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Development of strategies for energy storage in distribution grids with RES

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“*La vida no es la que uno vivió, sino la que uno recuerda*
y cómo la recuerda para contarla”
(“Vivir para Contarla”, Gabriel García Márquez)

To the ones who helped me to build and save positive memories, even in difficult times.

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Abstract

Energy Storage Systems (ESS) are key technological solutions for the sustainable transition and decarbonization of the electrical power system. In particular, battery storage stands out due to its interesting versatility in providing several applications and services along the energy value chain, which contributes to preserving flexibility as a characteristic to face the several challenges that represent moving from a system dominated by polluting generation sources (i.e. oil, natural gas, and coal) to a system based on renewable energy sources (RES).

The massive and accelerated integration of renewable sources, such as solar and wind, indicates that the intermittent nature that characterizes these sources will also be present in the electrical power network. Due to a significant percentage of these sources are integrated into the distribution networks (DN), that the DNs are aged and very close to their operational limits, and that increasingly more consumers are becoming empowered to manage and control their consumption, the approaching of the planning and operation problems has been changing to manage the uncertainties surrounding the processes and to devise strategies for designing a flexible, sustainable, and decarbonized electrical power network that is also economically accessible and fair.

Although BESSs are considered a key pillar in the electrical power network, their deployment into DNs is subject to economic, environmental, technical, and technological barriers, but mainly by the absence of a regulatory framework that promotes the integration of BESSs and allows their participation in the different markets to obtain a remuneration according to the benefit/service extracted from this technology. This context raises the question of how to plan and operate BESSs that can offer services to various stakeholders/players while taking advantage of the different markets when integrated into the DNs, considering the process ensures the quantification of the technical and economic impacts imposed by the technology and by the lack of tools to estimate a remuneration scheme for the provision of flexibility and storage services.

This work paper presents the results of a research project that aims to develop a methodology for supporting investment decision-making in BESS integrated into the DN whose planning and operation strategies are devised to deal with uncertain scenarios. Admitting that the methodology proposed is focused on the BESS integration decisions, instead of the comparison of the optimization methods and techniques, this considers the conceptual basis of planning and the current need of the power network to capture its essence. However, it is guaranteed that the optimization process and the uncertainties management are supported by methods and techniques with the robustness required by the subject addressed here.

In particular, this work considers that the planning and operation cannot be seen from a single perspective, the one from the DSO or distribution companies, but from multiple perspectives related to the stakeholders/players involved in the problem. Although the problem is not addressed from a multicriteria approach, the decision-making process allows the participation of more than one decision-maker promoting an economical and technically conciliatory process of the final decision, which is devised in a way that is accessible for the understanding of a broader range of stakeholders/players who nowadays are considered as those with the greatest potential to shape the future of the electrical system, the small-scale players.

The merits of this approach are discussed throughout the document due to the complexity of planning and operation of BESS integrated into the DNs under uncertain scenarios and from the perspective of small-scale investors. The combinatorial nature of the planning problem and the need to consider more realistic models of the DNs and the devices make this work proof that a hybrid approach between evolutionary computing and linear programming is advantageous. Moreover, the complexity involved in the decision-making process pinpoints its important contribution in providing a way to identify an investment decision in the absence of regulatory frameworks that reward flexibility and storage services, based on a conciliatory process that aims to reduce the possibility that a decision generates regret. For this reason, the planning and operation problems and decision-making process are decoupled to identify their contributions and ensure the robustness of the approaches as well.

The case studies considered to prove these approaches demonstrate that, given the current context of the electrical power system and the challenges it is facing, it is essential to quantify the impacts of storage technologies because the BESS planning into the DNs must be represented by detailed models of their operation (under a high temporal resolution, and due to the services it may provide). In addition, the cost of investing in BESS requires that the process for selecting the technology and the network interface and the sizing of the battery, which depends on several aspects, also be supported by more realistic models of the network and devices. This is because it is from this approach that valuable information can be provided to investors about investment opportunities and economic returns, and to regulatory entities about the need for incentives and regulatory frameworks that economically counterbalance the current costs of investment in BESS.

Resumo

Os Sistemas de Armazenamento de Energia (SAE) são a solução tecnológica chave na transição sustentável e a descarbonização do sistema elétrico. Especificamente, o Armazenamento em Baterias (SAEB) destaca pela sua interessante versatilidade para prover diversos aplicações e serviços ao longo da cadeia de valor da energia, com os quais pode contribuir para preservar a flexibilidade como uma caraterística com a qual pode enfrentar inúmeros desafios que implica passar dum sistema elétrico baseado em fontes de geração poluentes (nomeadamente, petróleo, gás natural e carvão) para um sistema baseado em fontes renováveis de geração de energia.

A integração massiva e acelerada de fontes renováveis, tais como a solar e a eólica, indica que no sistema elétrico também estará presente a natureza intermitente que carateriza a estas fontes. Devido a que uma percentagem significativa destas fontes estão a ser integradas ao nível das redes de distribuição, que tais redes estejam envelhecidas e muito próximas aos seus limites operativos e, que a cada dia mais consumidores estejam a se empoderar para gerir o seu consumo, a abordagem do problema do planeamento e operação do sistema elétrico tem estado a mudar ligeiramente no intento de gerir as incertezas associadas aos processos e de idear estratégias para desenhar um sistema quer flexível, sustentável, e descarbonizado, quer economicamente acessível e justo.

Embora os SAEBs sejam considerados um pilar fundamentar para o processo de transição do sistema elétrico, a sua integração nas redes de distribuição esta a ser posta em causa pelas inúmeras barreiras económicas, ambientais, técnicas e tecnológicas, mas, principalmente pela ausência de um enquadramento regulatório que promova a implementação dos SAEBs e que permita a sua participação nos diversos mercados para serem remunerados em concordância com o beneficio/serviço extraído a partir destas tecnologias. Este contexto leva à questão de como planear e operar SAEBs que possam oferecer serviços a vários atores do sistema e tomar vantagem dos diversos mercados nos quais possa participar quando integrados às redes de distribuição, considerando que no processo é garantida a quantificação dos impactos das componentes técnica e económica impostos pela própria tecnologia e pela falta de ferramentas para estimar uma remuneração pela provisão de flexibilidade e serviços de armazenamento.

Este trabalho apresenta os resultados de um projeto de investigação destinado a desenvolver uma metodologia para a toma de decisões de investimento para a integração de SAEBs nas redes de distribuição cujas estratégias para o planeamento e operação estejam desenhadas para lidar com cenários incertos. Admitindo que o foco principal da metodologia é a decisão da integração dos SAEB e não a comparação de métodos e técnicas de otimização, dita metodologia acolhe-se à base conceitual do planeamento e as

necessidades atuais do sistema para tentar capturar a sua essência. Contudo, é garantido que o processo de otimização e a gestão das incertezas sejam suportados por métodos e técnicas com a robustez que amerita o assunto aqui abordado.

Especificamente, este trabalho considera que o planeamento e a operação não podem ser mais vistos desde uma única perspetiva, aquela do operador da rede ou das empresas de distribuição, e sim desde múltiplas perspetivas associadas aos atores implicados no problema. Embora o problema não seja abordado desde um enfoque multicritério, o processo de toma da decisão permitir a participação de mais do que um decisor para promover um processo económico e tecnicamente conciliatório da decisão final, sendo este desenhado de forma acessível para o entendimento de atores do sistema que hoje são considerados como aqueles com o maior potencial para moldar o sistema elétrico do futuro, os atores de pequena escala.

Os méritos de esta abordagem são discutidos ao longo do documento pela complexidade que representa o planeamento e operação dos BAESs quando integrados a redes de distribuição sob cenários de incerteza e desde a perspetiva de investidores a pequena escala. A natureza combinatória do problema de planeamento e a necessidade de considerar modelos mais realistas das redes de distribuição e dos dispositivos fazem com que este trabalho seja prova de que uma abordagem baseada num híbrido entre computação evolucionaria e programação lineal é vantajosa. Também, complexidade que refere o processo de toma de decisões ressalta a sua importante contribuição ao prover um caminho para identificar uma decisão de inversão na ausência de quadro regulatórios que remunerem a flexibilidade e os serviços de armazenamento, baseado num processo conciliatório que visa reduzir a possibilidade de rejeitar uma decisão. Por isso, o problema do planeamento, operação e o processo de toma de decisões são desacoplados para identificar as contribuições de cada um, bem como para garantir a robustez da abordagem.

Os casos de estudo que acompanham estas abordagens demostram que, face ao contexto atual do sistema elétrico e aos desafios que está a tentar gerir, é fundamental quantificar os impactos das tecnologias de armazenamento pelo facto que, o planeamento dos SAEBs nas redes de distribuição devem estar baseados em modelos detalhados da sua operação (sob uma elevada resolução temporal e por motivo serviços que podem fornecer). Adicionalmente, os custos de investimentos em SAEB obrigam a que o processo de seleção da tecnologia e dimensionamento da bateria, o qual depende de múltiplos aspetos, também esteja baseado em modelos mais realistas da rede e dos dispositivos. Isto, porque é desde esta perspetiva que se pode oferecer informação valiosa aos investidores no que refere às oportunidades de investimento e retorno económico, bem como as entidades reguladoras relativamente às necessidades de incentivos e quadros regulatórios que economicamente contrariem os custos de investimento em SAEB.

Resumen

Los sistemas de Almacenamiento de Energía (SAE) son tecnologías clave para la transición sustentable y la descarbonización del sistema eléctrico. Especialmente, el Almacenamiento en Baterías (SAEB) resalta por su interesante versatilidad para proveer diversas aplicaciones y servicios a lo largo de la cadena de valor de la energía, con los cuales puede contribuir para preserve la flexibilidad como una característica para enfrentar los diversos desafíos que representa pasar de un sistema basado en fuentes de generación contaminantes (petróleo, gas natural y carbón) para un sistema basado en fuentes renovables de generación de energía.

La integración masiva y acelerada de las fuentes renovables, tales como la solar y la eólica, indican que en el sistema eléctrico también estará presente la naturaleza intermitente que caracteriza a estas fuentes. Debido a que un porcentaje significativo de ellas es integrado a nivel de distribución, que estas redes estén envejecidas y muy próximas sus límites operativos y, que cada día más consumidores estén empoderándose para gestionar y controlar su consumo, el enfoque del problema de planificación y operación del sistema eléctrico ha estado cambiando ligeramente en el intento de gestionar las incertidumbres asociadas a los procesos y de idear estrategias para diseñar un sistema flexible, sustentable y descarbonizado que también sea económicamente accesible y justo.

Aunque los SAEB sean considerados un pilar fundamental para el proceso de transición del sistema eléctrico, su integración en las redes de distribución está limitada por las diversas barreras económicas, ambientales, técnicas y tecnológicas, pero, principalmente por la ausencia de un marco regulatorio que promueva la implementación de los SAEBs y que permita a su participación en los diversos mercados para que sean remunerados de acuerdo con el beneficio/servicio extraído a partir de esta tecnología. Este contexto lleva a cuestionar como planear y operar SAEBs que puedan ofrecer servicios a varios actores del sistema y sacar ventaja de los diferentes mercados en los cuales puede participar una vez integrados a las redes de distribución, considerando que en el proceso se garantiza la cuantificación de los impactos de las componentes técnica y económica impuestos por la propia tecnología y por la falta de herramientas para estimar una remuneración para la provisión de flexibilidad y servicios de almacenamiento.

Este trabajo presenta los resultados de un proyecto de investigación destinado a desarrollar una metodología para la toma de decisiones de inversión para la integración de SAEBs en las redes de distribución cuyas estrategias para la planificación y operación estén diseñadas para enfrentar escenarios de incertidumbre. Admitiendo que el foco principal de la metodología es la decisión de integración de los SAEBs y no la comparación de métodos y técnicas de optimización, esta se acoge a la base conceptual de la planificación

y a las necesidades actuales del sistema para intentar capturar su esencia. No obstante, se garantiza que el proceso de optimización y la gestión de las incertidumbres sea soportado por métodos y técnicas con la robustez que amerita el asunto aquí abordado.

Específicamente, este trabajo considera que la planificación y la operación no pueden ser vistos desde una única perspectiva, aquella del operador de la red o de las empresas de distribución, y si desde múltiples perspectivas asociadas a los actores implicados en el problema. Aunque el problema no esté abordado desde un enfoque multicriterio, el proceso de toma de decisión permitir la participación de más que un decisor para promover un proceso económico y técnicamente conciliatorio de la decisión final, siendo este diseñado de forma accesible para el entendimiento de actores del sistema que hoy son considerados como aquellos con el mayor potencial para moldear el sistema eléctrico del futuro, los actores de pequeña escala.

Los méritos de este planteamiento son discutidos a lo largo del documento dada la complejidad que representa la planificación y operación de los SAEBs integrados a las redes de distribución bajo escenarios de incertidumbre y desde la perspectiva de inversionistas de pequeña escala. La naturaleza combinatoria del problema de planificación y la necesidad de considerar modelos más realistas de las redes y de los dispositivos hacen con que este trabajo sea prueba de que un planteamiento hibrido entre computación evolucionaria y programación lineal es ventajosa. Además, la complejidad que representa el proceso de toma de decisiones resalta su importante contribución al proveer un camino para identificar decisiones de inversión en ausencia de marcos regulatorios que remuneren la flexibilidad y servicios de almacenamiento, basado en un proceso conciliatorio con el que se pretende reducir la posibilidad de rechazo de una decisión. Por esto, el problema de planificación, operación y toma de decisiones son desacoplados para identificar las contribuciones de cada uno, así como para garantizar la robustez del planteamiento.

Los casos de estudios que acompañan estos planteamientos demuestran que, frente al contexto actual del sistema eléctrico y a los desafíos que intenta gestionar, es fundamental cuantificar los impactos de las tecnologías de almacenamiento porque la planificación de los SAEBs en las redes de distribución debe estar representados por modelos detallados de su operación (bajo una elevada resolución temporal y por motivo de los servicios que puede prestar). Además, los costos de las inversiones en BESS obligan a que el proceso de selección de la tecnología y el dimensionamiento de la batería, el cual depende de varios factores, también esté soportado por modelos más realistas de la red y de los dispositivos. Esto, porque é desde este enfoque que se puede ofrecer información valiosa a los inversionistas en lo que respecta a las oportunidades de inversión y retorno económico, así como a las entidades reguladoras en lo que se refiere a las necesidades de incentivos y marcos regulatorios que económicamente contrarresten los costos de inversión en SAEBs.

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Abbreviations

BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
DG	Distributed Generation
DISCO	Distribution Company
DN	Distribution Networks
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators
EPC	Engineering, Procurement, and Construction
EPSO	Evolutionary Particle Swarm Optimization
EoL	End of Life
ERSE	Entidade Reguladora dos Serviços Energéticos
ESS	Energy Storage Systems
EU	European Union
IEP	Independent Energy Provider
LAC	Latin America and the Caribbean
LP	Linear Programming
NECP	National Energy and Climate Plans
OPEX	Operating Expenditure
PV	Photovoltaics
PDF	Probability Distribution Functions
REC	Renewables Energy Community
RES	Renewable Energy Source
SDG	Sustainable Development Goals
SoC	State of Charge
SoF	State of Function
SoH	State of Health
TSO	Transport System Operator
USA	United States of America

Chapter 1

Introduction

1.1. Overview

This research focuses on studying and developing strategies for planning and operating Energy Storage Systems (ESS), specifically Battery Energy Storage Systems (BESS), within distribution networks (DN), able to deal with uncertain scenarios. Different DN planning and operation challenges, from the small-scale investors (such as aggregators, Independent Energy Providers, IEP, and Renewables Energy Communities, REC) perspectives, are addressed regarding the sustainable integration of BESS in the presence of Renewable Energy Sources (RES), namely solar photovoltaics (PV) systems.

The rise in RES has become the ESS as a technological solution that has the potential to revolutionize the electrical power system by providing it with several services [1], [2]. Specifically, BESS stands out given its modular characteristic permits decision-makers to customize (scaled up or down) the energy/power capacity regarding technical or economic needs revealed by the network and the physical location available to install the technology [3]. Nonetheless, several regulatory, economic, environmental, market, pricing, and other barriers/difficulties have limited the widespread deployment of the different ESS technologies [4], [5].

Without a clear and defined regulatory scheme for storage activities, from the perspective of small-scale investors, it is challenging to estimate the overall cost of a BESS project as close as possible to reality given the uncertainties surrounding the process. Therefore, it is necessary to consider detailed models of BESS and the uncertainties related to the operation (how energy traded is paid) and the planning process (e.g., load profiles, generation from RES, and network configuration [6]. Approaching scenarios that would happen is crucial because it allows decision-makers to obtain valuable information about the risk of regretting the decisions chosen [7].

This chapter aims to contextualize the subject that motivated this research work. A brief description of the problems studied is provided, and the research boundaries are established. Moreover, this chapter outlines objectives and identifies questions and hypotheses to illustrate the starting point of this research. Finally, the thesis structure and the content of each chapter are described.

1.2. Context and Motivation

Over a century ago, electricity generation, transmission, and distribution began supplying it to small and concentrated load centers through power networks usually limited by geographic boundaries. However, the ongoing growth of energy consumers and energy demand, and the integration of technological innovations into the electrical power systems led to a scenario where the expansion of the network was needed since energy generated must be driven to consumers significantly far away. Then, the electrical power network had to evolve into an interconnected system that continuously required more resources to electrify new areas or properly install electrical infrastructure; in other words, the power network grew over a centralized model where the problem to solve was mainly focused on the transport and distribution of energy over long distances to meet the current and future energy demands while maintaining the technical and quality parameters of the electrical network within standard values [8]–[10].

The centralized generation model has gradually been changing to a decentralized one as a response to some technical and non-technical challenges the electrical power system has been facing, namely [11]–[16]:

(i) To integrate Distributed Generation (DG) from RES into the electrical power network;
(ii) To empower the consumers (e.g. taking a more active role represented by demand response, self-consumption, microgrids, RECs actions, among others);
(iii) To deal with the energy markets liberalization and emerging energy business models;
(iv) To fight climate change and reduce global greenhouse gas emissions;
(v) To reach an energy transition to long-term carbon-neutrality, mitigate poverty, and promote sustainable development.

From this scope, flexibility has become a key quality to be reached by current electrical power systems since they must be reliable and cost-effective to deal with the uncertainties related to the energy demand and supply across all timescales (from milliseconds to hours) and for different amounts of power [17]–[19]. Although flexibility was traditionally handled through conventional generation units, the aspects pinpointed above have outlined that new “sources” of flexibility are needed [20] to balance the energy demand-supply mismatches [21] while dealing with problems such as voltage fluctuations, RES intermittency, network congestion, among others [22].

To cope with these, planners and operators have been devising strategies to reach an electrical power system that ensures an economical and reliable energy supply while attending to multiple uncertain scenarios and objectives. Researchers have also highlighted these subjects in the literature [10], [21], [23], [24] given power networks are one of the most critical infrastructures in a region or country that support other areas, namely, telecommunications, transportation, or water supply systems. Therefore, the careful planning and operation of the electrical power system is becoming a more complex task in which the decisions taken along this process may affect the economy of that region or country in the mid- and long-term.

1.2.1. Do distribution networks need ESS?

Sustainable development and the energy transition have attracted worldwide attention since they represent a needed shift where global, regional, and local actions must be taken to meet a decarbonized electricity sector as well as a flexible, reliable, and safe electrical power system [17], [19], [25]. These challenges push forward to an electrical power system based on a low-carbon (by moving from conventional generation technologies e.g., oil, natural gas, and coal, to an energy mix comprised of RES and ESS [26]), energy-efficient, reliable, and economically affordable energy supply model [21], [27], [28], where the role of consumers becomes more relevant and active. But, these changes also bring technical problems for the electrical power network e.g. the traditional principle of "generation follows demand" is no longer applied [25].

Some of the challenges and issues are summarized below:

(i) RES such as wind and solar PV are being integrated into the electrical power systems around the world as an action to fight climate change and its effects and as a response to fossil fuel prices [17], [19], [21]. Their penetration levels into the power networks are expected to substantially increase as the electricity sector moves to the decarbonization targets [29]. Therefore, the combination of high penetration levels of RES with the deregulation of the electricity sector, the progressive growth of energy demand (mainly, the peak demand), and the efforts in reducing energy storage costs have focused the attention on the ESS to improve the flexibility, reliability, and safety of the electrical power system [11], [17], [30].

(ii) According to [29], RES will share 68% and 91% of the global electricity production by 2030 and 2050, respectively, from approximately 28% in 2020. Therefore, it is expected that energy production from wind and solar PV will be responsible for supplying 46% and 70% of global electricity production by 2030 and 2050, respectively (from approximately 9% in 2020) thanks to the availability of their resources, the cost-competitive markets, and the low-cost in supplying energy when compared to fossil fuels. These targets have also focused on ESS as a useful technological solution to deal with the variable and intermittent nature of RES, the possible network congestion during periods of peak production, and production curtailment [5], [19], [31]–[34].

(iii) The empowerment of consumers leads them to take a more active role in deciding how and when energy is produced, consumed or shared [35]. Represented as self-consumers and prosumers, in an individual way or, by IEPs, RECS, and aggregators in a grouped way, they may influence the energy exchanges with the electrical power network by redefining the load profiles. This means reducing (shaving the peak load), increasing (fill the valley periods), or rescheduling energy demand (shifting the load behavior) [34]. According to [36] it is estimated that by 2030 around 50 GW of wind power and more than 50 GW of PV power can be owned by energy consumers, which means 17% and 21% of the total European Union (EU) installed capacity, respectively. These targets have also focused on ESS such as BESS, a useful technological solution to provide services to support these consumers' actions.

