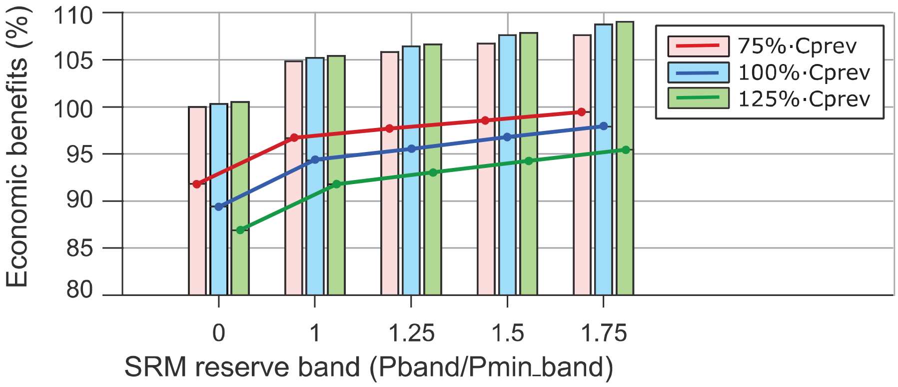


Figure A.10 – Comparative of market profits (bars) and total profits (lines) for different FRR reserve bands (Pmin_band, P^{bmin}= 1MW) and different ESS sizing (C^{prev} = 13.85kW) (BC: current ESS cost and imbalances prices).

ESS cost is reduced, total profits (market profits minus ESS costs) follow the same tendency as in the BC scenario. In all cases, including less ESS capacity is better from an economic point of view. However, it should not leave out that the NFL increases to a greater extent for small ESS sizing.

In case a maximum value for NFL was required, the ESS sizing would be chosen taking into account this constraint. For example, with a maximum NFL of 3 %, an ESS sizing of initial (100%) C^{prev} will be more profitable in all these three scenarios. If NFL was 2 %, the most profitable and reliable option would be to participate in FRR with 125 % of C^{prev}.

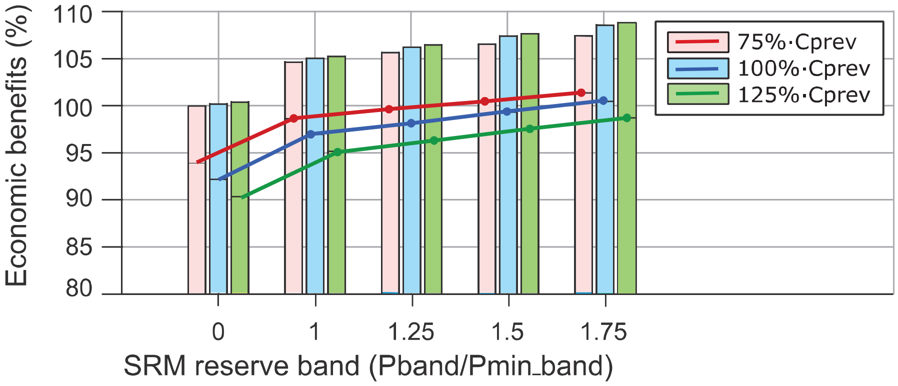


Figure A.11 – Comparative of market profits (bars) and total profits (lines) (Scenario C1: 25 % reduction of ESS cost, current energy imbalances prices).

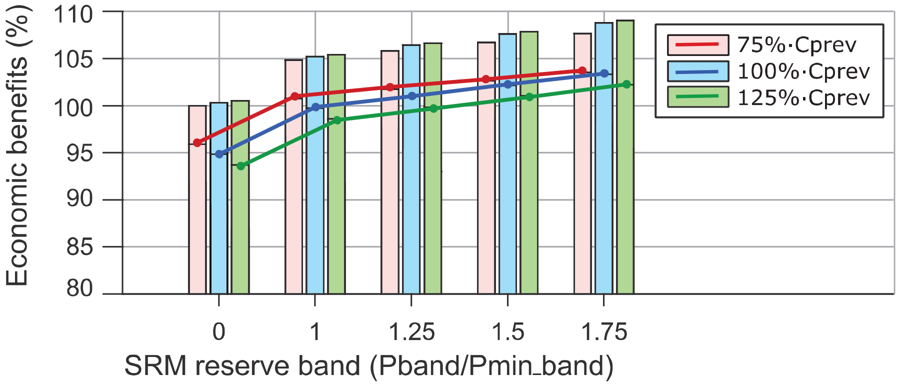


Figure A.12 – Comparative of market profits (bars) and total profits (lines) (Scenario C2: 50 % reduction of ESS cost, current energy imbalances prices).