(iv) Further RES units (mainly mid- and small-size ones) can be accommodated into the DN in a distributed framework because RES with lower energy density may be widespread as closer as possible to the demands/loads, avoiding the need for investments in network upgrades and reducing technical losses [36], [37]. Nonetheless, there are also expected more requirements to maintain the technical and quality parameters of the DNs within standard values because RES integration (mainly from the ones dependent on the weather) can lead to local congestion, overvoltage, voltage fluctuations, and slight increases in the short circuit currents, among others. As storage technologies such as BESS can also be framed in the concept of distributed resource [38], [39], DN planners and operators can consider this powerful characteristic to deal with the technical issues previously mentioned.

These challenges accentuate the relevance of achieving an electrical power system effectively managed [40] and capable of dealing with the uncertainties related to energy consumption, generation, and network behavior and configurations. In this context, flexibility plays an important role in varying energy production as a response to load changes to maintain the network's reliability, stability, and safety. Hour-to-hour energy balance implies varying the energy production setpoint of some units as needed. Minute-to-minute and millisecond-to-millisecond energy balances imply rapidly varying energy production setpoints through the ancillary services available. Then, it could be understandable that flexibility depends on the relationship between the mandatory time to balance the electrical power system and the response time of the generation technology used to do it [19], [41].

The flexibility provided by the DN could be represented by actions like avoiding congestion in the local network, shifting or shaving the load profiles, and mitigating power quality issues. As the integration of DGs continues at an accelerated growth, new "sources" of flexibility are required to ensure the technical and quality parameters within standard values, while deferring network upgrades (when traditional reinforcement is less cost-efficient) and supporting network transition [10].

ESS and specifically BESS are an effective technological solution with the potential for supporting RES integration and consumer empowerment, while providing the DN with several services [11], [42], [43]. BESS deployment can be a "source" of flexibility since it may capture surplus energy from the network and release it when technically needed or economically affordable[3], [5], [33], [34], e.g. BESS may charge/discharge as a response to changes in power flows on a feeder, which may contribute to dealing with technical constraints such as local voltage variations and/or feeder congestion while improving the DN reliability. Moreover, when BESS is integrated as close as possible to the connection point of a PV system it can counteract the rate of change of the energy produced, avoiding sudden voltage fluctuations in the network.

ESS can tackle several potential applications/services such as energy arbitrage, peak shaving, voltage support, reliability improvement, and network deferral [5], [31]–[34], [37], [44], [45], among others detailed in Section 2.4. According to [44], BESS applications can be classified into two main groups as follows: group A, or technical-support oriented, and group B, or profit-making oriented. In group A, ESS is used to improve the performance of the electrical power network. In group B, ESS is used to achieve a profitable business from the investors' perspective. Nevertheless, a new group focused on the benefits to energy consumers is emerging [46], [47].

As the sustainable development and energy transition advance, DISCOs, TSOs, and DSOs must deal with the technical issues and uncertain scenarios, which means DN planners, operators, and decision-makers must work on devising strategies for designing a technical, economic, social, and environmentally suitable electrical power system that attends to multiple scenarios and objectives [5], [10], [34], [44], [48]. Nowadays, ESS also provides versatility because its optimal size, location, and operation are relevant to achieving the objectives of the TSO/DSO, the investors, and consumers. This is no wonder given that ESS technologies have the potential to support the network by integrating different storage capacities to be operated at different timescales, which means they represent a wide flexible option that can bring significant incentives/benefits to the stakeholders/players.

1.2.2. Challenges to be faced regarding BESS planning and operation in DN

The planning and operation of the power network have traditionally been addressed to supply energy to the consumers by considering: (i) attending to the current and future energy demand; (ii) identifying the need for replacing the equipment that reaches the end of its useful life, and (iii) identifying the need for network expansion/reinforcement [8], [10]. With RES integration and consumer empowerment, both the objectives and uncertain scenarios (related to changes in load profiles, intermittent from RES and error forecasts, and network configuration, among others) have been enlarging the DN planning and operation problem due to their influence on the power flows, voltage profiles, load profiles, losses, and even, in the overall network operation [25], [32] and consequently on the profitability and benefits perceived by the different stakeholders/players.

In the DN, an inappropriate RES integration often results in low and rapid reverse currents and unpredictable changes in the current magnitude of a feeder, non-standard voltage profiles along a feeder, non-effective response of voltage regulators and capacitors, and/or non-effective operation of the protection and restoration schemes [23]. Therefore, innovative solutions in a variety of ways are needed to deal with different penetration levels of RES, its intermittent nature, and the two-way currents flowing in feeders/branches while ensuring technical and quality parameters of the electrical network within standard values. As well as this, there are other challenges the DN must face, which are summarized below:

(i) As RES does not follow the local energy demand it is crucial to find a solution to ensure the energy supply-demand balance as the RES penetration levels increase into the DN. This fact stands out when two scenarios are analyzed [32]: A) at middle-high energy demand if there is low RES production, an energy deficit might occur which may affect the stability and some technical and quality parameters of the network; B) at middle-low energy demand, if there is high RES production, local voltages could become higher and the power flows reversed. Both scenarios can be carefully approached from the perspective of integrating BESS in the DN planning and operation since BESS will allow RES to choose between releasing, storing, or losing the surplus energy [45] while enhancing the flexibility and reliability of the network. Therefore, it is expected to allow BESS integration into the DN to better manage it [19].

(ii) As the energy transition advances, DN requires dealing with the variable and intermittent RES nature by counteracting changes in energy production as fast as possible. Considering that energy produced from RES is environmentally and weather-dependent, there is no option to manage and control the natural resources and the energy produced. For example, if clouds suddenly cover a PV system, its production profile changes very fast, and voltage fluctuations occur. Even though there are several tools to forecast RES production, considering the aforementioned fact involves some degrees of inherent error [34], and the difference between the energy produced and forecasted influences the DN operation [37]. These are often the most significant aspects that limit the PV hosting capacity in the DN [31], nevertheless, BESS will be used to smooth rapid changes in the RES production and provide a firming capacity given this is a technological solution with a faster response time than other ESS technologies.

(iii) Around 700 million worldwide people still live without access to electricity [17], [25], [49], therefore, is expected an ongoing increase as new users are connected to the power network. According to [17] global electricity demand will likely rise between 90% and 240% by 2050 regarding the values reached in 2022, mainly, due to emerging economies (population growth reflects in demand growth). However, in the last few years, demand growth from consumers already connected has been affected by political, environmental, and economic situations. During the COVID-19 pandemic, energy demand recorded an unprecedented deviation from the forecasts decreasing around 2,5% in the first quarter of 2020. Countries that represent one-third of global energy demand accounted for a reduction of about 20% during the full lockdown [25], [50], being commercial and industrial consumption reduced while residential increased. According to [50], contrary to the energy consumption recorded in Sweden, Denmark, and Finland, countries such as Italy, France, and Spain showed larger decreases in energy consumption. Regarding LAC, Argentina, Brazil, and Mexico also showed a reduction in energy consumption, but Chile did not.

(iv) Political, environmental, and economic situations have recently been affecting electricity and regulation market prices as well as the demand forecast. By 2022, an increase of about 4% to 5% in the energy demand was expected, nevertheless, negative deviations were recorded because the energy prices skyrocket with Russian-Ukrainian war, [17], [51] which led to consumers to manage their consumption under other a more restrictive scope. Since then, the global energy demand has been growing but uncertainties over its growth rate remain. In fact, the wide range of demand growth by 2050 reported in the previous item occurs because the authors [17] consider scenarios based on political, social, and environmental commitments and targets.

(v) A profitable energy transition towards carbon-neutral production and energy supplies requires greater flexibility from the electrical power system to keep a continuous energy supply as the power system responds to changes in generation or consumption regardless of what causes the network disturbance [27]. Achieving proper flexibility without ignoring economic objectives is crucial in the BESS and DN planning approaches. Thus, decision-makers need to move from this classical model to a challenging one where the equilibrium between different criteria and uncertainties is considered. Moreover, new cooperation schemes between DSO and TSO are also required [19] to implement a functional architecture where different BESS interact with stakeholders, market operators, and DSO/TSO. As expected, cooperation schemes involve the creation/definition of commercial contracts focused on the flexibility provision.

(vi) Ongoing changes in the DN structure force planners and operators to deal with uncertainties that enlarge the DN planning and operation problem. To cope with these, the development of strategies to model the DN and the technological solution as close as possible to reality stands out as a crucial task to provide valuable information to decision-makers [3], [52]–[55].

(vii) The DN complexity is the main problem for its planning and operation since several constraints must be fulfilled, which means, the DN planning and operation problem is a large-scale problem that has a significant combinatorial characteristic and, as the size of the problem grows (as a consequence of using models as close as possible to the reality), the difficulty of finding a suitable solution also increases. Solving BESS planning and operation problems could take a long processing time, nevertheless, how the optimization problem is approached depends on the expected tradeoff between accuracy, reliability, and processing time [24], [44].

In summary, the DN has been experiencing a shift in the planning and operation paradigms given that the socioeconomic, environmental, and policy challenges added to the increment of RES integration have led planners and operators to deal with more temporal, spatial, and technological uncertainties while strategies to achieve a more sustainable system based on a low-carbon, reliable, and economically affordable energy supply model are developed [21], [27], [28], [30]. It could be said that the current planning approaches need to be more than simply determining the energy production required to meet the forecasted energy demand from a pool of sources that can be assumed as always available [31].

Innovative DN planning and operation strategies that properly deal with uncertainties and multiple scenarios are required to mitigate the risk of over/underinvesting and inappropriate technological integrations [1], [11], [56]. Considering energy production as a commodity that may be wasted if not preserved or consumed, BESS highlights as a key solution to be strategically integrated into DNs and provide services to those networks that are evolving to achieve a sustainable energy transition. Their modular characteristic makes them attractive to be easily customized and located into highly constrained DNs.

1.2.3. Treaties, agreements, and plans to improve power system flexibility, reliability and security

Improving the flexibility, reliability, and security of the electrical power network is relevant, particularly in the context of RES and BESS integration. Different treaties, agreements, and plans have been launched and approved aiming to achieve this objective.

On a global scale, some important instruments have arisen to face the challenges of ensuring sustainable energy development and mitigating climate change impacts. The Paris Agreement's central goal is focused on limiting the increase in global average temperature to well below 2 °C above the preindustrial levels and pursuing efforts to limit it to 1.5 °C [15], therefore, it calls for governments to take immediate action that contributes to achieve the goal. Regarding the SDG, in 2015, the United Nations introduced them as a plan of action characterized by its global nature and universal applicability that emphasizes environmental, social, and economic aspects of development, by setting sustainability at its center, which leads to work on strategies on different development field while tackling climate change and preserving the oceans and forests [13]. More recently, in 2023, about 200 governments defined an agreement at the Climate Change Conference of the Parties 28th session (COP28) that aims to triple RES capacity and double energy efficiency progress by 2030, which set batteries as a key technology that may play a decisive role in realizing this vision [30].

On a regional scale, a relevant case of effort is the one demonstrated by the European Union (EU), which around a decade ago, was the first major power in the world to set ambitious environmental policies while increasingly expanding and integrating its energy and climate targets. Surpassed only for the United States, the EU has been responsible for about 11% of global yearly CO_2 emissions (the most dominant greenhouse gas produced by fossil fuel burning) in the last years [57]. In this scope, in 2019 the EU Member States adopted the integrated national energy and climate plans (NECPs) for 2021-2030, agreed as part of the clean energy for all the Europeans packages. The NECPs outline how EU countries will reach their targets on strategic topics like energy efficiency; renewables; greenhouse gas emissions reductions; interconnections; and research and innovation [14],

[58]. In 2019, the EU Commission also launched the European Green Deal, a roadmap that enshrines its aim to be climate-neutral by 2050. This deal covers many sectors of the economy, such as transport, energy, agriculture, buildings, and industries. [12].

On a local scale, there are many differences between developed and developing countries. While most developed countries envision sustainable solutions for the future, developing countries have not started a real low-carbon transition, by this, they must rapidly increase their investments in clean energy to achieve their targets for 2030 [17]. Therefore, the SDGs, targets, and other goals framed on the sustainable energy transition have been set considering every national reality, capacity, and level of development by respecting national policies and priorities. Usually, emergent economies are focused on energy supply security and economic growth. Then, the sustainable energy transition actions are occasionally justified by the need for a global shift regarding the energy generation technologies used, from some conventional ones [5], [30].

As previously mentioned, EU Member States already have the NECPs for 2021-2030 [14] and the European Green Deal launched by the EU Commission to provide a roadmap for enshrining its goals to be climate-neutral by 2050 [12]. Regarding LAC, a regional initiative created in 2019 within the framework of the United Nations Climate Action Summit called the Renewables in Latin America and the Caribbean (RELAC) supports that it is expected to achieve penetration levels of RES of about 70% into the LAC electricity matrix by 2030 [59]. However, unlike the EU, each LAC country has been developing its roadmap to achieve its targets [60].

According to [29], the power sector is one of the largest contributors to global CO_2 emissions sharing 40% in 2022, pinpointing the relevance of identifying the gap between where we need to be and where we are. EU needs to ramp up RES installations around three times by 2030 and six times by 2050 (accounting for 3356 GW of installed capacity) while the United States of America (USA), and Latin America, and the Caribbean (LAC) need to ramp up RES installations around five and twelve times (for accounting 4911 GW of installed capacity), and three and eight times (accounting for 1959 GW of installed capacity), respectively[29]. As mentioned in [25], RES is still growing three times faster than fossil fuels and nuclear but still accounting for less than one-third of the increases in the global energy demand.

Wide RES deployment into the power system imposes new challenges for the decision-makers when the DN planning and operation problem is approached. As mentioned in Section 1.2.2, the intermittent nature of RES forces planers and operators to cope with different uncertainties and behaviors related to the availability of each energy resource. Particularly, generation from RES, like wind and solar, represents a challenge for electrical power systems with a low share of hydropower in the energy matrix since these renewable sources introduce variations in the generation side [30] that in a traditional scope are properly smoothed by using flexible generation units as hydropower. In contrast to the United States and EU countries, the relevant share of hydropower in the energy matrix of LAC countries facilitates the integration of distributed resources to provide system flexibility [17]. This is not a trivial fact when it is considered that as a result of the energy transition plans, several global, regional, and local actions are promoting the RES integration to reach the carbon-neutrality goals, which leads to increasing its penetration levels into the power networks as well as the challenges to be faced as a consequence of the uncertainties associated to generation from RES.

1.3. Thesis Scope, Research Challenges and Objectives

Economic growth and energy demand have always been linked. As an economy grows, the energy demand is also expected to grow and vice versa [5], [17], [61]. This strong dependence reflects the need for a region or country to thoroughly plan its power system in such a way as it can supply affordable and reliable energy to meet the current and future energy demand.

Until a few years ago, planning the power system implied finding a strategy that defines, at a minimum cost, when and where to install or upgrade substations, transmission and distribution lines, transformers, feeders, and/or generation units as close as possible to load centers/consumers, or when and where to replace them as a consequence of their end of life [8], [9]. As mentioned in Section 1.2.2, the several challenges the power system is facing have led decision-makers to experience a shift in the DN planning and operation paradigms that pinpoint the need for developing strategies that allow, even at a minimum cost and under consideration of uncertain scenarios, to build a sustainable electric power system as well.

The current power systems require increasing flexibility, network security, and reliability [30]. However, flexibility depends on the services conducted by the system operators and requires mandatory regulatory changes to be provided by the DSO [5], [19]. Therefore, regulators and policy-makers play the main role in defining the accepted "source" to provide flexibility and their remuneration schemes.

The present research ***aims to identify and develop new strategies to solve the problem of BESS planning and operation into the DN with RES integrated from the perspective of small-scale investors who would like to find a profitable business model to invest in BESS, even in the absence of any subsidies, incentives, or a***

regulatory framework that remunerates or mitigates the high investment costs that represent this type of storage technology.

The motivations described in Section 1.2 are crucial factors to be faced toward sustainable development of the electrical power system in which the decarbonization of the electricity sector also provides potential business opportunities (involving RES and BESS). To consider BESS integration into DN as an option to tackle emerging challenges is not a new proposal, nevertheless, many questions remain needing some answer or better definition, such as:

(i) How can the uncertainties introduced by the intermittent nature of RES, the consumer's empowerment, and the energy price fluctuations be addressed to consider their impact on the BESS planning and operation?

(ii) How can BESS support the sustainable energy transition from DN and provide flexibility and how can the proposal formulated be applied in real-life applications?

(iii) How can BESS be adequately integrated into the DN planning and operation problem aiming to obtain benefits from the perspective of different stakeholders/players?

(iv) How can the BESS planning and operation problem be addressed under a more realistic approach, but without the computational effort required to solve the optimal problem being prohibitive?

(v) How can technical, economic, and environmental objectives be addressed to deal with their impact on the BESS planning and operation problem?

(vi) How is the robustness of the proposed strategies demonstrated?

This research work aims to develop strategies that contribute to facing the challenges identified in Section 1.2.2 and provide new perspectives on the BESS planning and operation problem when integrated into the DNs with PV generation. The strategies proposed are optimized by introducing mathematical and heuristic approaches. In this context, the relevance of the technical and non-technical battery performance parameters is considered to analyze their impact on battery behavior and the revenues stream from storage activity in the absence of a clear and defined remuneration scheme. The idea is to quantify how necessary the battery parameters are regarding the income from its operation given the last ones are data input into the planning stage.

This research work also aims to develop strategies that contribute to better planning BESS into the DN as a resource with multiple potential sizes and locations given the versatility of this technology. A further focus is on the robustness of the uncertain scenarios surrounding the planning and operation process since they are key aspects that must be considered to cope with the challenges already identified in real-life situations.

In addition, it is relevant to also specify the boundaries of this research work. In this, forecasting models for energy prices, energy generation from PV systems, and load profiles are not addressed. In contrast, historical data is modeled from a Monte Carlo method perspective, introducing a probabilistic approach capable of estimating the risk of the optimization process. Moreover, the assumption of deferring investment in the DN reduces the need to compare economically BESS integration vs DN expansion. The results confirm that with the proposed strategies the boundaries set are overcome. Therefore, this thesis aims to contribute to the development of a new BESS planning and operation paradigm that considers a more realistic framework to approach the whole problem.

1.4. List of Publications

During the PhD course, scientific contributions related to this thesis were published as conference papers and/or journals as follows:

- **P. Agamez-Arias** and V. Miranda, "Impact of the C-Rates and AC-AC RTE on the Annual Cycles and Operation Cost of Different Battery Technologies That Provide Market Services", *2024 IEEE 22nd Mediterranean Electrotechnical Conference (MELECON)*, pp. 378-383, 2024, DOI: 10.1109/MELECON56669.2024.10608751.
- **P. Agamez-Arias** and V. Miranda, " BESS Operation Assessment Regarding the Rise in the Energy Prices", *5th Doctoral Congress Engineering (DCE23), Symposium on Electrical and Computer Engineering*, 2023, ISBN: 978-972-752-307-8.
- M. Loureiro, **P. Agamez-Arias**, T.J.A. Abreu, V. Miranda, "A DEEPSO-GMDH Model for Supporting the Battery Energy Storage Investment Planning Decision-Making", *Energy Conference (ENERGYCon) 2020 6th IEEE International*, pp. 539-544, 2020, DOI: 10.1109/ENERGYCon48941.2020.9236518.
- T. A. Abreu, **P. Agamez-Arias** and V. Miranda, "Battery storage sizing and location in distribution systems", *2019 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America)*, pp. 1-6, 2019, DOI: 10.1109/ISGT-LA.2019.8894980.
- Tiago Abreu, **Piedy Agamez-Arias** and Vladimiro Miranda, "Sistemas de Armazenamento de Energia como Modelo de Negócio na Ótica do Operador da Rede de Distribuição", *Anais da Conferência Ibero-Brasileira de Energia – CONIBEN Lisboa 2019*, pp. 668-686, IBEROJUR, ISBN:978-989-54869-0-8, 2019.
- **Piedy Agamez-Arias**, "Planning Models for Distribution Grid: A Brief Review", *U.Porto Journal of Engineering,* ISSN: 2183-6493, v.4, p.42-55, 2018, DOI: 10.24840/2183-6493_004.001_0004.

1.5. Structure of the Thesis

To achieve the objectives proposed and provide contributions this research and PhD thesis were organized into six chapters as shown in Figure 1-1, where arrows suggest reading sequences that may bypass some sections without loss of understanding.

This Chapter comprises an introduction to the planning and operation problem, a discussion about the DNs' status, and the challenges they must face to become a sustainable, efficient, reliable, and safe electrical power system. The PhD thesis scope, objectives, and research challenges to be achieved are also highlighted. A list of publications held in the framework of this research is also provided. Finally, the structure of this document and the thesis purpose are pinpointed.

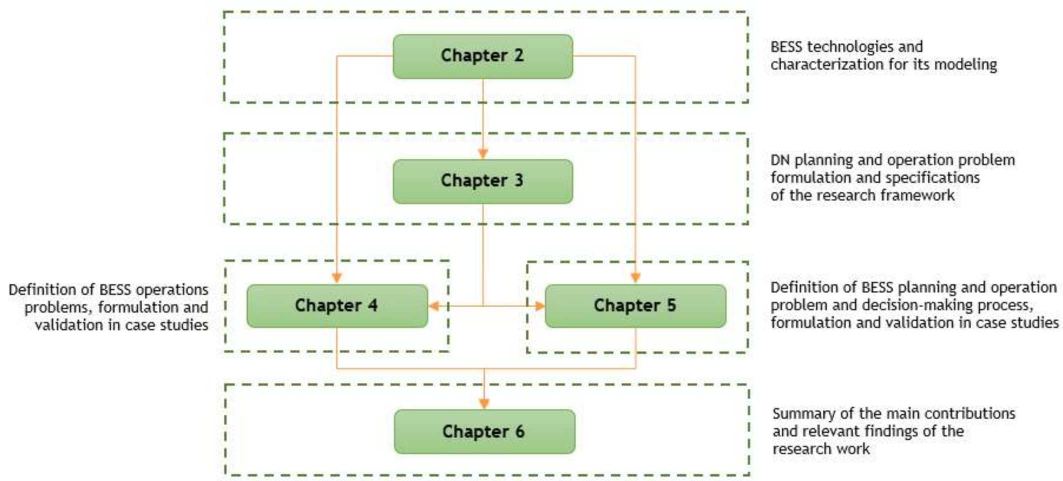


Figure 1-1. Structure of the thesis and research work to achieve proposed objectives.

Chapter 2 describes BESS technologies, structure, and their characteristics and useful parameters for their integration into the electrical power systems that are looking for solutions that improve the reliability and flexibility of the network while dealing with uncertain scenarios that enlarge the complexity of the network planning and operation problem. Potential applications for BESS when integrated into DN with high penetration levels of RES are highlighted. Finally, due to the lack of incentives, subsidies, and regulatory framework that remunerates the storage activities, different barriers and difficulties that limit the wide deployment of BESS into the DN are discussed and potential solutions are provided.

Chapter 3 reports state-of-the-art about the DN planning and operation problem when the integration of BESS is considered. Moreover, an overview of how the DN planning and operation problem has been handled in the literature given the evolution of the network structure is presented. Relevant mathematical and heuristic optimization techniques applied in the context of this research focus are analyzed. Business models for BESSs into the DN are discussed from the investors' perspective. Finally, some literature insights and gaps are discussed, clarifying the relevance of this research work concerning the BESS planning and operation problem.

Chapter 4 addresses the problem of identifying a suitable operation strategy for BESS integrated into de DN that considers the services to be provided and analyses the profitability of the storage activity even under a non-subsidized scheme given the returns from battery operation should cover, at least, the investment costs in the storage technology. Therefore, profit-making-oriented strategies that consider performance parameters for different battery technologies are studied from the small-scale investors' perspective to identify how these parameters influence battery behavior and revenue streams. Specifically, batteries must respond to two strategies: price arbitrage and simultaneously price/energy arbitrage and tertiary. As these operation strategies are highly related to the electricity and regulation market prices, stochastic scenarios for market prices based on the Monte Carlo method are approached to deal with the uncertainty and better represent the price volatility. Numerical simulations are carried out for ideal and non-ideal BESS models. Finally, results are discussed and conclusions about the chapter are provided.

Chapter 5 studies the BESS planning and operation problem when integrated into the DN from the perspective that BESS is owned by an IEP/Aggregator/REC that already operates a generation from RES, namely a distributed PV system. For this, a bi-level strategy is developed based on a hybrid optimization model built from the Evolutionary Particle Swarm Optimization (EPSO) for battery sizing, network interface technology selection and location in the upper-level, and Linear Programming (LP) for battery operation at the lower-level. Stochastic scenarios for modeling load profiles (residential and commercial), PV generation, and electricity market prices based on the Monte Carlo method are also approached to deal with uncertainties surrounding the problem. In addition, a decision-making process states that the most economic decision from the BESS owner's perspective could not be a feasible decision from the DSO/DISCO perspective when the latter evaluates additional technical criteria, then a conditional decision set is created to find a final decision economically feasible for BESS owner and also technically feasible for the DSO/DISCO via a conciliatory process. Numerical simulations are carried out for the modified CIGRE MV benchmark network and the IEEE 33-Bus system. Finally, results are discussed and conclusions about the chapter are provided.

Chapter 6 is the final chapter of this thesis where the main contributions, the most relevant findings, and the perspective of future work are summarized.

The main document has four appendices.

Appendix A outlines the characteristics that make different ESS suitable for storing energy. It also highlights the challenges they must still overcome in terms of how the energy is stored and the main factors that hinder their deployment within the electrical power system.

Appendix B summarizes the available data on planning objectives and constraints, network modeling, uncertainty management, and solution methods for solving the optimal planning problem, collected from the literature reviewed.

Appendix C summarizes analysis and findings from historical data of hydro pumping units that provided tertiary reserve to the Portuguese electrical power system in 2019, 2022, and 2023. Analyzing these data behaviors is relevant given this research work considers that BESS can replicate it.

Appendix D summarizes analysis and findings from historical data of the Portuguese electricity and regulation market prices in 2019, 2022, and 2023. Analyzing these data behaviors is relevant given market prices play a key role in profit-making-oriented strategies for battery operation.

Appendix E presents the test systems CIGRE MV benchmark network and IEEE 33-bus system used as case studies to assess the planning and operation strategies proposed.

1.6. Thesis Purpose

The thesis purpose is to provide answers to the following main research question: ***What would be a suitable technical and economic model for planning and operating BESS into the DN with RES already integrated, able to deal with uncertain scenarios related to energy demand, RES generation, and market prices, and to provide valuable information to small-scale investors about the profitability of the storage activity?***

A well-structured BESS planning and operation, viewed from the perspective of small-scale investors, can provide valuable insights to different stakeholders/players when batteries, uncertainties, and DN are modeled as close to reality as possible. Regardless of battery technology, in the absence of subsidies, incentives, or a regulatory framework that remunerates storage and flexibility activities, the revenue stream generated by the BESS application or service becomes solely responsible for repaying the loan and covering upfront investment costs

More realistic battery models are crucial to quantify the impacts of BESS efficiency on the revenue stream from battery operation. In addition, the management of uncertainties in energy prices, load profiles, and RES generation cannot be ignored because these network and market parameters also impact batteries' behavior and revenue stream when they respond to profit-making-oriented strategies under an AC network model.

As uncertainties are managed and the revenue stream is more realistic, the decisions (battery sizing, location, network interface selection, and technology selection) from optimal planning will also become more realistic. Even, when the optimal planning also considers the cost due to battery replacement/augmentation (by calendar life or lifecycle), and the cost due to battery recycling and disposal, decision-makers are demonstrating their efforts in ensuring decisions that contribute to a more sustainable, reliable, and flexible electricity sector. Moreover, by providing a decision-making strategy to find an economic decision from the BESS owner's perspective that is also technically feasible for DSO/DISCOs, BESS owners are demonstrating their efforts in getting involved in decisions related to electrical infrastructure and energy utilization under an accessible decision-making scheme to a broader of stakeholders/players.

In sum, more detailed technical and economic models for planning and operating BESS into the DN with RES already integrated would likely allow small-scale investors to identify the business opportunities and the profitability associated with them, and policymakers to find support mechanisms to incentivize and promote flexibility and storage applications/services with both technical and economic attractiveness.

Chapter 2

BESS Structure and Battery Technologies, Parameters, and Applications

BESSs have been recognized as a technological solution that may play a key role in facing the challenges the sustainable energy transition has brought to the current electrical power systems, e.g. reducing carbon emissions, increasing flexibility, energy production from RES, and improving reliability, among others. Although ESS can provide numerous potential services, it is relevant to consider that each technology contributes as allowed by its parameters and technological maturity.

In this Chapter, an initial background about definitions and concepts used throughout this research work is provided based on the consideration that BESS is a promissory storage technology that may improve the flexibility and reliability of the electrical power network. Therefore, identifying how BESS could be framed into the power networks and the potential application/services they may provide is crucial to properly approach this technological solution in the problem of planning and operation of the DN.

At first, the BESS structure is described aiming to identify the components responsible for its safe and efficient operation. Secondly, BESS technologies and their characteristics are detailed. In addition, the potential applications for BESS when integrated into the DN are identified. Lastly, the main barriers or difficulties that restrict the widespread deployment of these technologies are analyzed.

In summary, this chapter provides an outlook on BESSs and their potential integration into the DN, highlighting the benefits and challenges these technological solutions must overcome.

2.1 Overview

In recent years, the sustainable energy transition has attracted worldwide attention due to the challenge of replacing fossil fuels with low-carbon energy sources. For the electricity sector, the challenge means moving towards power systems predominated by energy production units from RES and changing how end-users manage their consumption. For this, the transition has meant the beginning of a transformation process toward a decarbonized power system based on a low-carbon, low-environmental degradation, energy-efficient, flexible, reliable, and economically affordable energy supply model [21], [25], [27].

As mentioned in Section 1.2, the energy transition and decarbonization have required several planned actions on a global, regional, and local scale, which has led to dealing with political, regulatory, institutional, economic, social, and cultural challenges. Nonetheless, the world share of fossil fuels used barely changed over one decade despite the falling cost of some RES technologies and the pressure on governments to act on climate change and environmental issues. According to [25], there was a general concern about RES investments given they have been around one-sixth of fossil fuel, which led to around 63% and 26% of the global electricity demand in 2019 being met by fossil fuels and renewable energy, respectively, compared to 67% and 19% in 2009 [62]. Recently, almost all of the investments have been directed to clean energy and environmentally friendly solutions [17], which led to around 60% and 30% of the global electricity demand in 2023 being met by fossil fuels and renewable energy, respectively.

ESSs as pumped storage hydro (PSH) are already integrated into the electrical power network and markets [3], [21], [30], [55], [63]. PSH is a mature technology with widespread commercial applications. However, its integration into the electrical network has not contributed to establishing a scalable business model for other storage technologies.

ESS technologies may provide several services/applications that can contribute to achieving the flexibility required by DNs and, in general, by electrical power systems [4].

The need for flexibility has significantly increased in the EU, accounting for 24% and 30% of the total EU electricity demand in 2030 and 2050, respectively, from 11% in 2021. The flexibility requirements across the EU significantly increase when the RES shares are around 75%. In the last years, utility-scale energy storage projects have been growing accounting for more than 9GWh in 2023, while the expected global installed capacity reaches a share of about 270GW by 2030 [58].

2.1.1 The role of ESS and BESS in the sustainable energy transition

The roles of ESS and BESS in the sustainable energy transition are still under definition because of the regulatory, economic, environmental, market, and pricing challenges these technologies must face [4], [5]. According to [29], there is a critical challenge related to storage uptake, given the wide range of policies required to support their deployment as technically needed, including incentives and regulatory frameworks, and even, education and awareness campaigns.

RES integration into the electrical power network has pinpointed the pioneering role of the ESS: mitigating the rapid and seasonal output changes and voltage fluctuations characteristics of these generation sources. Since then, ESS has gained more attention given the numerous potential roles they can play in reaching a more sustainable, flexible, reliable, resilient, and safe electrical power network. Aiming to integrate ESS into the power system, some relevant aspects must be considered, namely (i) the application for which the ESS will be used; (ii) the available storage technologies regarding their suitability for the application; and, (iii) the network requirements and constraints [2], [11].

It is expected that as soon as possible, ESS and BESS will contribute to reducing peak demands, flattening the load profile, optimizing the electricity price, supporting the system frequency, adding capacity, differing network investment, improving network reliability, etc., by taking advantage of its characteristic of storing energy or releasing it when technically needed or economically affordable[5], [33], [34]. No single ESS technology can fulfill the requirements for all electrical power system needs [44], therefore the ESS selection is a challenging task that must consider the ESS capacity, technological maturity, efficiency, response time, lifetime and cycles, power and energy capital cost, charging/discharging times, environmental impact, among others parameters described in detail in Section 2.2 and 2.3.

A summary of various ESS technologies for distribution networks in a commercial, proving, or developing stage is shown in Table A-1, Appendix A, based on the form the ESS stores the energy [3], [5], [11], [33], [64]–[66]. The table presents the characteristics and advantages that make different ESS technologies suitable for storing energy and the challenges they must overcome. According to Table A-1, each storage technology can play a set of roles mainly defined by the technical or economic needs revealed by the network, the technical and non-technical ESS parameters, the ESS capital expenditure, CAPEX, and the operational expenditure, OPEX, and the location available to install the technology.

2.1.2 Why are batteries suitable for energy storage?

In the traditional energy value chain, ESS were not considered an essential component of the structure given that energy production was mainly based on fossil fuels, and technically they offered the reliability and stability the power network needed. However, the ongoing increase in meeting economic and technically feasible electrical power networks, but also environmental, has contributed to considering ESSs a strategic solution to be integrated into the modern energy value chain [3].

As an electrochemical storage option, batteries stand out over other ESS by their unique characteristics. The most relevant one is related to the capability of BESS to align with a wide range of current needs of the electrical power networks and their potential to be located as a distributed resource given batteries' locations are not defined by geographical or natural endowments [67], instead BESS may be built in most of the locations and a matter of months [29]. In addition, the modular characteristic of BESS offers some advantages for investors [68], but also for DN planners and operators given the energy/power capacity could be customized (be scaled up or down). BESS is especially essential in densely populated areas, where traditional storage technologies such as PSH or CAES are not technical and economically feasible [69], and where environmental and geographical aspects become a constraint that cannot be ignored in the planning process [11], [67]. Moreover, the low cost for BESS O&M over time and easier replacement process add some attractiveness over other ESS [4].

Growing shares of RES such as wind and PV systems and changes in the behavior related to all types of loads (residential, commercial, and industrial) increase the variability of the net load in a network due to the uncertainties associated with each one [22], [24], [70], therefore, both aspects have been rising the need for flexibility in the electrical power system [71]. This need increases across all timescales and seasons [11], [58], nonetheless, it is short-term which sees the higher one [29].

Under a planned energy scenario, it is forecasted that the global energy storage capacity should increase to 1,5 TW by 2050 to keep pace with the accelerated growing share of RES, hence, the global capacity of BESS must grow at a yearly rate of 25%, while under a net zero emissions, the forecast is around 4TW [29]. According to [30], closing the gap between scenarios is one of the most important challenges in the power sector given the most conservative scenario provides forecasts based on the current energy and climate policies. including energy, climate, and related industrial policies. On the other hand, the same authors establish that only utility-scale BESS should increase more than 10 times by 2030 to meet the path to the net zero emissions target.

Undoubtedly, the value of BESS and other ESS is substantial and will increase shortly, affecting the entire energy value chain, increasing energy efficiency, power system flexibility and security, and reducing greenhouse gas emissions [19], [30], [58]. Compared to other ESSs, BESS is provided with unique characteristics such as modularity, high energy density, fast response times, high round trip efficiency, a wide range of applications, and fewer geographical and endowment requirements, which pinpoints this technological solution as the one capable of playing different roles in the sustainable energy transition.

For these reasons, batteries are the technological storage solution in the scope of this research work.

2.2 BESS Structure and Parameters

BESS's value proposition lies in the fact that these systems when needed, can extract electric energy from the power network (i.e., working as a load during its charging process), inject it into the power network (i.e., working as a generator during its discharging process) or, shift the load profile of the network through time by storing it and managing the ESS charge/discharge process [3], [33], [34], [64].

BESS and other ESS technologies (e.g. flywheels, supercapacitors, and thermal storage) can be considered technological solutions framed in the concept of distributed storage [18], [38], which is a powerful characteristic, particularly in the scope of the energy transition faced by power systems since they are moving to business and network models where it is envisaged that more energy be provided from RES [3]. When planned under the concept of distributed source, they can open a path to change the DN behavior and operation aiming to provide a safe, reliable, and flexible electrical power system.

Regardless of the BESS owner (i.e. DSO, an aggregator, an independent energy provider, or a REC), its integration into the DN implies a substantial investment cost. Therefore, the technology selection of the storage bank of BESS is a challenging task given many aspects such as the current state of development, investment cost, energy/power capacity/density, response time, calendar life, lifecycles, self-discharge, and efficiency, among other parameters, must be considered [3], [5], [66].

2.2.1 Battery energy storage system structure

A BESS comprises crucial components responsible for maintaining its efficient and safe operation. Figure 2-1 shows a basic BESS structure that includes the DC battery storage bank and its battery management system, and an interface that allows them to be coupled with the AC DN. This interface requires a Power Conversion System (PCS) and a step-up transformer. In addition, it includes a monitor, control, and communications systems, electrical protection and disconnection devices, and ancillary equipment (e.g. ventilation, cooling/heating systems, etc.) to manage the whole system [4], [55], [72]-[74].

(i) **Battery Storage Bank** consists of various electrochemical cells connected in parallel and/or series to achieve the required voltage and capacity. Cells convert the energy from electrical to chemical, and vice versa. Battery technologies mostly reported in the literature are described in section 2.3.

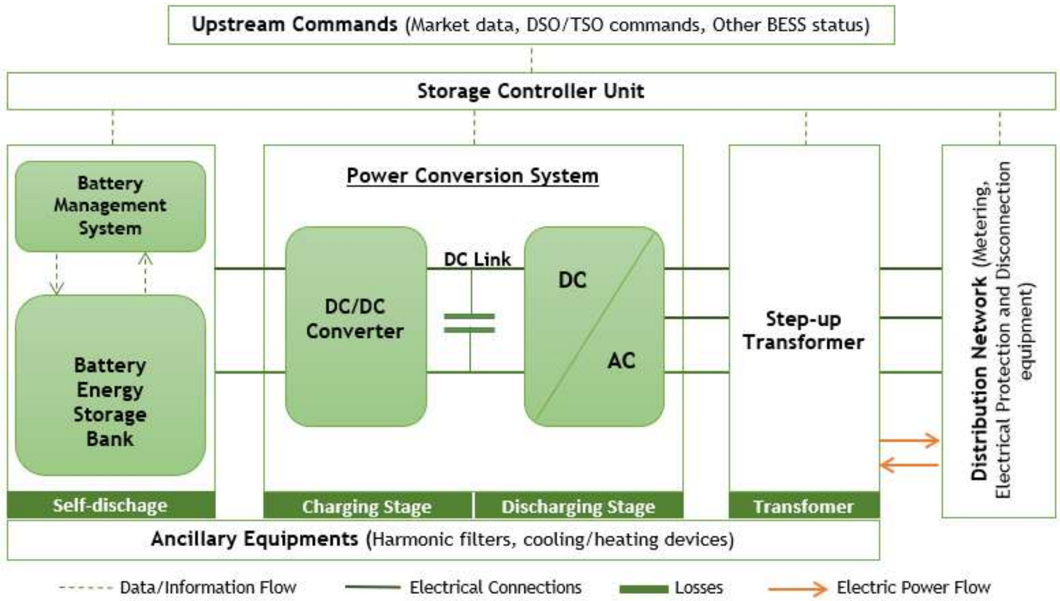


Figure 2-1. Basic Structure of a Battery Energy Storage System.
Adapted from: [4], [55], [72]–[74]

(ii) **Battery Management System** (BMS) is crucial for enhancing the performance of the storage bank. This monitors the battery cells to keep the storage bank within a safe operation range. In addition, the BMS measures and predicts crucial information about the storage bank such as the temperature of the cells, the State of Charge, the State of Health, and the State of Function (states defined in section 2.2.2). In addition, when available, BMS collects inputs from different sources such as measurements at the Point of Common Coupling (PCC), weather forecasts, energy market data, and commands from DSOs, TSOs, and aggregators [72].

(iii) **Power Conversion System** (PCS) is essential to storing and delivering DC power to an AC DN. Then, the DC power discharged from the battery is converted to AC power and injected into DN, while the AC power from the DN is converted to DC power to charge the battery. PCS effectively gives BESS the characteristic of following a charge-discharge behavior regarding the application for which BESS is used, see section 2.4. PCS may provide a fast and accurate response after accessing different battery parameters (e.g. SoC and DOD) and other external signals.

(iv) **Step-up Power Transformer** could be considered optional equipment because the integration of this component depends on the voltage level at the connection point with the external network (e.g. PCS can directly cope with some low-voltage networks). Therefore, if there is a difference between the voltage from the BESS side and the DN side the step-up power transformer is required. This transformer and the harmonic filters (included in the ancillary equipment) enable the reduction of the harmonic contents of the current and voltage waveforms obtained from the PCS.

(v) The **Storage Controller Unit** (SCU) monitors, controls, protects, communicates, and schedules the components of the BESS (e.g. communicates the active/reactive power set-points to the PCS as required by the application followed by BESS). Besides, it communicates with external or upstream devices to ensure an optimal BESS operation. Moreover, after communicating with systems of other electric sector stakeholders (e.g. DSO, markets operator) it can optimize BESS behavior from technical and economic perspectives by defining a BESS schedule regarding the application followed. For example, Under a voltage control application, this unit sends a charge command to BESS when the overvoltage occurs in a monitored node of the network, on the contrary, it sends a discharge command to BESS during a peak load or undervoltage period [75].

(vi) The **Ancillary Equipment** regulates the internal battery environment to ensure a suitable operating temperature and air distribution. Moreover, it must manage energy consumption from the auxiliary components since it varies based on the system's operation. By meeting optimal temperature, ensuring efficient power usage, and being resistant to environmental challenges (e.g. dust and sand), this component contributes to extending the BES lifespan and optimizing its operation.

The design of the BESS components can vary as required by technological, security, size, and operation aspects. In the scope of this study, the step-up power transformer is an essential component in the BESS structure since it approaches the problem of integrating into DNs. Thus, the overall focus is on the battery energy storage bank, and the efficiency of the PCS and the step-up power transformer.