This sensitivity analysis has been carried out taking into account market prices of the Iberian Market. However, a variation in market prices would change the optimal ESS sizing for market participation. In this paper, the influence of energy imbalances prices in total profits is also analyzed in Figure A.13 and Figure A.14.

The sensitivity analysis under different energy imbalances prices is described below. As can be observed, the real-time operation with larger ESS capacity reduces energy imbalances. If these energy imbalances are not remunerated or they are penalized, the economic results differ highly from the BC scenario and the optimal ESS varies.

Firstly, the more profitable decision is to select a smaller ESS sizing in the scenario with current energy imbalances prices (Figure A.10). Whereas, in scenario EI1 (Figure A.13) where imbalances are not paid, the optimal ESS sizing will be between 75-100 % of C^{prev} considering the participation only in energy markets (no FRR), and an ESS sizing of C^{prev} (13.85 MWh) for the participation in both markets.

In scenario EI2 (Figure A.14), all energy imbalances are more penalized with a price equal to the DM price. It can be concluded clearly that the optimal ESS sizing will be C^{prev} considering the participation only in energy markets. Another conclusion is that economic results selecting a smaller ESS sizing are worse for DM, IMs and FRR participation, compared to other ESS sizing, because this real-time operation has a great number of energy imbalances and NFL penalties.

Therefore, the selected ESS sizing will be equal or greater than C_{prev} (13.85 MWh) for the participation in both markets depending on the FRR reserve band offered in the auction (P^{band}). With small FRR reserve bands, the optimal ESS will be closer than the C^{prev} and while the FRR

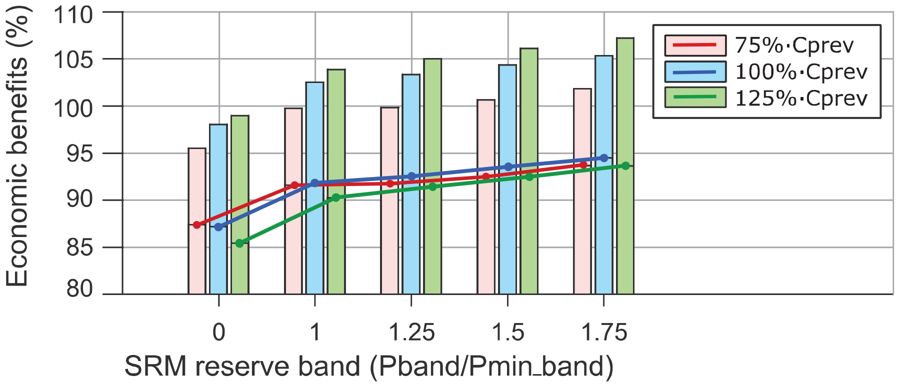


Figure A.13 – Comparative of market profits (bars) and total profits (lines) (Scenario EI1: current ESS cost, energy imbalances are not paid).