2.2.2 Technical and non-technical battery parameters

Identifying the most relevant technical and non-technical parameters that define a BESS is essential to properly modeling its integration into the DN. Different aspects affect BESS behavior and performance, e.g. battery chemistry, size, weight, age, and usage history, in addition to environmental conditions such as temperature. From this perspective, the detailed modeling of BESS and the DN to which it is connected to solve the BESS planning and operation problem is very complex, nevertheless, it is crucial to find a dependable solution that would adequately reflect the technical and economic impacts of these systems [5], [55].

BESS parameters are transversal to different battery technologies, which allows their comparison and evaluation [3]–[5], [55], [65], [74]. These parameters are relevant because the lack of incentives, subsidies, or regulatory framework leads to depending on the revenues from battery operation (regardless of the application BESS is following) to assess the economic feasibility of BESS projects [4], [51], [76].

The technical parameters directly influence BESS and DN behavior and operation. The definitions below aim to define and clarify each parameter [5], [55].

(i) **Energy Capacity** provides information on how much charge the battery can hold. This is an essential parameter to be focused on given that it decays over time (because of its calendar or lifecycle). It is measured in KWh or MWh.

(ii) **Specific Energy** is related to the amount of energy that can be stored per unit mass of the storage material.

(iii) **Energy Density** refers to how much energy can be stored per unit volume of the storage material. It is measured in kWh/L. Current and estimated values are reported in [4].

(iv) **Power Capacity** provides information about the maximum rate at which energy can be transferred into and out of the device. Nevertheless, in real-scale applications, the power capacity is restricted by the PCS and the step-up transformer since they are part of the essential structure used by a BESS to exchange active/reactive power with DN. It is measured in KW or MW. A range of current/estimated values are reported in [11].

(v) **Specific Power** is related to the amount of energy that can be stored per unit of time, i.e., the rated power output, per unit mass of the storage material. It is measured in kW/kg.

(vi) **Power Density** refers to the amount of energy that can be stored per unit of time, i.e., the rated power output per unit volume of the storage material. It is measured in kW/L. Current and estimated values are reported in [4].

(vii) **C-rates** or **Charge/Discharge Powers Limit** provide information on how quickly a battery can be fully charged or discharged in one hour (e.g., a battery with a discharge rate of 2C can be fully discharged in half an hour). Usually, the charging process is slower than the discharging process since there is a restricted range of temperatures within which the battery can be charged [38]. Therefore, C-rates should not be too high because they increase the battery temperature, which influences battery lifespan [16].

(viii) **Useful Storable Energy** is related to the energy capacity a BESS can use after considering the minimum and maximum energy levels that may be reached by the storage bank as allowed by their technical limits. As for BESS operations, it is unfavorable to totally discharge the battery, then, the minimum energy level a battery can fall is always more than 0% [77].

(ix) **State of Charge** (SoC or BSoC) indicates the charge level or remaining energy capacity. Thus, it is defined as a fraction of the energy capacity, e.g. if a battery with an energy capacity of 500Ah is at 80% SoC, theoretically, the remaining energy stored is 400Ah. Nevertheless, batteries are complex electrochemical devices affected by temperature variations, aging, and lifecycle, thus the SoC estimation is a challenging task developed by the BMS [77].

(x) **The State of Health** (SoH) depicts the storage bank's overall health after cycling and how long it has left to achieve its purpose regarding a brand-new storage bank [75]. This parameter is affected by cycles, capacity fading, and changes in the internal resistance of the batteries. SoH estimation is also a challenging task developed by the BMS [74].

(xi) **State of Function** (SoF) provides information about whether the battery meets the requirements of the applications for which BESS is used under real operating conditions.

(xii) **Depth of discharge** (DoD) refers to the fraction (%) of the maximum energy stored in a battery that can be discharged. This is a complement to the SoC since as one increases, the other decreases. In batteries, the energy stored cannot be extracted without causing degradation (which is mainly caused by calendric aging and cyclic aging) or a serious and irreparable negative impact on the battery storage bank, nevertheless, each technology describes its lifecycle-DoD relationships [78]. This parameter is usually limited to 80%, but only manufacturers may provide suitable value.

(xiii) **Self-discharge** represents the stored energy loss when the BESS is in an idle/rest stage (parasitic losses present in electrochemical reactions). The amount of energy loss is strongly related to battery technology; thus, it is inherent and unavoidable. This is another crucial parameter to be considered because it affects the overall efficiency of the BESS [5]. Self-discharge is measured as a fraction (%) of the storage capacity per unit of time.

(xiv) **Round-Trip Efficiency** (RTE) provides information on the ratio of output-to-input energy for a battery storage bank throughout the charge/discharge cycle [3], [4]. RTE can be reported as AC-AC when accounting for the ratio of output-to-input energy at the DN side shown in Figure 2-1 and DC-DC when accounting for the losses related to the self-discharge and the DC-DC converter [55]. RTE is expressed in percentage (%).

(xv) **Response Time** is related to the time required by the BESS (mainly, by the storage bank and PCS), to change from idle/rest stage to charging/discharging, at rated power. This parameter is relevant given that some applications for which BESS can be used have a threshold of time, restricting the technologies that can be considered.

Non-technical parameters have slight or no influence on BESS and the distribution network behavior and operation. Nevertheless, they are essential to a suitable approach to the BESS planning problem in the DN [5], [55], [79].

(i) **Calendar Life** refers to the maximum duration in which BESS reaches its end of life, which means the number of years BESS can operate before taking place an irreversible loss of capacity (a range of current/estimated values are reported in Section 2.3, Table 2.1. Nevertheless, some aspects affect the calendrical life of non-flow batteries. For example, in lithium-ion batteries, the temperature, SoC, DOD, and the time in an idle stage contribute to the loss of capacity of the storage bank [16], [75].

(ii) **Cycles** provide information about the times the charge-discharge pair is completed regarding the application for which BESS is used.

(iii) **Lifecycles** represent the total number of cycles a BESS can provide before reaches its end of life; for the nonflow technologies reported in Section 2.3, this is a function of the DOD. A range of current/estimated values are reported in Table 2.1.

(iv) **End of Life** (EoL) is related to BESS ceasing its function due to degradation. Then, BESS can no longer achieve its purpose given the augmentation of the internal resistance of the battery and the reduction of available peak power. It is considered that the EoL is reached when BESS energy capacity does not meet 60%-80% of its nominal value [55], [75], [79].

(v) **Modularity** indicates that the unitary size of the battery is a module or container of battery cells that includes BMS and ancillary equipment. Each container presents a specific storage capacity and charge/discharge powers; thus, the total BESS size is obtained from the sum of battery containers. This parameter is of paramount importance when BESS is integrated into the DN because it allows battery size to be adjusted to local network needs/constraints.

(vi) **Total Ownership Cost** provides information about the cost BESS represents for its owner. It mainly includes investment, maintenance, EoL, and replacement costs. Regarding the owner (i.e. DSO, an aggregator, an IEP, or a REC) and the business model used to operate BESS, the operation cost may or may not be included.

(vii) **Investment cost** refers to the monetary investment required to produce per unit of power (Power Cost) and per unit of energy (Energy Cost), in addition to the investment required for balancing the plant and integrating the BESS project into the power system. It is measured in \$/kW and/or \$/kWh [34]. A range of current/estimated values regarding their energy/power capacity are reported in Section 2.3, Table 2.1.

(viii) **Operation cost** is a fixed cost that represents the cost necessary to keep BESS operational as long as BESS is functioning. It does not fluctuate as the energy throughput. It is measured in $/kWh-yr.

(ix) **Maintenance Cost** is also considered a fixed cost that includes all costs incurred for maintenance, trivial repairs, and replacements of damaged battery cells. It is expressed as an annual fraction (%) of the investment cost.

(xvi) **Replacement cost** provides information about the cost of replacing the storage bank aiming to deal with the loss of the storage capacity and meet performance requirements needed by the applications for which BESS is used. This cost is important because the battery life is smaller than the other BESS components, thus, for economic reasons, it is suitable to replace the storage bank. A range of current/estimated values are reported in [4].

(xvii) **Recycling and Disposal Costs** provide information about how expensive ($/kWh) it is to recycle hazardous materials contained in batteries, at EoL. According to [55], these costs are considered as the inverse physical operation of construction currently determined on a project-by-project basis. Services for recycling and disposal of batteries have not been sufficiently developed [30]. A range of current/estimated values are reported in [4].

2.3 Battery Storage Technologies

The battery storage bank is a differentiating component among BESS since the technology chosen is crucial for its applicability in electrical power systems. There are several battery technologies with different current stages of maturity, nevertheless, battery technologies such as sodium-sulfur (NaS), sodium nickel chloride (ZEBRA or $NaNiCl_2$), lead-acid, lithium-ion (Li-ion), nickel-cadmium (Ni-Cd), vanadium redox (VRFB), zinc-bromine (ZnBr), zinc-air (Zn-Air), and iron chromium (Fe-Cr) are either in use or potentially suitable for being integrated into the electrical power system [38].

A suitable battery technology selection depends on parameters such as energy/power capacity, required performance, investment cost, and application/services to provide, among others [11]. Given that the purpose of this section is focused on discussing the parameters of battery technologies that enable their integration into DN, the parameters are reported in Table 2.1 [4], [5], [11], [34], [65]. The information about working principles can be seen in detail in [5], [33], [64], [69]. In addition, detailed information about the advantages and challenges battery technologies still need to overcome are reported in Table A-1 in Appendix A.

Table 2.1 Battery Technologies and Parameters.
Adapted from: [4], [5], [11], [34], [65]

Battery Technology	*Maturity*	*Installation Cost* ($/kWh / $/kW)	*Replacement Cost* ($/KW in average)	*Calendar Life* (years)	*Lifecycles*	*Response Time*	*Self-discharge* (% per day)	*Charge Time*	*Discharge Time*	*RTE* (%)	*Environmental Impact*
NaS	⁕	0.3k-0.5k /1.9k-4.1k	>150	10-20	2500+	Fast	0.2-20	m-h	s-h	75-90	●
ZEBRA	⁜	1.2k-1.7k /2.8k -4k	> 155	8-15	2600+	Fast	0.6-15	h	s-h	85-90	◊
Lead-Acid	⁕	0.4k-0.6k /1.1k-2.5k	> 140	5-15	2000-	Very Fast	<0.4	m-h	s-h	65-80	●
Li-ion	⁜	0.4k-0.5k /1.7k-2.4k	> 300	5-15	4500-	Very Fast	<0.3	m-h	m-h	85-92	◊
Ni-Cd	⁕	0.5k-0.7k /1.9k-3.5k	> 440	10-20	2000+	Very Fast	<0.6	m-h	S-h	60-70	●
VRFB	⁜	0.2k-0.4k /1.1k-1.4k	> 110	10-20	12000+	Very Fast	<0.2	h-t	m-h	65-75	◊
Zn-Br	□	0.1k-0.3k /0.9k-1.2k	> 165	5-10	2000+	Fast	<0.2	h-t	s-h	60-75	Δ
Zn-Air	□	0.2k-0.35k /1.1k-1.2k	> 75	5-10	1000-	Very Fast	<0.2	h-t	s-h	50-60	Δ
Fe-Cr	□	0.4k-0.5k /1.2k-1.3k	> 25	10-15	10000+	Very Fast	<0.2	h-t	s-h	70-75	◊

⁕, Commercialized; ⁜, Commercializing; □, Developing; ●, High; Δ, Medium; ◊, Medium/low; s, seconds; m, minutes; h, hours; t, month;

(i) **NaS** is a relatively mature technology. This is an interesting choice because of its cycle life, RTE, high energy density, and discharge time. Besides, its pulse power capacity (up to 30 seconds) at over six times its continuous capacity makes this technology technical and economically useful for short-term applications. The main challenges of NaS are related to its high investment cost, the significant increases of self-discharge as corrosion in insulators occurs, and high-temperature requirements for operations which influence the overall BESS performance (NaS requires a heat source fed from the stored energy).

(ii) **ZEBRA** shares similarities with NaS technology, nevertheless, this is a potentially safer alternative given its improved resistance to overcharging, DOD, and maintenance requirements. Parameters such as cycle life, RTE, higher energy density (compared to NaS), and discharge time are relevant to considering this technology a suitable option. In addition, ZEBRA materials are fully recyclable, which makes it sustainable and circular storage technology. The main challenges of ZEBRA are related to its investment cost and the significant increase in self-discharge when idle/resting due to the parasitic heating requirements. Similar to NaS technology, the high-temperature requirements for ZEBRA operation influence the overall BESS performance.

(iii) **Lead-Acid** is the oldest mature battery technology. This is the most widely used technology, usually chosen for several applications (mainly, UPS for data, telecommunication systems, and energy management applications, RES output smoothening, and power source for electric vehicles) given its ruggedness, safe operation, temperature tolerance, faster response time, lower self-discharge, and lower investment cost compared to other technologies. Concerning the challenges, Lead-Acid must deal with the efficiency it reaches (RTE), short cycle life, intensive maintenance requirements, and the fact it contains materials that make it a non-sustainable technology.

(iv) **Li-ion** is currently the most promising and fastest-rising technology [16] likely because of its widespread use in electric vehicle applications. This has become a suitable choice because of its lightweight, high-energy density, long cycle life, high RTE, and low self-discharge. However, Li-ion technology faces some drawbacks such as high investment costs, the need for a special protection circuit for its safe operation, cycle life dependent on temperature, and the cost-to-energy ratio is one of the costliest among battery technologies.

(v) **Ni-Cd** is a reliable technology that may deal with rigorous operation conditions. It stands out by its lower maintenance requirements, higher energy density, and more attractive cycle life when compared to Lead-Acid. The main challenges of Ni-Cd are related to its investment cost (compared to lead-acid), the toxic nature of the cadmium and nickel leads to environmental concerns, and the memory effect makes battery capacity decrease if it frequently operates at low DoD.

(vi) **VRFB** is one of the most mature batteries flow technologies. This is an interesting choice because of its suitable response time, small parasitic losses, very high cycle life (usually considered unlimited compared to their battery technologies), and long storage durations [30]. The main challenges of this technology are the investment cost and RTE (given chemical solutions with the potential of leakage, pumping, and shunt current losses affecting this parameter). However, VRFB is becoming competitive, with important investments in China, where a 200 MW/800 MWh BESS project was designed to alleviate peak loads.

(vii) **Zn-Br** is in an advanced development stage given some charging efficiency problems are being solved, rendering this flow battery attractive and capable of operating in extreme conditions. This technology is interesting because its energy/power capacity can individually be scaled up, and battery operation with a DOD of 100% contributes to improving its performance. However, some challenges related to parasitic losses when the BESS is idle/resting, low RTE, and the risk associated with vapors from bromine leakage (it is highly corrosive and toxic) must be faced.

(viii) **Zn-Air** is the most technically feasible, and potentially the least expensive option among metal-air batteries, which is currently in the developing stage. Nonetheless, its marketability is limited by its non-attractive RTE values and other aspects such as the avoidance of CO_2 impacts from the air on the cathode and electrolyte, and similarly to Zn-Br, the avoidance of dendrite formation.

(ix) **Fe-Cr** is another promising flow battery given its low investment cost (related to the rich reserves of active material), the lower toxicity of the electrolyte, and its long cycle life. However, its marketability is mainly restricted by the important loss of capacity.

In this section, other battery storage technologies are not considered given they are in the research and development stage. Thus, there is a lack of information related to their parameters and costs, which limits a suitable comparison with other advanced or mature technologies.

2.4 Application of BESS in Distribution Networks

Traditionally, electrical power systems considered five main and sequential stages: energy sources, generation units (supplied side), transmission networks, distribution networks, and energy consumers (demand side). The prolific integration of RES and the empowerment of consumers have been changing paradigms of the electrical power network expansion, planning, and operation. However, the changes have also brought several advantages and important challenges that decision-makers must face [33].

Since BESS operates charging, discharging, and accumulating energy, this is a solution capable of influencing the power system when integrated on both the supply, network, and demand sides. By supplying or demanding energy as needed, batteries could reach a strategic role in becoming the convergent point between a network issue and a potential service (application) provided by BESS [11], [30], [44], [71].

BESS may provide a wide range of services to different stakeholders/players of the electric power system. Nevertheless, considering the battery parameters in the optimal BESS planning and operation into the DN is the most effective way to reduce the impacts of the investment costs while taking advantage of their benefits to choose the battery that better fulfills the application requirements [34] while satisfying technical constraints related to the available locations into the network [53], [54].

BESS applications are organized in this section according to the side of the electric power network that benefits from their services. Thus, the organization does not reflect the location where BESS is integrated.

2.4.1 BESS applications for supporting stakeholders' activities

The electrical power system is comprised of stakeholders/players like conventional and RES generation operators, DSO, TSO, and consumers (also called prosumers when producing a part of its energy consumption). In recent years, new stakeholders such as IEPs and Aggregators have become relevant given that, as BESS owners, they may provide services while taking advantage of BESS operations.

(i) **Peak shaving and load smoothing** are strategies that use the battery charge/discharge process to reduce the energy demand during peak periods. Hence, batteries charge during load off-peak periods (usually, lower electricity prices) and discharge during load peak periods (usually, higher electricity prices) [64]. The objective of this strategy can be considered both technical and economic because peak shaving can relieve stress on the electrical power network, reduce network congestion (by modifying the load profile), and improve its stability, efficiency, and flexibility. Even from a consumer's perspective, this strategy can reduce their electricity invoice by mitigating the need to use electricity from the electrical network during peak load periods. This application requires technologies that achieve a fast response time and long storage duration, such as lead–acid, NaS, Li-ion, Ni-Cd, and VRFB [33], [66].

(ii) **Price/Energy Arbitrage** is a trading strategy to charge the battery during periods of lower prices (usually, non-peak load periods) and to discharge it during periods of higher prices (usually, peak load periods) [39], [65], [72] to profit from price differences between markets or periods, which could suggest that a BESS optimally sized and operated is more profitable as electricity market price volatility increases [30], [80]. Even when the objective of this strategy is purely economic, the arbitrage can highlight operational benefits like improving network efficiency and flexibility if the local peak demand occurs during periods of the highest price since BESS can supply the energy locally. This application requires technologies that can achieve moderately fast response time, relatively long storage duration, and a higher RTE, such as lead–acid, NaS, Li-ion, Ni-Cd, VRFB, and potentially Fe–Cr [4], [5], [11]. Figure 2-2 shows an example of a battery operation over 10 days (generic model with 10% of minimum SoC, 90% of DOD, 100% of AC-AC- RTE) when the operation costs were minimized following the energy arbitrage strategy regarding the market prices model as approached in Chapter 4.

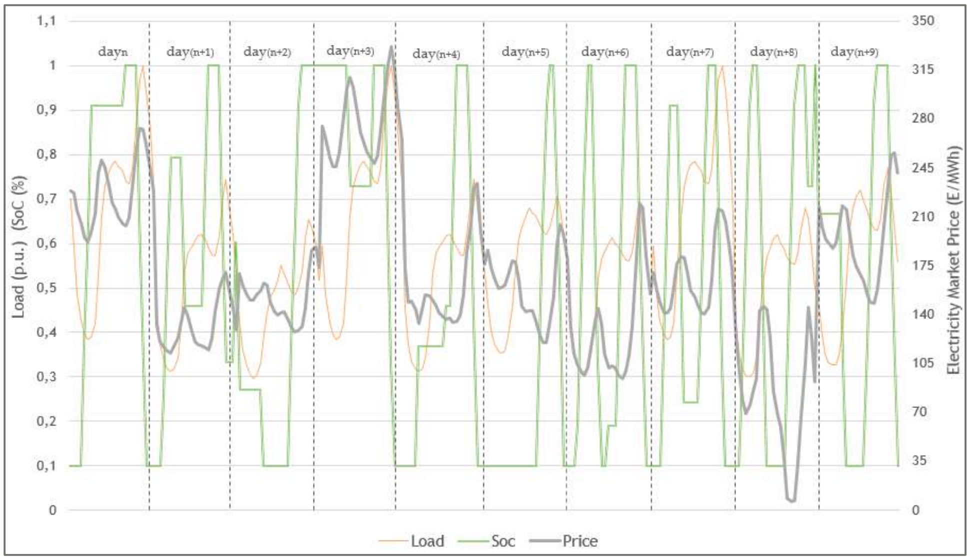


Figure 2-2. Example of energy arbitrage: battery operation over 10 days.

2.4.2 BESS applications for supporting DSO

Considering that the responsibilities of the DSO are focused on providing a reliable, economical, efficient, and safe energy supply, BESS may perform a crucial role in achieving these goals. Therefore, BESS may provide services such as upgrade deferral (also called in the literature capacity firming), local voltage control, and contingency network support.

(i) **Upgrade deferral and capacity firming** are strategies that allow operators to postpone or avoid the costly upgrades needed by the electrical network. A network upgrade is frequently required to fulfill some technical parameters that could be affected by the growing demand, changes in load profiles, high penetration levels of RES, and changes in voltage profiles [38], [39]. Therefore, the economic difference between investing in BESS integration and the time defer that BESS provides to invest in traditional network upgrades, represents the benefit. According to [58] global needs for deferring network investments could reach around 14.3 GW by 2026. This application requires technologies that can provide a significant energy/power capacity, moderate fast response, and long storage duration, such as lead-acid, NaS, ZEBRA, Li-ion, Ni-Cd, VRFB, and ZnBr [33], [66].