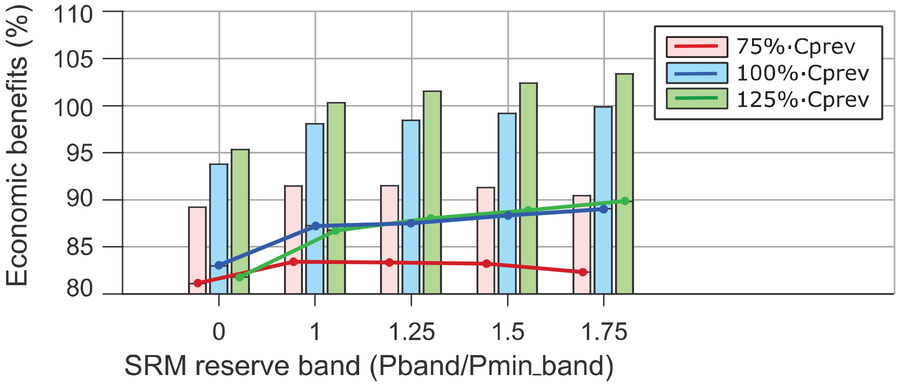


Figure A.14 – Comparative of market profits (bars) and total profits (lines) (Scenario EI2: current ESS cost, energy imbalances are penalized).

reserve band is more than 1.25 MW, an increase in the ESS sizing will result in a more profitable market results and total results.

The research presented in Section A.4 was published in [211] by Amaia González-Garrido, Andoni Saez de Ibarra, Haizea Gaztañaga, Aitor Milo, and Pablo Eguia "Sensitivity Analysis of the Storage System Sizing for Solar Plants in Energy and Reserve Markets" *Int. Conf. on the European Energy Market (EEM),* Lodz, June 2018

A.6 Conclusion and proposed improvements

With the objective of maximizing the profitability of RES plants with ESS in electricity markets, the participation in Frequency Restoration Reserve could be an additional source of revenues for them. However, this market participation and operation requires advanced energy management strategies in order to assure a reliable operation during the whole year due to the high uncertainty of FRR requirements (AGC signal).

The energy management strategy defines the optimal trade-off between annual market profits, battery operational and degradation costs, and market technical fulfillments of FRR, with the aim of finding a profitable and reliable operation, as well as reducing the overall battery cost.

Regarding market participation results from Section A.3, market benefits have been improved 6.42% from base case (EM1) and FRR non-compliance level has been reduced as much as possible, up to 1.49%, thanks to the rule-based strategy (FRR6), MPC control and RT strategy, which gives priority to follow the AGC signal from incurring in energy imbalances and which increases SOC operating windows in certain hours.

Afterward, Section A.5 shown the influence of ESS sizing and FRR participation in the techno-economic results under different market and costs' scenarios. The selection of ESS capacity plays an important role in assuring a reliable market operation which leads to increase the market revenues. However, the high ESS acquisition cost could results in a reduction of the profitability of the plant.

On the one hand, ESS cost reduction is not enough to increase the profitability of the PV plant under current market conditions in the Iberian Market. In these scenarios, an increase in the ESS sizing allows a more reliable real-time operation and reducing the FRR non-compliance level. On the other hand, assuming a scenario which penalizes more the energy imbalances committed by power plants, a minimum ESS sizing is required for reducing enough these imbalances. After that minimum value, the plant profitability increases with the addition of more ESS capacity.

In conclusion, the maximum plant profitability will be delimited by the market framework, market prices, storage system costs, and technical constraints. Nevertheless, the optimization of the design variables (ESS sizing and reserve band) and an advanced EMS in real-time operation will be crucial to achieve this maximum value.

Nevertheless, all the exposed results in this Appendix A are obtained when rule-based optimization is applied for FRR participation. Several main improvements are incorporated into the optimization in Section 4.2:

- The objective function only takes into account the market revenues obtained from the energy market, so as it tries to maximize the energy arbitrage. The expected revenues for FRR participation should be included and optimized. Therefore, an economic and technical trade-off will be achieved, by taking advantage of both markets as well as ensuring a more reliable RT operation.
- The consideration of real energy imbalances prices in the objective function results in a fully economic strategy, instead of techno-economic strategy. On the one hand, the EMS strategy prioritizes energy arbitrage in two hours rather than having enough stored energy to smooth and mitigate solar variation and intermittency. A great amount of energy imbalances is committed in case of partly cloudy days, as shown [237]. On the other hand, high non-compliance of FRR is achieved during daytime participation. In conclusion, "forced strategy" should be implemented to minimize imbalances.
- ESS efficiency should be included to calculate more accurate operation. Two variables should be defined to ESS power output.
- FRR market constrained should be included in the optimization to limit the energy and power from energy market, according to the FRR participation.

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Notation

Abbreviations

ACE	Area Control Error
aFRR	automatic Frequency Restoration Reserve
AGC	Automatic Generation Control
AS	Ancillary Services
BC	Base Case
BMS	Battery Management System
BL	Base Line for PV+ESS analysis
BP	Base Point for WP+ESS analysis
BSP	Balancing Service Provider
BRP	Balance Responsible Parties
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
CIM	Continuous Intraday Market
CR	Cost Reduction scenario for WP+ESS analysis
CRF	Capital Recovery Factor
CSP	Concentrated Solar Power
DM	Day-Ahead Market
DLC	Double Layer Capacitor
DOD	Depth-of-Discharge
DOE	United States Department of Energy
DSO	Distribution System Operator
EFR	Enhanced Frequency Response
EM	Energy Markets
EMS	Energy Management Strategy
ENTSO-E	European Network of Transmission System Operators
EPA	Environmental Protection Agency

ESS	Energy Storage System
ETS	Emission Trading System
EU	European Union
FCR	Frequency Containment Reserve
FEC	Full Equivalent Cycles
FERC	Federal Energy Regulatory Commission
FES	Flywheel Energy Storage
FIT	Feed-in-Tariff
FRR	Frequency Restoration Reserve
FS	Future Scenario for PV+ESS analysis
GHG	Greenhouse Gas
H2	Hydrogen fuel cells
H2	Hydrogen Storage
IB	Imbalance settlement
IM	Intraday Market
ISO	Independent System Operators
ISO-NE	Independent System Operator New England
LA	Lead-Acid
LCOE	Levelized Costs of Energy
Li-ion	Lithium-ion
mFRR	manual Frequency Restoration Reserve
MG	Microgrid
MILP	Mix-Integer Linear Programming
MISO	Midcontinent Independent System Operator
MO	Market Operator
MPC	Model Predictive Control
NaS	Sodium Sulfur
NIMH	Nickel Metal Hydride
NYISO	New York Independent System Operator
O&M	Operations and maintenance

PCC	Point of Common Coupling
PCTL	Percentile
PHS	Pumped-Hydro Storage
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PV	Solar Photovoltaic
R&D	Research and Development
RCP	Shared Peninsular Regulation
REE	Red Eléctrica de España (Spanish TSO)
RES	Renewable Energy Resource
VRB	Vanadium Redox Battery
RPS	Renewable Portfolio Standards
RR	Replacement Reserve
RT	Real-Time
RTO	Regional Transmission Operator
RZ	Regulation Zones
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
SOC	State of Charge
SOH	State of Health
TOU	Time-Of-Use
TSO	Transmission System Operator
UNFCCC	United Nations Climate Change Conferences
USA	United States of America
VPP	Virtual Power Plant
WP	Wind Power

Symbols

$AGC_{RZ,h}$	Hourly AGC energy signal per RZ	[MWh]
$AGC_{r,h}$	Hourly AGC energy signal per RZ	[MWh]
$AGC_{r,k}$	Hourly AGC power signal per RZ	[MW]
CPI	Consumer Price Index	[%]
$C_{k,r}^{ESS}$	ESS capacity for each ESS at sample k	[MWh]
C_{r}^{ini}	Optimal ESS nominal capacity for individual operation	[MWh]
C^{prev}	Initial ESS nominal capacity for a previous research	[MWh]
C_{r}^{nom}	ESS nominal capacity considered in the EMS	[MWh]
c^{MW}	Acquisition power-related costs of the ESS	[M€/MW]
c^{MWh}	Acquisition energy-related costs of the ESS	[M€/MWh]
c^{PV}	Acquisition costs of the PV plant	[M€/MW]
c^{WP}	Acquisition costs of the WP plant	[M€/MW]
D	The optimization day	[-]
$D-1$	The day before the optimization day	[-]
d	Discount rate	[%]
d^{eval}	Number of days evaluated in the ESS aging model	[day]
d^{y}	Number of days per year	[day]
DOD	Depth of discharge	[%]
EoL	End of Life	[yr]
$E_{k_{end},r}^{ESS}$	Energy available for each ESS at the end of the day	[MWh]
$E_{k,r}^{ESS}$	Energy available for each ESS at sample k	[MWh]
$E_{r,k}^{dw}$	Downward FRR energy at sample k	[MWh]