(ii) **Local voltage control** is a strategy in which BESS reacts dynamically to changes in active and reactive power to ensure that the voltage levels are between technical/regulatory limits [64]. With the ongoing RES integration, the voltage profiles tend to become more volatile because of the multiple and eventually intermittent power injections along the distribution feeders. Even when the main objective of this strategy is purely technical, the local voltage control can also provide benefits like deferring network upgrades, improving network stability and flexibility, and reducing technical networks. This application requires technologies that can provide a significant energy/power capacity, fast response, and a long cycle life such as lead–acid, NaS, ZEBRA, Li-ion, Ni-Cd, and Zn-Br [33], [66].

(iii) **Contingency support and Reliability improvement** strategies allow operators to mitigate the effects of power outages and avoid oversizing network assets; thus, it requires analyzing and assessing the contingency criteria known as “N-1” during the planning stage. The objective of this strategy may be technical and economic given that power outages are usually expressed as an index with a corresponding cost, which is associated with the unsupplied demands over a specified period (technically called Energy Not Supplied, ENS) [34]. This application may provide benefits like improving network efficiency, resiliency and saving operational costs from power interruptions if BESS is properly sized and located. For this, technologies must stand out by their significant energy/power capacity, moderate fast response, and RTE such as lead–acid, NaS, ZEBRA, Lead-acid, Li-ion, Ni-Cd, and Zn-B [33], [66]. Figure 2-3 shows an example of reliability improvement benefits obtained from a distributed BESS integrated into the CIGRE MV DN Benchmark (in the European configuration) [81] with a 25% penetration level of RES (PV generation) after sizing and location of the batteries following the strategy approached in Chapter 5.

For this, the contingency criteria were evaluated for seven scenarios as described below:

- E0, normal network configuration at maximum load period considering BESS operation;
- E1, total load transfer at maximum load period considering BESS operation;
- E2, total load transfer at maximum load period without considering BESS operation;
- E3, total load transfer at medium load period considering BESS operation;
- E4, total load transfer at medium load period without considering BESS operation;
- E5, total load transfer at minimum load period considering BESS operation;
- E6, total load transfer at minimum load period without considering BESS operation.

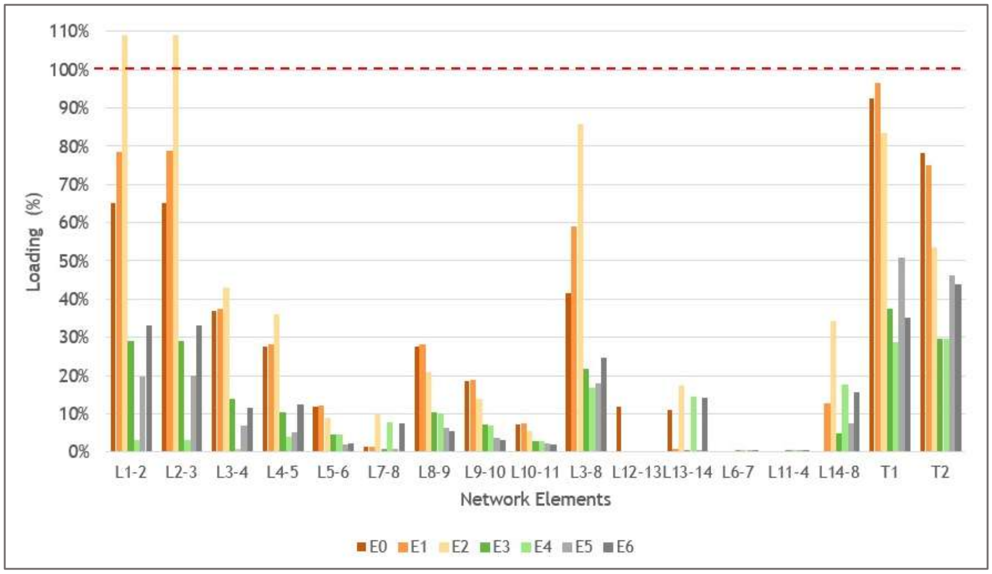


Figure 2-3. Example of reliability improvement benefit: loadability of the network elements.

As noted, with the solution obtained the loadability of the network elements significantly reduced in most of them when the security criteria were evaluated for different load levels. In contrast, the security criteria evaluated without the distributed BESS integration even suggest the need for partial power outages because of the feeders' capacity constraint. In addition, this fact also suggests the need for upgrading some network elements such as the feeders.

2.4.3 BESS applications for supporting TSO

BESS integrated into DN may provide services to the TSO. Recently, generation units and other ESS technologies already integrated into the DN provide services such as ancillary services[72].

(i) **Frequency regulation and capacity reserve** are strategies that aim to mitigate the supply-demand imbalance by using active power reserves to maintain the frequency of the electrical power system as close as possible to 50Hz/60Hz. The different frequency services are characterized by having different activation ramps (according to the time they take to be available) that are used successively [52]. Primary and secondary levels are automatically activated, while the third is manually activated. Regarding the primary level, BESS impacts could be relatively small compared to a large and interconnected power system that requires a very fast response for energy balancing. Moreover, if this service is still mandatory and non-remunerated [82], [83], it limits a market-driven provision of primary frequency. Concerning secondary and tertiary levels, the requirements for BESS to perform these services vary from country to country, however, the BESS profitability under this application depends on the capacity requirements and the market structure. This application requires technologies that can achieve fast response time, suitable storage duration, medium to high C-rates, higher capacity, and DOD, such as lead–acid, NaS, Li-ion, Ni-Cd, VRFB, and Zn-Br [4], [5], [11]. Detailed information about this application is provided in Chapter 5.

(ii) **Transmission investment deferral and congestion avoidance** are strategies that represent an added value when the transmission network faces local impact on its operational limits because of the large shares of RES integrated into the DN, especially under scenarios where RES production is higher than local load, leading to congestions in transmission network components. Even though the objectives of these strategies are mainly technical, they can highlight economic benefits related to the investment deferral on network upgrades [30]. Then, BESS integrated into the DN can charge or discharge the excesses of energy generated from RES or supply the energy stored to the local demand respectively.

(iii) **Grid booster** is a novelty strategy that allows the transmission lines to use their total capacity to transport additional volumes of energy under contingency criteria "N-1". As the large shares of RES continue, more regional bottlenecks in the network transmission and transmission line outages could be expected, which means an increased need for network expansion. However, a paradigm shift occurs when BESSs are integrated into the transmission level to provide synthetic inertia, dynamic voltage control, contingency support, and congestion management. BESS capacity and discharge time are the main challenges when planning a transmission network under this perspective, nonetheless, they are as fast (response time) as required by this strategy and can be located based on the power flow sensitivity on specific lines [84]. Grid booster is an application used in Germany to deploy utility-scale batteries. Germany's regulator has approved 950 MW of storage assets as part of the network development plan, and around 450 MW are under construction in two of Germany's control areas [30]. Although this application does not consider BESS integration into the DN, it is mentioned in this section due to its novelty and relevance for reaching a sustainable energy transition in the electricity sector.

2.4.4 BESS applications for supporting RES integration

BESS beneficiating RES has comprised the pioneer applications for these technologies. The increase in the share of RES as a generation source has led to the consideration of BESS as a key technology that mitigates the RES intermittency in energy supplied (rapid and seasonal output changes) [43].

(i) **Smoothing fluctuations** is a strategy used to counteract, to a certain extent, the rapid changes in power output from RES such as wind and PV systems; thus, they are needed BESS technologies with suitable response time for the short term [42]. The objective of this strategy is mainly technical given that BESSs smooth the variations by charging or discharging as indicated by the power direction variation, reducing the voltage fluctuations and the need for activating the primary frequency reserve in the electrical power system. This application requires technologies that, in addition to a very fast response time, report a suitable storage duration such as ZEBRA, lead–acid, NaS, and Li-ion [4], [38]

(ii) **Curtailment minimization** is a strategy that reduces the amount of energy from RES that could be curtailed as a DN requires given the potential violations of operation parameters of the network (e.g., voltage profiles or loadability). The objective of this strategy is mainly technical but its benefits can be economically measured given that BESS charges during excess of high energy production and discharge when needed [32], [34], [67].BESS capacity, response time, and discharge time are the main challenges when planning a local BESS integration under this perspective. This application requires technologies such as ZEBRA, lead–acid, Li-ion, and VRFB [5].

(iii) **Load following** is a strategy that follows the real-time load to mitigate the mismatches between energy demand and RES output. This strategy is a valuable local service BESS may provide to ensure predefined interchange between areas between standard values. The objective of this strategy is mainly technical, but its benefits can be economically measured based on the technical issues avoided. BESS capacity, response time, and discharge time are the main challenges when planning a local BESS integration under this perspective. This application requires technologies that, in addition to a fast response time, report a suitable storage duration such as ZEBRA, lead–acid, NaS, and Li-ion [4], [5], [38]

2.5 Difficulties in the Widespread Deployment of BESS into the DN

BESSs have numerous applications and benefits when integrated into DN. However, some regulatory, economic, environmental, market, and pricing, among other difficulties or barriers have been restricting the widespread deployment of these technologies [3]-[5], [29], [30]. Table 2-2 presents information about the types of difficulties that limit the deployment of BESS, the problems introduced by each one, and the potential solutions that could contribute to overcoming them.

Table 2.2 Difficulties to BESS Deployment into the DN and Potential Solutions.
Adapted from: [3]–[5], [29], [30]

Type	*Issue*	*Description*	*Potential Solution*
Regulatory	- BESS ownership and control - Procedure rules and discrepancies - Coordination with other resources - Uncertain compensation mechanism	- Limited options available to become a BESS investor create restrictions for new and small-scale investors - Investors must develop comprehensive analysis based on each market structure, which is time-consuming and costly - BESS must communicate and be coordinated with distributed resources also integrated into the network, which could be a complex process - There is no regulatory framework to compensate services, which may lead to missed opportunities	- Developing diverse feasible business models and creating fair participation in markets - Modifying or establishing regulations in the framework of the energy transition and climate change goals - Defining and establishing communication and operation schemes that allow BESS to take an active role in providing services that increase the network flexibility, reliability, and resilience - Defining the role of BESS and establishing mechanisms that consider flexibility as a value-added of BESS
Technical and Technological	- Limited availability of mature technologies with a more certain range of values for their parameters - High investment cost	- Limited availability of technologies in an advanced maturity stage with uncertain technical parameters - The initial BESS investment cost is still prohibitively high when compared to other ESS	- Analyzing parameters like cycle life, RTE, and DOD for a specific BESS application to obtain a revenue window instead of a specific value - Funding R&D projects aiming to identify cost impacts on profitability and strategies for cost reduction

Type	*Issue*	*Description*	*Potential Solution*
Economic	- Uncertain revenue mechanism - O&M and replacement cost	- Without incentives and/or market returns to recover the investment cost, BESS does not achieve economic viability - The service provided by BESS affects its degradation and performance	- Defining that a BESS providing system services receives, at least, compensation based on the marginal cost of its technology - Identifying predictive maintenance actions that allow BESS to extend its lifespan or delay the replacement needs
Market and Pricing	- Lack of clear market rules - Unavailability of a mechanism for pricing energy from BESS services	- Absence of clear market rules and incentives discourages players from investing in BESS - The complexity in pricing energy from BESS makes it difficult to determine fair revenues for BESS owners	- Defining agreements similar to the current PPA used for RES - Establishing incentives regarding the services provided to mitigate the investment risk - Creating special markets and proper compensation mechanisms
Knowledge and modeling	- Different range of values for battery parameters - Information from utilities, regulators, and researchers differs - Uncertainty management	- There are significant differences between the reported values for BESS parameters and costs, which limits fair use and comparison - The wide range of values reported for BESS parameters influences the results from studies developed - Different assumptions made for dealing with BESS parameters (neglecting or overlooking) impact on the accuracy of the studies	- Modelling and developing studies as close as possible to real scenarios of BESS integration - Reporting technical and non-technical parameters of BESS should also consider aspects related to its integration (e.g utility-scale, microgrid connection) - Managing uncertainties by using probabilistic methods is useful for BESS planning and operation

Type	*Issue*	*Description*	*Potential Solution*
Environmental	- Time-consuming process and requirements - Need for non-hazardous and advanced materials	- Obtaining the permits needed can delay the integration of a BESS project, eventually increasing EPC costs - Some BESS technologies use hazardous materials, which increase environmental concerns and requirements	- Accelerating procedures by prioritizing the short or medium-term need for integration of the project - Providing complete and clear information about materials, risk (e.g. toxicity), recycling, and disposal procedures

It is of paramount importance to identify and discuss the difficulties that limit BESS deployment into the DN given each type of difficulty is related to some issues that need to be managed to take advantage of the services and benefits BESS may provide. Although BESS integration into the DN covers a wide spectrum of benefits, currently, the successful penetration of BESS and other ESSs is determined by the planning and operation strategies approached by decision-makers regarding the BESS owner, given the decision made must be provided according to a realistic perspective as possible. For this reason, this research work considers that the absence of incentives and a regulatory framework that remunerates the storage activity forces planners and decision-makers to model the uncertainties surrounding the BESS planning and operation problem and the battery performance parameters to establish potential revenue windows for BESS investors, mainly, small-scale investors, which must find profitable business models to invest in BESS.

2.6 Conclusions

This chapter discusses the key components that comprise the BESS structure, the battery technologies, characteristics, potential applications, and difficulties in their wide deployment into the DN. Nevertheless, this outlook should not be considered a detailed review that addresses the problem of BESS as a key strategy for the energy transition from every perspective. Some interesting topics concerning other energy storage technologies, BESS applications, and management and control strategies are not referred to given, in the author’s understanding, they would not significantly contribute to standing out the benefits, challenges, and difficulties of the current state of the art of the problem approached in this research work. Hence, the focus is on the potential and real-life aspects that may contribute to accelerating BESS deployment into the DN since it provides the support needed for the contribution this research work brings.

Batteries are a storage technology considered a linchpin in delivering clean and sustainable energy transitions while ensuring energy security. From the perspective of the electrical power system and the utilities, together with RES, batteries stand out by their potential to provide reliable support to the energy supply and demand at different time scales. Therefore, it is still essential to find strategies capable of considering most of the technical and non-technical BESS parameters to study and analyze the BESS as flexible, reliable, and safe technological solutions that provide flexibility, reliability, and safety to the DN, especially when there are numerous regulatory, economic, environmental, market, pricing, and other difficulties that are restricting feasibility and profitability of BESS projects regardless the battery technology and the services provided.

Planning and operating batteries in the DN forces planners and decision-makers to devise strategies that consider the main parameters that impact battery operation and revenues stream from its storage activity as well as the parameters and network constraints that impact battery sizing, location, network interface selection, and technology selection while dealing with the surrounding uncertainties related to energy consumption, prices, generation, among others. From this perspective, the planning process is a complex task that involves hard optimization problems. However, BESS deployment not only depends on improving technical and non-technical battery parameters, but also on operational strategy. In addition, it requires substantial cost reduction, a regulatory framework that remunerates storage activity, or policies that provide incentives or subsidies to BESS investors.

The next chapter introduces some milestones in the theory of BESS planning and operation problems related to this research work. Hence, the approaches to the battery operation problem and the battery sizing, location, interface, and technology selection problem are studied. Reviewing the complexity of the BESS planning problem in the scope of the research objectives proposed in this work enables the design of strategies to integrate BESS owned by medium and small-scale investors into the DN.

Chapter 3

BESS Planning and Operation into Distribution Networks with RES: A Brief Review

The traditional paradigm of the planning and operation of the distribution network has been changing as some technical and non-technical challenges such as RES integration, consumer empowerment, energy market liberalization, and energy transition, among others, are introduced into the distribution network [11]–[15], [41], [42]. From the traditional perspective, the planning process is developed by the owner or the responsible for operating the DN, who must ensure the upgrade and expansion of the network to meet the current and future energy demand in a reliable, economical, and safe way, while keeping the technical and quality parameters within standard values [9], [10]. This meant the DN planning and operation process followed a centralized and reactive approach, in which the main decisions taken were shaped by a central authority and under a hierarchical network structure.

Although the traditional perspective is still used in some places, an ongoing need to accommodate technological innovations, the participation of new stakeholders, and proper network operation under the existing regulatory frameworks have been a great driver in the design and guiding of the DN planning and operation in the modern era [61]. In [31], authors mentioned that getting a "correct answer" for DN planning problems is not feasible from the traditional perspective when it considers the integration of distributed resources because, at least, its integration should be evaluated under a sequential-time power flow solutions performed over a significant period.

This Chapter explores how the DN planning and operation has been approached to deal with the potential integration of technological solutions like BESS in a transformation era that aims for a decarbonized, environmentally friendly, energy-efficient, flexible, reliable, and economically affordable electrical power system [17], [30].

3.1 Overview

As previously mentioned, the traditional DN planning and operation is approached from a centralized perspective focused on ensuring that energy can be supplied to consumers over long distances. Usually, this considers the load forecasted under a time horizon as the primary driver of the investment decisions to upgrade/expand a reliable network with reduced energy losses (minimize CAPEX and OPEX) [85]. This decision-making process is a complex task enlarged by the need to deal with simultaneous aspects such as the uncertainty related to the energy demand, the multiple options for sizing and location of new/upgraded network components, and the network configuration [22], [86], [87].

In the modern era, the paradigms have changed since the potential of integrating and exploring distributed resources such as RES and ESS has been recognized [10], [34], [43]. Even though it is well-known that one of the main drawbacks of integrating distributed resources into the DN is related to the CAPEX or investment cost, from a global context it is also known that their optimal planning and operation can lead to significant cost savings for the whole system [32], [39], [52], [88], [89]. In the literature is mentioned that, ESS integration could be more promising if they do not compete against RES as wind [1], or if they simultaneous services [2], [39].

The decentralized approaches rose with the integration of RES such as wind and solar PV and have been positioned as a needed approach as several targets are established toward a sustainable DNs transition [26]. From this perspective, the DN planning and operation process must deal with technical aspects like bidirectional power flows, voltage fluctuations, uncertainties related to the intermittent nature of the renewable generation, and uncertainties related to the energy demand, among others [22], [24], [70].

To consider BESS in the process of DN planning and operation means selecting BESS technologies and finding an optimal location, size (e.g., energy/power capacity and charge/discharge rates), and operation schedule (which depends on the application/services BESS will provide to the network). For this, a set of constraints related to BESS performance parameters such as RTE and SOC, and technical parameters of the network must be fulfilled [34], [37], [54].

Figure 3-1 shows the general scheme usually followed regarding the BESS planning process. It starts with the identification of the problems described by the DSO (network congestions, loss reduction, peak demands, etc.) and the potential BESS investors (DSO, IEP, Aggregators, or REC). Next, the problem is formulated based on the services the DSO needs, the services to be provided by the BESS owner, and DN requirements [2], [34]. After that, the business and revenue models are designed based on a problem that needs to be optimized, namely in the form of objectives, constraints, and penalties.

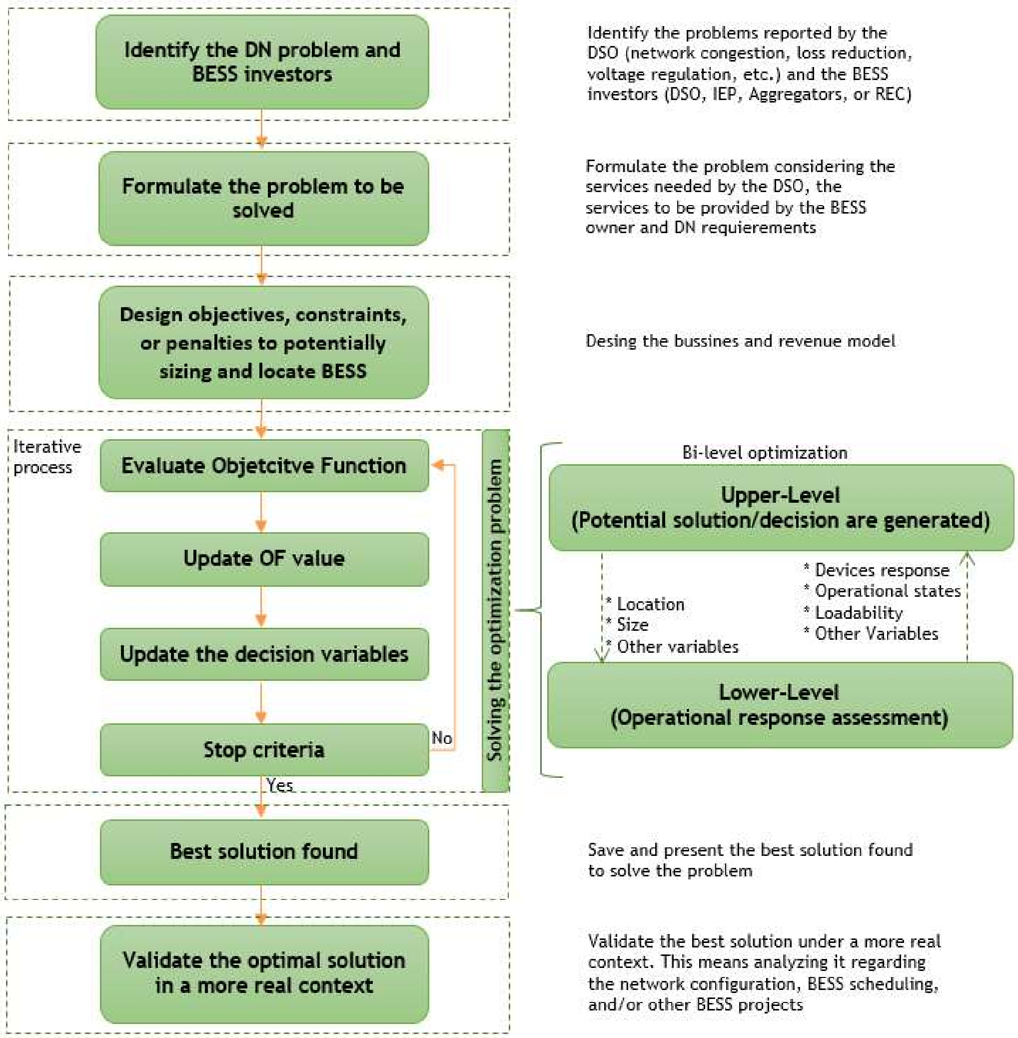


Figure 3-1. General scheme for a BESS planning process under a bi-level optimization approach.

In the next step, the optimization problem is solved under an interconnected and iterative approach taking the optimization algorithm and methods chosen into account [43], [53]. Once the optimal solution is found, it could be validated under a more real context or additional criteria if necessary [54], [90] because, for example, criteria such as reliability and security are measured of the goodness of a plan but, they involve complex judgments that must be assessed for each candidate plan [85].

Planning and operating BESS into the DNs without a regulatory framework and defined business models raise further challenges for the decision-makers given its integration must be technical and economically justified, which means that its deployment depends on the most cost-effective option chosen to operate BESS [76], [89]. As mentioned in Section 2.4, BESS may provide several services to the DN, nonetheless, it could not be straightforward to translate/quantify all of them into economic benefits, which makes it difficult to compare BESSs and ESS impartially.

This chapter aims to present a review directly focused on the research work here approached. Therefore, it presents the developments in planning methodology for integrating and operating BESSs into DNs. The BESS planning problem is defined based on approaches, perspectives, and objectives identified in the literature review. Optimization methods already used to solve the planning and operation problems are presented to pinpoint the complexity of these problems and provide the necessary justification for the contribution this research work brought.

3.2 BESS Owners and Business Models

Defining feasible business models and estimating potential incentives/subsidies required for BESS integration into the DN is complex because policies and regulatory frameworks are needed to support its deployment in the electrical network and profitability in the markets [5], [91]. Nevertheless, the policies and regulatory framework must be defined as soon as possible, given the high RES integration, the changes in energy demand (mainly, load profiles), and the liberalization of the electricity sector are pinpointing BESS and other ESS as key technological solutions to improve the flexibility, reliability, and safety of the electrical power system [17]. Therefore, clear rules for potential BESS owners may answer the question of who can own and operate these systems given it is expected that from the perspective of the DSOs, BESS will be mainly used to minimize technical network issues [30].

A profitable business model must consider sales, investment cost, O&M cost, expenses, and liabilities, among other metrics, to formulate a suitable strategy for generating profit. These strategies refer to revenue models focused on generating sales without taking metrics like costs and liabilities into account, and to business models that consider additional aspects such as market behaviors, players/stakeholders, and technical, social, and environmental policies. According to [92] an effective business model must consider 3 relevant elements: (i) the role of the investor in the market, (ii) the value proposition, and (iii) the revenue model.

In the current energy value chain, the potential roles of the investors could be developed in the production, transportation/distribution, trading, and consumption side. Production refers to the energy produced and sold. Trading means buying the energy produced on the production side and selling it to consumers. Consumption refers to the purchase of energy by the consumers, which is transported and distributed through the electrical network and produced at the production side. The value proposition may follow a technical-support-orientated, profit-making-orientated, or hybrid perspective since it is related to the application/services BESS can provide [37], [44] as previously mentioned in Sections 1.2 and 2.4. Concerning revenue models, they are often confused with business models and revenue streams, however, the revenue model is used to establish/predict revenue streams based on the strategy used [76], [91]. According to [30], BESS could provide simultaneous services to increase its revenue stream, but it also increases the complexity of the business model.

The potential services/benefits BESS may provide are offering new horizons to the traditional research areas because they are relevant for both the DN planning and operation framework and the business models that different types of investors can develop once a regulatory framework allows it [5]. For example, RES and BESS located close to consumers poses challenges to the survival of the traditional DN business model [56] because when BESS is owned by new players/stakeholders that produce energy to satisfy their needs and maximize their profits, what product will DISCOs sell?, and how should the responsibilities be managed whether wide deployments behind-the-meter lead to DSO/DISCO losing their visibility and control on the network?. On the other hand, when BESS is owned by DISCOs, a hybrid value proposition could be considered to improve the revenue stream. In [37], a hybrid value proposition from a DISCO perspective (load following and price arbitrage) demonstrated that the BESS capacity required is over 30% of RES capacity when batteries are located at the RES side but could be around 25% of RES capacity when batteries are optimally located.

As noted, it is of paramount importance to identify and detail the potential business models for BESSs and how they contribute to establishing the revenue streams and lifecycle costs (which impact the BESS planning level), in addition to the role taken by the BESS investor (e.g., owner, commercial control, or service contractor) [5], [37], [46], [93].

3.2.1 DISCO-owned models

This business model considers distribution companies, namely DISCOs, as the BESS owners to provide storage services and to operate BESS under a technical-support-orientated perspective given that it is expected to be easy for them to comply with the regulatory framework. Therefore, the revenue model would mainly reflect the benefits of saving investment costs and avoiding operational expenses while considering technical loss reduction and reliability improvements [71]. For this, BESS owners may consider applications/services such as [94]:

(i) **Upgrade deferral** defers costly investments related to the network infrastructure by shifting, reducing, or managing peak load. According to [39], BESS integrated into the DN under this application tends to be affected by increases in the load growth rate, and [70] considers that the PV penetration levels are also relevant. Therefore, proper load forecasting and PV penetration levels must be considered to determine the financial feasibility of integrating BESS.

(ii) **Ancillary services** consider BESS operating to provide frequency regulation or voltage support. Therefore, this avoids operational costs by keeping the electrical network´s technical and quality parameters within standard values while improving its flexibility.

(iii) **Capacity reserve** avoids operational costs by providing capacity power reserve while ensuring network reliability and flexibility.

(iv) **Peak-shaving and capacity firming** defer costly investments and operational costs by reducing the need to purchase energy during peak periods, which also reduces network congestion. According to [70], the investment cost in BESS and the electricity prices are key aspects that allow DISCOs to justify a feasible benefit through BESS integration. In [37], a DISCO integrates BESS to reduce the energy exchanges at the substation and the power loss while taking advantage of participating in day-ahead markets to reduce its energy procurement cost under-regulated and deregulated markets.

(v) **Smoothing fluctuations and Curtailments minimization** avoid operational costs by keeping technical and quality parameters of the electrical network within standard values while improving the flexibility of the network [88]. These are applications/services considered to complement RES integrations in coordinated BESS-RESS planning and the impact they brought to the network due to their intermittent nature. According to [32], when a BESS was integrated into the test systems the wind power utilization increased by 18,3%, while cost savings were reduced by almost 11%.

DISCOs can simultaneously offer the services previously mentioned and other profit-making-orientated under a hybrid revenue strategy. However, a diversified model will depend on the revenue scheme adopted as allowed by the regulatory framework approved.

3.2.2 IEP/Aggregators-owned model

These models consider BESS to be owned or managed by independent companies that can own RES or not. They would provide energy and storage services to DISCOs, DSOs, or large energy consumers under a commercial contract, service agreement, or power purchase agreement, which means that they would operate BESS under a profit-making-orientated perspective given that it is expected to achieve a profitable business model. Therefore, the revenue model would mainly consider exploiting the volatility of energy markets and trading arbitrage. For this, BESS owners may consider applications/services such as [94]:

(i) **Price/Energy arbitrage** aims to obtain income from the difference between buying energy when electricity prices are lower and selling it when they are higher. Authors in [95] identified that taking advantage of price variations depends on technical parameters like efficiency. Specifically, they found that an improvement of about 10% in storage efficiency increased 3% of the annual revenue stream of IEP/Aggregators that used storage together with a wind generator.

(ii) **Ancillary services and capacity reserve** consider BESS operating to provide flexibility services as required by the DSO/TSO. Nevertheless, a cooperation scheme between the IEP, DSO, and TSO is required for BESS to interact with them through functional architecture.

(iii) **Capacity firming** refers to a BESS operating to support DSO activities by ensuring energy availability during peak periods to avoid network congestion.

(iv) **Peak-shaving and load smoothing** offer benefits to the DSO which defers costly investments and operational costs by modifying the load profile.

(v) **Smoothing fluctuations and Curtailments minimization** refer to a BESS operating to complement RES integration. Therefore, avoid operational costs by locally dealing with intermittence, fluctuations, and curtailments [95] while ensuring technical and quality parameters at the connection point to the DN and maximizing the usage of the RES [67]. In [2] an ESS is integrated to add value for an IEP owner (who already owns the wind system) and the DISCO via a cost/benefit analysis, taking advantage of the ESS to store the spilled wind energy (releasing it when economically needed) and of reducing DN losses by optimally allocating the ESS.

Recently in Portugal, an auction that considered PV projects with storage integrated could receive a fixed premium for flexibility. This auction established that producers receive the auction closing price and the price of the electricity market, in return for the payment to the national electrical power system of risk coverage insurance, that is, when the price of the electricity market exceeds the marginal cost of activating a combined cycle unit, this difference must be returned [96].

3.2.3 Shared or Community Energy-owned model

This model considers BESS to be owned by a collective or group of users, namely a community. They would trade in market environments, and provide flexibility and storage services to DSOs, or large energy consumers. As mentioned in Section 1.2, a new group of

BESS applications/services is emerging given that its main goal is to share the costs of investing in BESS and benefit from BESS applications with all community or collective group members/shareholders. Nevertheless, it may provide services to the DSO or IEP through an aggregator. For this, BESS owners may consider applications/services such as [94]:

(i) **Price/Energy arbitrage** aims to reduce the energy price of the community participants by taking advantage of the difference between buying energy when electricity prices are lower and selling it when they are higher. Authors in [97] consider the integration of a community PV system and concentrated BESS owner by an aggregator to maximize the revenue stream of the latter while providing economic benefits to the former by taking advantage of electricity price gaps. They found that by installing batteries an aggregator can increase their profits and reduce the peak demand of the community.

(ii) **Demand response, peak shaving, and load smoothing** refer to BESS operating to change the load profile to reduce customers' high demand charges or as a requirement made by the DSO. In [93], a decentralized market design based on the DSO-aggregators-prosumers allows DSOs to obtain flexibility from aggregators, who incentivize their prosumers to manage the demand. The market structure accounts for potential flexibility contracts that limit the negotiation to each prosumer with a unique aggregator, and an ICT infrastructure to ensure that it is not possible to make one participant better off without making another worse off.

(iii) **Ancillary services, capacity reserve, and other services to the DSO** refer to BESS operating to provide flexible services as required by the DSO/TSO. This application/service may be implemented through an Aggregator that could or could not manage the demand response [97]. Therefore, a cooperation scheme to interact with the community members/shareholders is required.

(iv) **RES integration** refers to BESS used to store and release energy when technical or economically interesting for the community participants. From the current community energy regulation perspective, if the energy origin is not renewable (e.g. energy from batteries) it cannot be shared with the community members/shareholders [98]. This has led to largely deploying batteries behind-the-meter [56], but could also lead to suboptimal management of the resources and overinvestment in PV systems.

As BESS owners, shared or community, IEPs, and Aggregators can simultaneously offer the services previously described and other technical-support-orientated under hybrid operation strategies. Nevertheless, the main challenge is related to the regulatory framework required to provide flexibility to the network and the cooperation structure required to interact with DSO/TSO [19], because, as expected cooperation schemes involve the creation/definition of commercial contracts focused on the flexibility provision.

3.3 Battery Storage Planning Problem

Planning battery storage into the DN requires following a similar process to the ones used to plan distributed resources such as DG from RES [34]. Based on the planning criteria and constraints, the investments required to achieve a DN as designed by the optimal solution are identified. Specifically, BESS and other ESS needs must be considered in the problem formulation to find a suitable solution [6]. Therefore, integrating BESS and ESSs into the DN is challenging given there are different battery technologies with characteristic settings for their parameters [22] that must be fulfilled.

The general planning problem involves determining the location or locations for BESS and how big they should be as allowed by operational conditions imposed by both BESS scheduling and network behavior, along the planning horizon. Traditionally, planning horizons approached for the DN planning problem can be divided into short-term (from 1 to 5 years), long-term (from 5 to 20 years), and horizon-year (more than 20 years) planning [9], [30] but, even dealing with uncertainties surrounding the process the DSOs could be forced to perform planning schemes periodically. As the planning horizon is longer, the optimization process is more challenging given the interdependency between the stages [10] and the need to determine the optimal time to install the asset [34].

A generic DN planning could naturally be considered a mixed-integer linear/non-linear programming problem [34], [37], [99] with an inherent combinatorial nature, thus, it is described by discrete (binary) and continuous variables, represented for example, by installing new assets and the power flow, respectively [100]. As batteries are a different type of asset that can provide multiple services, they will also impose their inherent objective and constraints to better achieve the expected behavior when integrated into a DN with RES [101]. Specifically, the BESS planning problem is usually represented by three freedom degrees: size (usually, influenced by network parameters and location e.g. DN/substation, RES, or consumer side), location (usually, influenced by physical availability), and battery technology selection (usually, influenced by CAPEX, OPEX and application/service to provide). However, the complexity of the planning process could be increased if another binary variable like interface technology selection is added to the problem (also denominated C-rate, it may increase the possible combinations to be evaluated), or reduced if the location or battery technology is already known, which means they are not considered as a discrete variable of the problem [102].

Figure 3-1 shows a general scheme of the optimization process for planning BESS into the DN in the modern era. As mentioned in Section 3.1, an interconnected and iterative scheme is considered to solve the optimization problem based on a bi-level optimization (interaction between upper and lower-level). Under this scheme, the upper-level is a generator of potential solutions or decisions, which are provided to the lower-level, while the lower-level is responsible for simulating and evaluating every solution as indicated by the objective function and for the time horizon. Hence, it provides feedback to the upper-level, which will generate a new potential solution until it reaches the stop criteria [43], [53], [89], [100]. This scheme's main advantage is the capability to implement heuristic and/or hybrid methods by decoupling the planning and operation problems [94]. However, two questions must be carefully answered: (i) what are the objectives to achieve? (does it describe by single or multiple objectives?), and (ii) what methods can be used to explore the feasible areas to find the optimal solution?.

3.3.1 General formulation of the planning problem

A formulation for DN planning that is as close as possible to reality increases the complexity of the problem. As planning decisions impact the network operation, solving the operation problem related to the lower level is also challenging because it should be assessed for the planning horizon under a sufficient number of scenarios that properly represent the uncertainties surrounding the process [85], [86], [103]. Considering several scenarios increases the robustness of the planning results but also becomes the problem computationally expensive [43], [103].

The general BESS planning problem into the DN may be formulated as presented below [24], [37], [104] in Equation 3-1 to Equation 3-4:

$$Min\, F(x) = \min\, [\, f_i(x) + f_{i+1}(x), \dots\, f_n(x)\,] \tag{3-1}$$

Subject to:

$$x \in \Omega \tag{3-2}$$

$$G(x) = 0 \tag{3-3}$$

$$h_l \leq H(x) \leq h_g \tag{3-4}$$

Where:

F_x, is the value achieved by the objective function (OF) or fitness function.

f_i, is the i^{th} objective in the function and n, indicates the number of objectives.

x, represents the vector of binary decision variables.

Ω, is the search space defined by the set of combinations of the decision variables.

$G(x)$, are the set of equality constraints, for example, BESS energy balance.

$H(x)$, are the set of inequality constraints, for example, network constraints, SoC.

$h_l$and h_g, are the lower and upper value that $H(x)$ can take.

Regarding the boundaries of the planning problem, they are mainly defined by the (i) modeling of the DN and BESS which is dependent on the required accuracy from the optimization process, (ii) the complexity of the operational stage of the DN, and the planning horizon. The short-term horizon usually does not consider network evolution, thus, in the optimization process, the lower level is the main responsible for providing suitable information to the upper-level so it can generate a new potential solution. In contrast, long-term horizon planning considers several aspects of the future DN such as the forecast of demand growth, changes in load profiles, loads and RES integration, changes in DN configuration, fuel costs, and energy market costs, among others [9], [34]. Therefore, the investment plan identified must reflect the impacts of the calendar/cycle life of BESSs.

Another relevant aspect is related to the centralized or decentralized perspective approach. Specifically, for the BESS planning, a central perspective could not properly represent all the stakeholders/players and their objectives because it is mainly focused on the DN needs and IEP, Aggregators or RECs will invest in a BESS project only if the solution is cost-effective from its perspective [2]. On the other hand, a distributed perspective could represent all the stakeholders/players, even the DISCOs, given BESS planning is mainly focused on minimizing/maximizing cost/benefits from the player perspective.

For this research work, Table B-1, Appendix B, summarizes the available data on planning objectives, network modeling, uncertainty management, and solution methods for solving the optimal planning problem, collected from the literature reviewed.

3.3.2 Planning objectives and constraints

BESS planning may solve the problem of its optimal size, location, technology selection, and others. Nonetheless, the objectives to be achieved and the constraints to be satisfied can be multiple [24] because they depend on the BESS applications/services to be provided [34] and the BESS-owner business purpose. The objectives can be technical (DN losses, voltage limits) and economic (investment costs, rate of return, revenue stream) [40], [44], [53], [88], [104]–[106], but also environmental (reduced CO_2 emissions) [32], or social (community benefits). Thus, the decision-maker must design, quantify, and model every objective and rewrite Equation 3-1, as needed, to integrally optimize it.

While the terms in Equation 3-1 are measured in the same base unit (usually economic), this formulation is considered mono-objective. On the other hand, a multi-objective formulation considers objectives with different base units, which could be more challenging given the direction to generate the next potential solution may change [107], and improving one objective could deteriorate another. This formulation is typically implemented when a distributed resource must offer benefits for two or more stakeholders/players.

A generic objective function that only considered BESS planning into the DN with RES is shown in Equation 3-5. Some terms have already been defined in Section 2.2.2, nevertheless, they are mathematically expressed below.

$$Min: OF_{BESS} = \left[C_I(x) + C_{O\&M}(x) + C_R(x) + C_{RD}(x) + C_P(x) - C_{RS}(x) - C_{S/I}(x) \right] \quad (3\text{-}5)$$

Where:

$\boldsymbol{C_I(x)}$ is the one-shot investment cost required to integrate BESS into the DN. As shown in Equation 3-6 it represents the sum of C_I^P, Power capital cost, and C_I^E, Energy capital cost. In the planning process $C_I(x)$ is converted to an annualized value by multiplying it by an annuity factors (AF) determined as shown in Equation 3-7, where r denotes the discount rate, and L is the BESS calendar lifetime [4], [34], [78].

$$C_I(x) = C_I^P + C_I^E \quad (3\text{-}6)$$

$$AF = \frac{r(1+r)^L}{(1+r)^L - 1} \quad (3\text{-}7)$$

$\boldsymbol{C_{O\&M}(x)}$, represent the annual cost of BESS Operation and Maintenance. Since these systems do not contain rotary parts, maintenance requirements and costs are usually considered negligible [34], [55].

$\boldsymbol{C_R(x)}$ is the sum of the costs of replacing/augmenting the storage bank, Re_b, along the life expectancy of the project, T [39]. Equation 3-8 expresses the total replacement cost, where the frequency of replacement, FR_{Sn}, is determined considering the life expectancy of the project, T (Equation 3-9), the battery cycles per year reached, C_y, the battery lifecycle, C_{tl}. In non-flow technologies, both C_y and C_{tl} are dependent on the DOD while in flow batteries the FR_{Sn}^n is mainly due to T [101]. Annualized $C_R(x)$ can be calculated by using Equation 3-7 [4]. Disregarding cycling aging in the optimal BESS planning into the DN, the economic assessment could be inaccurate because the replacement cost of the battery storage bank may not be properly modeled [78].

$$C_R = \sum_N^{FR_{Sn}} \frac{Re_b}{(1+r)^{N*L}} \quad (3\text{-}8)$$

$$FR_{Sn}^n = T/[1/(C_y/C_{lt})] \quad (3\text{-}9)$$

$\boldsymbol{C_{RD}(x)}$ represent the recycling and disposal costs. They are not widely documented in the literature for all battery technologies [108]. According to [55], $C_{RD}(x)$ is determined by the difference between the costs of recycling BESS materials (storage bank) and the incomes received from their sale ($/pounds). This term is strongly driven by factors such as (i) the need for supporting the upstream supply chain for battery manufacturing, and (ii) the reduction of environmental impacts throughout the life expectancy of BESS project when batteries are not properly recycled [74]. $C_{RD}(x)$ will grow in relevance due to financial, risk, and environmental considerations.

$\boldsymbol{C_P(x)}$ is the penalization cost. This term ensures that a solution generated at the upper-level that violates constraints or deviates from the desired performance parameters could not be located near the potential optimal solutions. In the literature, this term is used, for example, to ensure voltage limits [6], assets loadability [53], [54], or technical losses are between standard values and to prefer solutions with less environmental impacts [101].

$\boldsymbol{C_{S/I}}$ represent the set of incomes a decision-maker can consider and subtract from the investment due to an economic benefit received by the BESS integration [20]. As mentioned in Section 2.5, a non-regulatory definition for $C_{S/I}$ could be considered a barrier to a profitable BESS integration [5]. Nevertheless, researchers have been working on showing the importance of defining them by providing information to policymakers [54], [91], [109].

$\boldsymbol{C_{RS}(x)}$ represent the revenue stream from BESS behavior. From the BESS owner's perspective, this is an important term in the OF because it indicates the expected yearly income by BESS application/service that amortizes repayment of the loan and upfront investment costs [4]. As mentioned in Section 2.4 there are several applications/services BESS may provide. Then, this term is expressed based on the service provided. This term will be approached in detail in Section 3.4.