$E_{r,k}^{uw}$	Upward FRR energy at sample k	[MWh]
FLH	Full-Load Hours	[h]
G_y	Annual RES generation per year	[MWh]
$Q_{r,k}^{ESS}$	Current ESS capacity	[Ah]
$Q_{T,SOC,t}^{loss_{cal}}$	Capacity fade loss due to calendar effect	[%]
K_H	Subset of samples for optimization horizon	[-]
K_r	Subset of samples for each RES plant	[-]
k	Subscript for each sample	[-]
$k-1$	Subscript for the previous sample	[-]
k_{end}	Sample at the end of the day	[-]
k_{eval}	Final sample for EMS evaluation	[-]
k_{ini}	Sample at the beginning of the day	[-]
k_{sr}	Sample at sunrise time	[-]
k_{ss}	Sample at sunset time	[-]
$I_{r,k}$	Discharging current	[A]
Io	RES investment costs	[M€]
IRR	Internal Rate of Return	[%]
i	Interest rate	[%]
M	Multiplier for technical terms in the optimization	[-]
n	Expected number of ESS replacements	[-]
n_{eval}	Evaluation period for ESS aging model	[yr]
OF_y	Fixed operations and maintenance costs per year	[M€/MW]
OV_y	Variable operations and maintenance costs per year	[M€/MWh]
$P_{r,k}^{CIM}$	CIM schedule power for RES plant at sample k	[MW]

$P_{r,k}^{DM}$	DM schedule power for RES plant at sample k	[MW]
$PC_{RZ,h}$	Hourly Participation Coefficient per RZ	[%]
$P_{PV,k}^{real*}$	RES generation power after equalization at sample k	[MW]
$P_{RZ,h}^{dw}$	Hourly downward FRR assigned power per RZ	[MW]
$P_{RZ,h}^{up}$	Hourly upward FRR assigned power per RZ	[MW]
$P_{RZ,k}^{band}$	Hourly FRR band assigned power per RZ	[MW]
$P_{need,h}^{dw}$	Hourly TSO downward FRR need power in auction	[MW]
$P_{need,h}^{up}$	Hourly TSO upward FRR need power in auction	[MW]
$P_{r,k}^{ESSin}$	ESS power applied to the ESS	[MW]
$P_{r,k}^{ESSout}$	ESS output power to the ESS	[MW]
$P_{r,k}^{band}$	FRR band availability power for RES plant at sample k	[MW]
$P_{r,k}^{ch}$	Charging ESS power for each ESS at sample k	[MW]
$P_{r,k}^{dch}$	Discharging ESS power for each ESS at sample k	[MW]
$P_{r,k}^{dw}$	Downward FRR power for each RES at sample k	[MW]
$P_{r,k}^{grid}$	Final grid output power	[MW]
$P_{r,k}^{grid*}$	Grid power set-point power	[MW]
$P_{r,k}^{imb-}$	Negative energy imbalance power at sample k	[MW]
$P_{r,k}^{imb+}$	Positive energy imbalance power at sample k	[MW]
P_{k}^{MKT}	DM+IM schedule power at sample k (rule-based opt.)	[MW]
$P_{r,k}^{pred}$	RES generation forecast power at sample k	[MW]
$P_{r,k}^{real}$	Real (instantaneous) RES generation power at sample k	[MW]
$P_{r,k}^{uw}$	Upward FRR power for each RES at sample k	[MW]
P_{r}^{bmax}	Maximum hourly FRR availability power	[MW]
P_{r}^{bmin}	Minimum hourly FRR availability power	[MW]