Equation 3-5 could be slightly modified as required by the decision-maker to better represent the planning problem and the objectives to be achieved, for instance, in [32], the objective function also considers minimizing the pollution emission cost given BESS is integrated to reduce the use of a Micro-turbine already installed into the DN. Authors in [6], introduce in the objective function a penalization factor to ensure that solutions are forbidden when voltage bus violations occur at any point along the planning horizon, while authors in [1] the voltage profile improvement was added as a specific term.

This objective function will be subject to several operation and technical constraints with which decision-makers ensure the DN's reliable and safe operation [44]. Most typical constraints are associated with network modeling and operational limits of DN assets, nevertheless, other constraints are also considered in some approaches, e.g. authors in [78] consider constraining the BESS planning problems to an available budget.

3.3.3 DN network modeling

To represent a BESS planning problem constrained by the power network, models based on the power flow (PF) equations must be developed [11], [34]. Two main PF equation sets are frequently used to model the network constraints, the balanced AC and DC PF. In addition, an unbalanced three-phase PF is used when a decision-maker cannot ignore the network unbalances mainly due to the loads. For AC PF the active/reactive power, bus voltages, and network losses are considered and calculated based on a more real network model (non-linear model solved following an iterative method) that may represent a high execution time and risk of divergence. A generic AC PF formulation is shown below. This formulation is dominated by non-linear equations given they describe the relationship between voltages at DN buses/nodes, phase angles, and power flows in the network. Equations 3-10 to Equation 3-15 show the key equations used in AC PF [22].

$$P_i = \sum_{j=1}^{N} |V_i| \left|V_j\right| \left[\mathrm{G}_{ij}\cos\left(\theta_i - \theta_j\right) + \mathrm{B}_{ij}\sin\left(\theta_i - \theta_j\right)\right] \tag{3-10}$$

$$Q_i = \sum_{j=1}^{N} |V_i| \left|V_j\right| \left[\mathrm{G}_{ij}\sin\left(\theta_i - \theta_j\right) - \mathrm{B}_{ij}\cos\left(\theta_i - \theta_j\right)\right] \tag{3-11}$$

Where: P_i is the active power injected at bus i; Q_i is the reactive power injected at bus i; $|V_i|$ and $\left|V_j\right|$ are the magnitudes of the voltage at buses i and j; and θ_i and θ_j are the angles of the voltages at buses i and j. Therefore, voltage limits and power flow are determined as shown below:

$$P_{ij} = v_i^2 g_{ij} - v_i v_j\left[\mathrm{g}_{ij}\cos\left(\theta_{ij}\right) + \mathrm{b}_{ij}\sin\left(\theta_{ij}\right)\right] \tag{3-12}$$

$$Q_{ij} = -v_i^2 b_{ij} + v_i v_j\left[\mathrm{b}_{ij}\cos\left(\theta_{ij}\right) - \mathrm{g}_{ij}\sin\left(\theta_{ij}\right)\right] \tag{3-13}$$

$$v_i^{min} \le v_i \le v_i^{max} \tag{3-14}$$

$$P_{ij} \le P_{ij}^{max} \tag{3-15}$$

Where: P_{ij} is the active power flowing from bus i to j; v_i^{min} and v_i^{max} are the maximum and minimum voltage considered between the normal operational range (usually, 0,9pu and 1.05pu, respectively). Concerning BESS constraints, they are presented in Section 3.4.

AC PF is used as some BESS/ESS applications require network parameters, for example, for voltage support applications it is crucial to calculate bus voltages, or for loss reduction applications, calculating network losses is necessary. AC PF has been used in [2], [16], [22], [32], [37], [39].

For DC PF, the network losses are ignored, and bus voltages are considered equal to one per unit (ignoring the reactive power), therefore, it converges fast but sacrifices accuracy because the PF is calculated as a non-iterative solution. Some DC PFs are modified to consider network losses or bus voltages, but these approaches preserve their linear nature, which makes their results differ from those of AC PFs [44]. A generic DC PF formulation is shown in Equation 3-16 to Equation 3-18.

$$P_{k,t} = \sum_{k=1}^{K} Pl_{k,t} - \sum_{k=1}^{K} Pg_{k,t} \tag{3-16}$$

$$P_{PF,t} = A * P_t \tag{3-17}$$

$$P_{jk,t}^{min} \leq P_{jk,t} \leq P_{jk,t}^{max} \tag{3-18}$$

Where: j, k are buses, t is the period in which PF is calculated, $P_{k,t}$ is the power in k at t, $Pl_{k,t}$ is the power consumed in k at t, $Pg_{k,t}$ is the power generated in k at t, P_t is the power flow matrix in t, A is the network sensitivity matrix, $P_{jk,t}$ the power flow in a branch of the previous matrix at t, $P_{PF,t}$ is the matrix for period t of every $P_{k,t}$ in the network. $P_{jk,t}^{max}$ is the maximum power flow in the j,k branch and $P_{jk,t}^{min}$ is the minimum power flow in the j,k branch.

In [53] and [54] authors use a DC PF for scheduling BESS under an electricity price arbitrage application. Authors in [67] also use a DC PF for BESS scheduling under an

3.3.4 Solution methods for planning problems

The optimal sizing, location and battery selection to integrate in a DN is not straightforward. As using AC PF or DC PF has a direct effect on the optimization method to be used and the results, an appropriate selection of the methods may also play a crucial role in the planning process. Four main types of methods could be used for DN planning: (i) Analytical, (ii) Mathematical, (iii) Heuristic/Meta-heuristic, and (iv) Artificial Neural Network [10], [34], [44]. The hybridization between these models may contribute to achieving the best optimal solutions. Usually, hybridization combines two or more algorithms with different strengths to eliminate the limitations of a single approach, and, therefore, high-quality results could be obtained [11], [44].

Analytical methods perform well in optimization that find solutions from an algebraic function, which may be directly derived to implement repetitive calculations or simulations. For BESS allocation, this allows better visualization of ESS sizing. Nonetheless, it requires a long time to converge given the computational complexity and the possibility of being readily trapped at a local optimum. For large and complex systems this method is not suitable [11]. Analytical models include optimization through the deviation of cost-benefit analysis [2], [75], constructing bus voltage sensitivity matrix to observe the impact of variables, and advanced algorithms such as parallel branch and bound, benders decomposition, among others [34], [44].

Mathematical models use numerical methods to find an optimal solution using an approximated model of the problem approached, where the OF can be evaluated under an iterative process. Solvers like CPLEX or GAMS can efficiently handle these models. Nevertheless, they are not for modeling non-linear, large-scale, and long-term ESS allocation problems [10], [44]. Mathematical models include dynamic programming (DP) [95], linear programming (LP) [39], [53], [54], mixed integer linear programming (MILP) [22], and interior point algorithms [1].

Heuristic methods are optimization techniques based on random and iterative procedures that are flexible, model-free, and avoid local optimums [10], [34]. Compared to analytical and mathematical models, they have some drawbacks since they cannot always guarantee the best optimal solution is found [11], and the search method used (random and iterative) is quite time-consuming because individuals are randomly generated but, populations are generated considering the problem constraints. Therefore, adaptive or modified approaches are designed to obtain Meta-heuristic methods that enhance the optimization performance [110]. Heuristic methods can effectively deal with the discrete nature of the problem and the non-linearity of objectives and constraints, therefore, they may be successfully applied to solve the planning problem, being capable of determining a size, location, and/or technology selection (or combination of technologies) as a concentrated or distributed resource [53], [71]. Many Heuristic/Meta-heuristic methods have been used to solve the problem of planning BESS into the DN with and without RES including genetic algorithms (GA) [16], [39], [71], tabu search (TS) [6], simulated annealing (SA) differential evolution (DE) [32], particle swarm optimization (PSO) [6], [16], Fuzzy Particle Swarm Optimization (FPSO) [37], and evolutionary particle swarm optimization (EPSO) [53], hybrid multi-objective particle swarm optimization (HMOPSO) [1], and differential evolutionary Particle swarm optimization [54].

Artificial neural networks are powerful for modeling complex mappings, pattern recognition, and function approximation because they can be trained to predict and generalize. They can optimize highly non-linear planning problems or the power flows of the network [54] by transforming them into a simple input-output form, saving efforts in solving complex equations compared to analytical and heuristic models. Artificial neural networks can learn from many examples to extract core features within a multidimensional information domain, being able to perform high-quality forecasts.

Characterizing and explaining all types of methods is out of the scope of this research work. Nevertheless, authors in [44] explain each type of algorithm based on a generic flowchart while authors in [11] and [99] provide a detailed review of the optimization models and tools widely used.

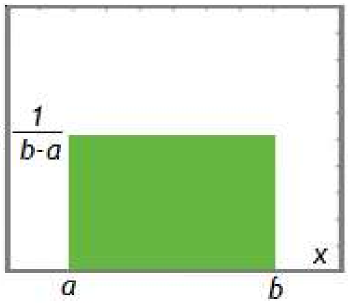
3.3.5 Uncertainties management

The planning problem requires some input parameters along the planning horizon. These parameters are usually related to load, network configuration, generation from distributed resources, energy prices from electricity markets, etc. According to [87], uncertainty management is one of the main issues decision-makers must face in a power system given the reliability of the planning process is sensitive to the future values of the parameters and techniques to forecast them involve inherent errors [34], which could cause optimal results do not work as expected in real-life situations.

Probabilistic methods are one of the most popular algorithms used to manage uncertainties, they use probability distribution functions (PDFs) to model the uncertain variable and represent it by a set of scenarios [52]. Then, uncertainties are often managed as a set of possible future scenarios with a probability of occurring where each scenario represents a certain outcome of a parameter of uncertainty. The most used methods are probabilistic power flow [1], [6], [22], [39], Forward-Backward Sweep power flow [71], Monte-Carlo methods [32], [39], [53], [54], [76], point estimate methods [1], [6], stochastic programming, chance-constrained programming, fuzzy logic, factor method [45], clustering techniques [22], and forecasting toolbox [37].

In [6], the probabilistic PF was executed for every season separately aiming to investigate the behavior of the parameter that better represented the uncertainties related to every season. The same seasonal classification of the data was considered by [22] to manage the uncertainties of PV generation. Concerning [1], it was executed as a constraint to a problem that discretizes the continuous wind generation scenarios based on the point estimate methods.

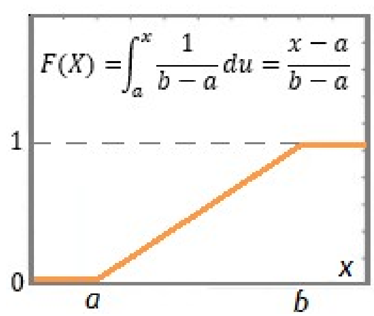
As Monte Carlo is the method considered to manage the uncertainties surrounding the planning and operation problems here approached, this method is used by considering the explanation presented as follows. To use this method probability distributions are constructed based on possible outcomes a variable might take. For example, Equation 3-19 shows the formulation of a uniform distribution based on an illustrative explanation. For this type of distribution regardless of the value taken by the variable x, the outcome $f(x)$ is equally likely when x is between a and b.

$f(x) =$ 

$$f(x) = \begin{cases} \frac{1}{b-a}, & for\ a \leq x \leq b \\ 0, & for\ \ x < a,\ x > b \end{cases} \tag{3-19}$$

Using Monte Carlo to manage uncertainties allows decision-makers to identify how likely could be an outcome $f(x)$ if the variable x takes an uncertain value [111]. Therefore, by creating histograms of probability distributions it is possible to identify the distribution function that fits a histogram. This is useful because it is possible to quantitatively assess the risk associated with each value that the variable x could take.

With the Monte Carlo Method, an uncertain value could be replaced with a function generating random samples from the probability distribution, $f(x)$, previously fitted. A random value from a probability distribution is equally likely to be that one from its respective cumulative density function given the cumulative function is obtained by integrating the probability distribution $f(x)$. From this approach, considering the uniform distribution expressed in Equation 3-19, its respective cumulative density function is presented in Equation 3-20, which is also based on an illustrative explanation. Regarding the shape of each cumulative curve, more values are generated where the cumulative curve is at its steepest.



$$F(X) = \begin{cases} 0, & x < a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & x \geq b \end{cases} \tag{3-20}$$

Concerning a normal or Gaussian distribution, the detailed formulation can be found in [111], [112]. However, an illustrative explanation is shown in Figure 3-2. Figure 3-2a shows an example of a probability distribution of normalized values of the variable x explained by a 12-bar histogram, whose distribution function fitted corresponds to a normal distribution with mean μ and standard deviation σ (Figure 3-2b). The respective cumulative density function is shown in Figure 3-2c. As noted, it describes the cumulative probability of a given value of the variable x.

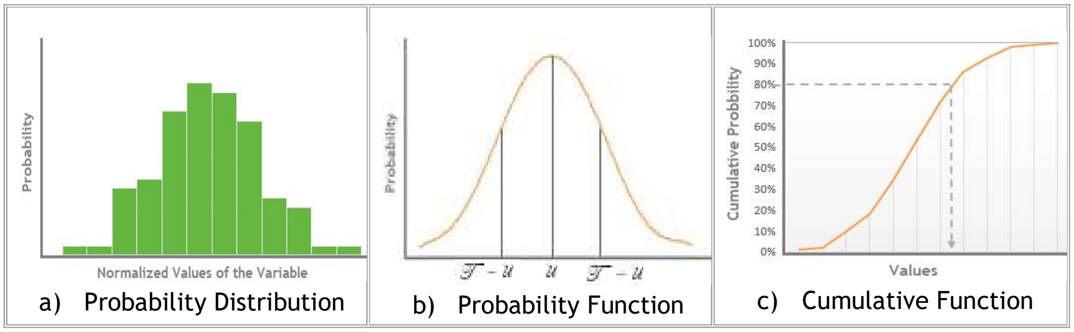


Figure 3-2. Main steps of the Monte Carlo Method for Managing Uncertainties.

3.4 Battery Storage Operation Problem

From the traditional DN perspective, its operation could be defined as the task of providing different dispatches to active assets regarding the network configuration and conditions which is challenging. Nevertheless, its complexity may significantly increase when the DN is operated under contingency scenarios [8], [85]. Nowadays, the DN operation problem is usually approached depending on the perspective of each stakeholder/player. A DSO may consider the DN operation process as one technical-support orientated where the active assets are controlled and managed to economically supply energy to the demand as allowed by the operational constraints (e.g. voltage in buses and loadability in lines or feeders), and the regulatory quality requirements to ensure the flexibility and reliability of the DN. In contrast, an IEP or an Aggregator that owns RES could consider an operation strategy profit-making orientated that fulfills the technical and network constraints.

Concerning BESS operation clear rules for different stakeholders/players may answer the question of who can own and operate these systems given it is expected that from the perspective of the DSOs, BESS will be mainly used to minimize technical network issues [30]. Therefore, in the absence of policies and regulatory frameworks that define and remunerate the storage and flexibility activity, operating BESS could be determined by an objective function that aims to maximize benefits such as cost saving [88], efficiency, or revenue stream [39], [54], or minimize operation cost [76], smoothing voltage fluctuation [6], [16], [22] and energy not supplied [34].

Regardless of the objective function to optimize or the revenue model defined, the integration of BESS into the DN means scheduling the most suitable periods for charging and discharging the batteries as allowed by the batteries and network constraints [6], [16],

[53], [88]. Nevertheless, the operation problem could be enlarged when BESS must attend to objectives or fulfill requirements from different stakeholders/players, mainly from DSO, because the DN network must be modeled, studied, and assessed in detail. According to [2], when BESS was integrated into a DN to fulfill requirements from an IEP or Aggregator and the DSO (arbitrage, curtailment reduction, and loss minimization) it was found a high difficulty to achieve a feasible solution; in fact, the problem was solved only when the less expensive technology was considered.

3.4.1 Storage bank modeling

Modeling the storage bank to represent its characteristics and behavior is essential for designing strategies and reaching an optimal operation for BESS (charging and discharging process) and a more reliable revenue stream [5]. A proper battery model should be able to predict, throughout the BESS life, its behavior for different operating conditions while providing a reliable estimative for SoC and SoH values [75], and also the degradation of the battery. Therefore, in the context of planning and operation BESS in the DN it is useful to design a battery model non-dependent on the technology given one of the objectives of the planning problem is related to the battery technology selection.

Regarding the scope of the study, batteries can be represented under [5], [69]:

(i) **Electrochemical models** that express the chemical processes in the battery, therefore, it is strongly dependent on battery technology. This model is a complex but reliable one that describes battery characteristics like the mass, energy, and components of the battery cell, among others. The advantages of this model are related to the capability to represent quantities such as voltage, current, and temperature of the cells; for this reason, they are frequently used to optimize the design of the cells.

(ii) **Electrical models** that consider batteries a circuit equivalent, therefore, batteries are described by electrical components such as a voltage source, resistors, and capacitors. Thus, some effects like the temperature effect in batteries are modeled by a pair resistor-capacitor. This model is frequently used for co-design/co-simulate batteries with other electrical circuits/systems.

(iii) **Mathematical models** that aim to describe the battery behavior and predict the efficiency, and useful storage capacity, among others, based on empirical equations or stochastic methods. Although this model does not represent information related to cells' current or voltage, it is suitable to be used in a wide range of BESS applications, therefore, this model is interesting in the context of the planning and operation approach.

One of the battery models widely used in the literature to represent battery behavior is similar to the one used in the operation of hydropower stations, then describing the reservoir behavior as a Markov process, the volume in a reservoir at any period t is related to the volume in the reservoir at period $t-1$ and the inflow and outflow occurred in the period t; in other words, each period interacts with its adjacent periods (before and after). Called the balance equation, it is rewritten to represent battery energy balance as shown in Equation 3-19 for an ideal battery model (where energy losses from the charge/discharge process are not considered) and 3-20 for a non-ideal battery model.

$$SoC_t = SoC_{(t-1)} + Ebl_t - Ebg_t \tag{3-19}$$

$$SoC_t = -\delta S + SoC_{(t-1)} + n_c n_{in} Ebl_t - \frac{Ebg_t}{n_{out}} \tag{3-20}$$

Where:

δ, represent the battery self-discharge, Ebl_t, represents the energy charged along the charging stage of the battery at period t, and Ebg_t represent the energy discharging along the discharging stage of the battery at period t, and n_c, n_{in} and n_{out}, represent the battery efficiency, and the network interface technology efficiency to and from the battery, respectively.

3.4.2 Operation objectives and revenue models

As mentioned in previous sections, in the absence of incentives, subsidies, or regulatory framework, the revenue models from battery operation are exclusively responsible for supporting the economic feasibility of BESS projects [4], [51], [76]. Therefore, an operation problem formulated as close as possible to reality may increase the complexity of the optimization process but also provide more accurate information about BESS behavior and revenue stream. As shown in Figure 3-1, in the decoupled BESS planning and operation optimization approach, the lower level is responsible for the optimal BESS operation [94], therefore, it is necessary to simulate and evaluate every solution provided from the upper-level, along the time horizon, as indicated by the objective function and its constraints. However, this is a challenging task given obtaining a BESS behavior as close as possible to reality requires a sufficient number of scenarios that properly represent the uncertainties surrounding the process [85], [86], [103].

BESS can provide a wide range of applications/services to the electrical network and different stakeholders/players may be involved, therefore, important difficulties in defining a generic formulation to describe BESS operation in the DN given that players could follow a technical-support-orientated, profit-making-orientated, or hybrid perspective to support BESS operation. As mentioned in Section 3.2 the revenue and the business model can vary according to BESS-owner, and the network and environmental requirements, nevertheless, the optimization process must define the Ebl_t and Ebg_t at any t, and the total operation cost up to the horizon time, T.

Since this research work is focused on planning and operating BESS into the DN from the perspective of small-scale investors who need to obtain valuable information about the feasibility of a profit-making-oriented approach, the BESS operation problem is reviewed in the scope of batteries participating in the market environments, namely in electricity and capacity reserve markets under price/energy arbitrage and capacity reserve applications, respectively. Special attention is given to battery technical and non-technical parameters modeling and the management of price uncertainty.

Several researchers have studied BESS participating in market environments. In [80], various storage technologies were modeled considering self-discharge and RTE parameters to evaluate their response to energy arbitrage and to find the power and energy capacities that maximize the internal rate return. Findings revealed that profits are mainly determined by performance parameters. In [91], the revenues from non-ideal models of storage technologies that respond to electricity and regulation market prices were also maximized. Even, under deterministic price models, findings revealed that batteries are profitable for none of the businesses modeled due to their investment cost. However, simultaneous participation in both markets allows batteries with long discharge times and low investment costs to be near breakeven costs.

Authors in [79] modeled batteries based on the current SoH, C-rates, and RTE parameters, and price uncertainties based on an agglomerative hierarchical clustering to optimally size and select battery technology. Battery cycling degradation was considered to optimize battery operation as a response to peak shaving and energy arbitrage. Results suggested that, in contrast to other performance parameters, battery lifecycle does not limit the achievable revenues. In [53] and [54] ideal battery models that operate at different C-rates respond to electricity market prices which were modeled based on a Monte Carlo simulation. After finding the optimal BESS size and location in a test system, results showed a trade-off between C-rates and storage capacity that allows BESS owners to meet a range of investment opportunities. In [43] a non-ideal Li-Ion battery model was approached to optimally size and location storage systems that provide energy and ancillary services. Findings revealed Li-Ion batteries were only integrated after reducing their investment cost by 30%, then, it was also found that revenues from arbitrage are roughly the same for the markets considered.