dd

P_r^{conv}	ESS maximum power (ESS converter power)	[MW]
P_{rk}^{AGC}	AGC power for each RES at sample k	[MW]
R_y^{ESS}	ESS replacement costs for each year	[M€]
R^{ESS}	Total ESS replacement costs	[M€/MWh]
RR_h	Hourly Reserve Rate	[-]
r	Subscript for each RES plant	[-]
$r_{RZ,h}^{dw}$	Hourly ratio for downward FRR band power per RZ	[MW]
$r_{RZ,h}^{up}$	Hourly ratio for upward FRR band power per RZ	[MW]
r_k^{dw}	Ratio for downward FRR band power	[%]
r_k^{up}	Ratio for upward FRR band power	[%]
$\underline{SOC}^{FRR}$	Minimum SOC energy value for FRR participation	[%]
$\overline{SOC}^{FRR}$	Maximum SOC energy value for FRR participation	[%]
$\underline{SOC}^{end}$	Minimum SOC energy value at the end of the day	[%]
$\overline{SOC}^{end}$	Maximum SOC energy value at the end of the day	[%]
$\underline{SOC}^{opt}$	Minimum SOC energy limits for optimization	[%]
$\overline{SOC}^{opt}$	Maximum SOC energy limits for optimization	[%]
$\underline{SOC}^{rt}$	Minimum SOC energy value for RT operation	[%]
$\overline{SOC}^{rt}$	Maximum SOC energy value for RT operation	[%]
$SOC_{r,k}^{ESS}$	State of Charge for each ESS at sample k	[%]
SOC_r^{ini}	State of Charge (current, initial condition) for each ESS	[%]
SOH_r^{ini}	State of Health (current, initial condition) for each ESS	[%]
SOH^{min}	Minimum State of Health	[%]
$SOH_{r,k}$	State of Health for each ESS at sample k	[%]
$u_{r,k}$	Binary variable to charge or discharge for each ESS	[0/1]

$v_{r,k}$	Binary variable for FRR participation for each RES	[0/1]
Y	Lifetime of the renewable asset	[yr]
z^{cal}	Linear calendar coefficient	[-]
z^{cy}	Linear cycling coefficient	[-]
Ψ^{PV}	Expected PV lifetime	[yr]
Ψ^{WP}	Expected WP lifetime	[yr]
ψ^{conv}	Expected converter lifetime	[yr]
Ψ_r^{ESS}	Expected ESS lifetime associated to a RES plant	[yr]
$\gamma_{r,k}^{+/-/b}$	Risk factors for each RES plant at sample k	[-]
$\eta^{ch/dch}$	ESS charging and discharging efficiency	[%]
λ_k^{CIM}	CIM price at sample k	[€/MWh]
λ_k^{DM}	DM price at sample k	[€/MWh]
λ_k^{band}	FRR band price at sample k	[€/MWh]
λ_k^{dw}	Downward FRR energy at sample k	[€/MWh]
λ_k^{imb-}	Negative energy imbalance price at sample k	[€/MWh]
λ_k^{imb+}	Positive energy imbalance price at sample k	[€/MWh]
λ_k^{uw}	Upward FRR energy at sample k	[€/MWh]
Δi	Period of time for maximum energy deviation eq.	[-]
Δk	Time step for the optimization	[-]
$\Delta P_{r,k}^{pred}$	Variation of RES generation forecast for each RES	[MW]
ΔP_r	Power difference for RES equalization at sample k	[MW]
$\Delta SOH_{r,k}^{cy,cal}$	Capacity fade due to cycling or calendar effects	[MWh]
ΔSOH_r^{acc}	Accumulated capacity fade from previous aging analysis	[MWh]
Δt	Real-time period	[-]

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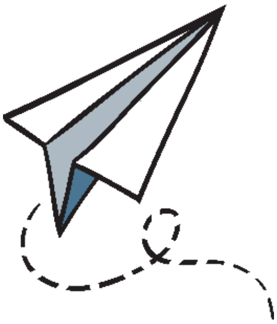

Turning an Ending into a New Beginning