Energy arbitrage strategies for maximizing battery profit regarding operation decisions focused on price-quantity bids in the day ahead market (DAM) and quantity-only in the real-time market were approached in [63]. Charge and discharge losses and rates were modeled to analyze how the annual cycles are affected by each strategy. Findings suggested that the battery made more bids in DAM, which impacted the storage lifecycle. In [113] authors studied bidding strategies for BESS in electricity markets. Battery cycle life was considered a key parameter that could limit its operational strategy. For this, battery self-discharge and efficiency were modeled aiming to maximize the profits of bidding in day-ahead markets. Results support embedding battery cycle life into the bidding strategy is beneficial for batteries since their degradation is reduced by not providing regulation service in some periods compared to the case of not embedding it. In addition, they found batteries would be deeply involved in regulation markets to take advantage of low prices in off-peak periods to compensate for the energy loss as a consequence of their efficiencies.

Interesting efforts have been made to approach the battery operation problem to study how to maximize revenues or minimize operation costs while responding to electricity/regulation market prices. Even when some battery parameters have previously been modeled, still being necessary to analyze how AC-AC RTE, DOD, and C-rates parameters affect the annual cycles and operation costs (or revenue) of batteries that respond to electricity and regulation market prices modeled to deal with uncertainty

3.4.3 Constraints

The strategies used to design BESS business and revenue models require a set of equations and inequations to describe the limitations or conditions that a solution must satisfy given they shape the search space of an optimal solution to the problem. Batteries are a different type of asset that can provide multiple services, therefore, their inherent constraints must be considered to better achieve the expected behavior when integrated into a DN with RES [101]. Similarly to objectives, constraints to be fulfilled can be multiple [24] because they are also dependent on the BESS applications/services to be provided [34] and the BESS-owner business purpose.

A generic set of constraints is shown in Equation 3-21 to Equation 3-23. From a general perspective, these constraints are proposed to raise different aspects such as physical limitations, system requirements, and availability, among others.

$$0 \leq Ebl_t, Ebg_t \tag{3-21}$$

$$SoC_t^{min} \leq SoC_t \leq SoC_t^{max} \tag{3-22}$$

$$Ebl_t, Ebg_t \leq S * \gamma \tag{3-22}$$

Where:

Equation 3-21 indicates that Ebl_t and Ebg_t must be non-negative. The minimum SoC_t at any t in Equation3-22 are defined according to the battery technology since they should not be totally discharged [6], while the maximum refers to a value usually defined as the battery capacity. In Equation 3-23, the maximum value of Ebl_t and Ebg_t, at any t, are obtained by multiply battery size, S, and C-rate, γ, which represents the maximum flow of energy in the battery. From this formulation C-rate, γ, pinpoints given it represent the smart charging and discharging a BESS owner can implement to control the BESS charge/discharge process and prorogate de BESS EoL [11].

3.5 Conclusions

BESS and other ESS will play an important role in the sustainable transition of electrical power networks because they may accelerate both the penetration levels and RES generation. They can also improve the economic and technical use of the existing electrical infrastructure by providing flexibility and reliability. Nonetheless, integrating BESS into the DN is a challenging task because the process of location, network interface selection, and technology selection must consider several aspects related to batteries, the network configuration, and the energy markets to find a suitable technical solution from the DN perspective, but also feasible and profitable business model from BESS investor perspective.

Planning BESS in the DN has been addressed through central and distributed approaches, with the most frequent objective (in a mono-objective approach) of minimizing a cost function (where the CAPEX of BESS plays an important role) by considering several technical, economic, and environmental constraints. A few approaches also propose minimizing technical and environmental objectives, namely CO_2 emissions reductions (in a multi-objective approach). Concerning the planning framework for BESS in the DN, models with different complexity have pinpointed the relevance of characterizing the DN, modeling the uncertainties surrounding the planning problem, modeling the batteries, and considering different BESS owners whose operation strategies for batteries are profit-making-oriented, technical-support-oriented, or a hybrid between them.

The optimization methods used to solve the BESS planning problem are mainly based on mathematical methods, heuristic methods, or a hybrid between both. Implementing these techniques depends on the perspective of the planning problem, the objectives to be reached, the BESS service to provide, and, even, how detailed the batteries models are considered. Regardless of the optimization method used, the complexity of planning BESS into the DN could force planners and decision-makers to simply solve a real problem by making assumptions such as:

(i) Providing specific available points to locate BESS into the DN. This reduces, at least, one degree of complexity of the planning problem given the solution method deals with a reduced search space.

(ii) Considering specific load and generation profiles without dealing with uncertainties or providing a reduced set of curves to represent data variation along days and seasons, which impact the revenue stream regardless of the service BESS will provide.

(iii) Using a specific battery technology model. This means that findings are blinded by technological dependency.

(iv) Modeling BESS operation strategy under an ideal approach. This means that natural BESS behaviors, like energy losses, were not considered.

(v) Modeling the DN under a DC PF approach. This approach limits a suitable understanding of the natural behavior of typical DNs where technical parameters of the network and assets are affected due to network congestion, voltage fluctuations, reverse power flow from RES production (given the high penetration levels of RES production), and energy losses, among others.

By the aforementioned, it is important to achieve a suitable trade-off between the detail of the planning problem and the accuracy of the optimization method to be implemented, meaning that the whole planning process must propose a BESS planning methodology with a high compromise between both aspects.

Current literature also suggests that there is a gap in approaching the planning and operation of BESS into the DNs with RES already integrated from the perspective of the small-scale investors, able to deal with multiple uncertain scenarios related to energy demand, RES generation, and energy prices while providing valuable information about the profitability of the storage activity and the whole business model. That includes considering BESSs are owned by small-scale investors could lead to a profit-making orientated approach where, in the absence of subsidies, incentives, or a regulatory framework that remunerates the storage and flexibility activities, the non-dependent battery model and a proper revenue model play an essential role in determining the feasibility and profitability of a business model given only the revenue stream from the BESS application/service is responsible for amortizing repayment of the loan and upfront investment costs.

More realistic battery models are crucial to quantify the impacts of BESS efficiency on the revenue stream from battery operation and the impact of cycling aging on the frequency and replacement cost required to upgrade the BESS capacity. In addition, probabilistic management of uncertain scenarios for energy prices, load profiles, and RES generation cannot be ignored because the network and market parameters also impact batteries' behavior and revenue stream when they respond to applications such as price/energy arbitrage, load leveling/shifting applications, capacity firming, upgrade deferral, among others, evaluated under an AC network model.

The following chapters approach the BESS planning and operation problem in DNs with RES integrated. Specifically, in Chapter 4 the BESS operation problem is approached under profit-making-orientated strategies, therefore their formulation is presented for a more realistic BESS model and validated for different case studies aiming to provide valuable information on the opportunity of investment and economic return from BESS operation, as well as on the relevance of performance parameters of the battery influencing behavior and revenue stream.

Chapter 4

Performance Assessment of Batteries Operating under Profit-Making Oriented Strategies

4.1 Overview

Battery performance assessment is the process by which batteries are evaluated to identify how well they perform under specific conditions; in other words, this is a process where the battery performance parameters take a crucial role in allowing decision-makers to identify battery behaviors regarding different operation strategies and how those behaviors influence the revenue stream, battery lifespan, and other aspects to be considered when planning BESS into the DN.

The findings and facts reported in the literature and mentioned in previous Chapters evidence why batteries have been considered as a technology with the potential to revolutionize and modify the way electrical power networks should be planned and operated to achieve a low-carbon, energy-efficient, flexible, reliable, and economically affordable electrical power system [21], [25], [27].

Flexibility is a characteristic that electrical power systems must improve as RES integration grows. Providing flexibility from the "supply side" was usual in the past, but relying solely on the "supply side" solutions is currently expensive and environmentally non-friendly. Therefore, new players like IEP, Aggregators, and RECs, have become promisors because they could invest in BESS projects to provide flexibility and other storage services to the electrical power system once cooperation schemes between DSO and TSO are defined (which refers to implementing functional schemes that allow distributed resources interact with market operators and DSO/TSO) [19].

Authors in [30] reported that providing ancillary services to the power system is one of the main applications in which batteries could participate, however, they should grow parallelly with RES uptake. Therefore, DSOs, TSOs, and decision-makers should be capable of facing new challenges and contributing to the improvement of the technical parameters of the power network [11]-[15], [41], [42].

The optimal BESS planning and operation into the power network requires dealing with both investment costs and the risk related to the operation costs. From the planners and decision-makers perspective, it is important to identify the aspects that define a suitable operation strategy a battery will follow because when the investment costs in batteries are prohibitive and economic feasibility is not always discerned due to the lack of incentives, subsidies, or regulatory framework [17], [41], the revenue stream from its operation should, at least, cover the whole costs along the planning horizon [89]. According to [30] there is a lack of information about the battery performance and lifespan in real-life projects. Therefore, analyzing battery behavior based on more realistic battery models could help decision-makers make better decisions when planning BESS into the DN [91].

It is essential to admit that tools are needed to define a BESS revenue model (in the form of an optimization problem) that allows decision-makers to extract valuable information about the most relevant business models in which to invest and what battery technologies and technological interfaces are suitable to be integrated based on the application/service to be provided. Authors in [29] reported that private investors pushed forward with 75% of the investment in energy assets between 2013 and 2020. They privileged lower-risk investments while prioritizing economic revenues. As risk stems from uncertainties [114], the last ones must be properly managed to determine, although theoretical, the profitability of a business model [11], [34], [44] regardless of the BESS owner.

Nowadays, small-scale BESS investors do not trade in market environments because a regulatory framework that remunerates storage activities and other technical requirements must be defined or regulated. Nevertheless, efforts continue to be made [20] given their potential to invest in BESS and provide several storage services to the electrical power network cannot be ignored.

As discussed in Chapter 3, the BESS planning and operation problem is usually decoupled and solved under a bi-level optimization scheme in which the optimal BESS operation is located in the lower level [53], [89]. The aspects that impact BESS behavior and consequently influence the revenue stream, the replacement cost, and the battery lifespan should be considered when optimally planning and operating BESS. Hence, the main objective of this Chapter is to assess the battery performance and the revenue model when batteries follow profit-making-oriented operation strategies.

Unexpectedly, it could be considered it is not "too difficult" to estimate revenue streams from BESS operation given it can be calculated as the difference between incomes from energy sold during battery discharge and the payments by energy bought during battery charge. Although this explanation seems conceptually simple, the path to determine the amounts received and paid is not because revenue streams from the BESS that provide profit-making-oriented services are influenced not only by volatility in the market prices [91] but also by performance parameters such as the RTE [95] and the operation strategy.

Small-scale BESS investors need to estimate a reliable economic revenue window when BESS is integrated into the power network to provide profit-making-oriented services, this can only be achieved with detailed models, not only about the devices but also about uncertainties surrounding the operation process [4], [34], which include market price uncertainties [91]. Therefore, in this Chapter batteries are assessed considering:

(i) Price/Energy arbitrage and simultaneously Price/Energy arbitrage and Tertiary reserve are the operation strategies to which batteries must respond.

(ii) Monte Carlo is the probabilistic method used here to manage uncertainties from market prices.

(iii) Non-ideal battery models defined by technical and non-technical parameters such as energy/power capacity, useful storage energy, self-discharge, DOD, C-rates, SoC, DC-DC/AC-AC RTE, lifecycle, and calendar life take relevance in this work.

Market prices and battery models are the input data to the optimization tool for the BESS operation proposed here. The outputs are the BESS charging/discharging decisions (for a year represented by the 8760 periods), the revenue stream, the frequency of the storage bank replacement, and the battery lifespan. In general, the tool proposed here provides valuable and reliable information on the investment opportunity as well as on the relevance of battery performance parameters influencing behavior and revenue stream.

4.2 Battery Energy Storage for Market Services

Batteries are electrochemical devices that transform chemical energy into electrical energy (discharging process) or electrical energy into chemical energy (charging process) in a reversible process as a response to a signal, i.e. price, loadability, voltage, etc, strongly related to the services to provide. Technical-support-oriented services mainly include congestion avoidance, power quality improvement, upgrade deferral, capacity firming, etc, and profit-making-oriented mainly include price/energy arbitrage, ancillary services, voltage regulation, capacity reserve, or self-consumption, among others[4], [31], [33], [34]. Regardless of the BESS owners, a revenue model that aims to profit-making-oriented services tends to maximize the revenue stream [54], [80], [88] or minimize the expenditures [53], [79], [101] from battery operation.

Energy prices from the different markets related to the services previously mentioned also play an important role in the revenue model defined to assess battery operation, even more so currently, since the volatility some markets have been experiencing since 2022 has also been boosting RES integrations into the power networks [29] and with it, the need for a new source of flexibility and storage services [20] to deal with demand-supply mismatches [21] and voltage fluctuations, RES intermittency, network congestion, among others technical issues already identified [22]. In addition, volatility in the prices of critical materials required for battery manufacturing has also impacted the CAPEX of BESS projects [30]. Therefore, decision-makers need to design operation strategies for batteries under a more realistic revenue model given it will obtain more reliable revenue streams [5].

Before the rises in prices recorded in 2022 for all electricity markets, prices were not a common topic among small-scale investors. Nonetheless, nowadays, identifying what factors influence the rise or fall of wholesale electricity prices, how the hourly electricity price influences consumers, as well as how it is possible to take advantage of the electricity market prices are aspects that have gained more and more relevance when it is considered to invest in storage projects integrated into power systems with high penetration levels of RES. According to [80] when an ESS is unprofitable under a real-time market operation strategy the same could happen in a day-a-market operation strategy given prices in the former are generally more volatile. On the other hand, authors in [63] reported that a battery makes more bids under a day-ahead-market operation strategy than a real-time-market operation strategy. This could mean the former is riskier given that battery dispatches require more adjustments.

In the EU, the rise or fall of prices in the wholesale markets is generally pushed by variations in prices of fossil fuels, energy generated from RES, and energy consumed. As gas prices reached historic highs at the end of 2021 [115], [116] due to the pressures imposed by the war between Russia and Ukraine, all the EU markets also recorded significant rises in energy markets even in 2022. Nevertheless, in the same year, some governments cooperated in designing a mechanism for decoupling the gas and electricity prices [117], to mitigate the volatility in electricity prices due to the volatility in gas prices.

These facts about the market prices in addition to the technological characteristics of the storage technologies mentioned in Chapter 2 pinpoint BESS as a key pillar in the energy transition [30] because they can provide flexibility at different capacities/timescales and the reliability needed by the power system [3], [11] whether they are properly exploited.

Considering that this chapter aims to assess battery performance when it operates under profit-making-oriented strategies, namely price/energy arbitrage and tertiary reserve, it is necessary to analyze electricity and regulation markets to model their behaviors. As market behaviors vary from country to country, in the scope of this work, Portuguese markets will provide the input data to assess BESS operation.

4.2.1 The electricity market price and the price/energy arbitrage

In the Iberian Peninsula, MIBEL (*Mercado Ibérico de Eletricidade* for its acronym in Portuguese) is responsible for managing the two Iberian markets, OMIE (Spanish Centre) with the competence of day-ahead and intraday market management, and OMIP (Portuguese Centre) with the competence of managing forward markets [118]. However, each TSO is still responsible for operating its respective electrical power system [119].

OMIE manages the daily market based on 24 day-ahead sessions, in which market agents submit their energy bids to execute buying/selling transactions. At each session/period, bids are accepted based on their economic merit, thus, the electricity price and volume of energy are defined following the pay-as-clear model. The energy supply curve starts by responding to demand with cheaper energy bids, which usually means the ones from RES (this occurs because RES are paid as agreed in auctions and marginal costs are equal to zero), however, when these sources become scarcer, successively more expensive offers are used [120]. OMIE also manages an intraday market based on six bidding sessions, in which agents adjust the day-ahead market results by submitting offers according to expected real-time needs [121]. After each day-ahead and intraday session, market results are analyzed by the TSO aiming to validate their technical viability and to ensure that market results can be technically accommodated in the electrical power network.

Figure 4-1 shows the real-time electricity market price behavior reported by OMIE over the last 5 years for the Portuguese area [120]. Bars represent the interval of values in which the electricity market prices fluctuated per quarter per year. The starting and ending points are the minimum and maximum electricity price recorded while gray lines represent the arithmetic mean. As noted, real-time electricity market prices significantly increased in the second half of 2021 (due to the uncertainties about gas provision and the volatility in gas prices [115], [116]). For this reason, in 2022, the maximum electricity market prices skyrocketed by 800% compared to prices recorded in 2019 and 2020. In 2023, although the share of energy generated from RES was still high and minimum market prices fell to zero in some periods (because marginal costs were almost non-existent) [120], the mid-values of electricity prices were still higher than the maximums recorded before 2021, nevertheless, they were lower than those recorded in 2022.

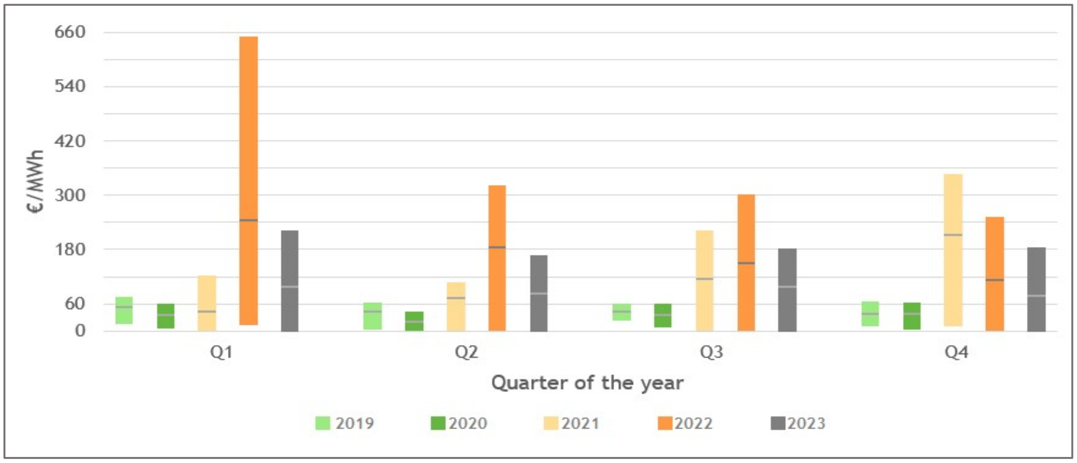


Figure 4-1. Electricity market price behavior reported by OMIE over the last 5 years in Portugal

Considering that in this work one of the profit-making-oriented strategies to implement is the price/energy arbitrage, electricity market prices recorded by OMIE for 2019, 2022, and 2023 are taken as the signal to which battery operation must respond. From these years, some interesting facts identified from the electricity market price behaviors can be summarized as follows:

(i) **2019:** The lower electricity market price values, lower volatility in electricity prices, and lower shares of energy generated from RES than those recorded for subsequent years. Concerning tCO_2/MWh, this year could be considered mid-carbon intensity compared to contributions over the last 15 years [122].

(ii) **2022:** The highest electricity market price values, highest volatility in electricity prices, and mid shares of energy generated from RES than those recorded for previous and subsequent years. Concerning tCO_2/MWh contributions, this year could be considered mid-lower carbon intensity compared to contributions over the last 15 years [122].

(iii) **2023:** Mid electricity market price values, mid volatility in electricity prices, and mid shares of energy generated from RES compared to those recorded for previous years. Concerning tCO_2/MWh, this year could be considered mid-lower carbon intensity compared to contributions over the last 15 years [122].

Moreover, BESS is considered a price-taker, and real-time electricity market prices are modeled as described in Section 4.3 to deal with price uncertainty.

4.2.2 The regulation market and the tertiary reserve service

One of the challenges the TSO faces is related to the energy balance over time. Since energy consumption is always changing, there is expected to be a slight difference between this and the energy generated and supplied to the power network, which leads to variations in the frequency of the power system [72], [91], [123]. Frequency regulation and capacity reserve are the services that aim to solve these problems by using active power reserves to maintain the power system frequency as close as possible to 50 Hz in the EU, and 60 Hz in the LAC.

In the EU, as established by ENTSO-E, the active power reserves are characterized by having different activation ramps (according to the time they take to be available), which are used coordinately [82], [83], [123]. Specifically, In Portugal, the "*Diretiva n.º 18/2023, de 22 de dezembro*" and the "*Diretiva n.º 19/2023, de 26 de dezembro*" approved the implementation of reserve band markets for frequency restoring with manual activation, and modifications to the *Manual de Procedimentos da Gestão Global do Sistema* (MPGGS), respectively [124]–[126]. Therefore, In Portugal, the power active reserves services can be summarized as follows:

(i) **Primary reserve** is mandatory and unpaid service. No actions from the SO are required for its activation because generation units locally vary their set points between 4% and 6% of their nominal power after an event causes a frequency deviation ≤ 20 mHz. Its total activation should take up to 15 seconds for deviations ≤ 1,5 GW or 100 mHz, or up to 30 seconds for deviations between 1,5 and 3 GW or 100 and 200 mHz [125], [126].

(ii) **Secondary reserve** uses Automatic Generation Control (AGC) to allow physical units to change their set points within 30 seconds and 5 minutes after an event that causes an important loss of generation, pumping, or storage unit. TSO stipulates the reserve requirements for each period. In Portugal, this service is voluntary, paid, and traded in market environments [125] being PICASSO the platform established for the exchange of balancing energy from frequency restoration reserves participating in AGC [127]. According to PICASSO, this reserve, currently called frequency restoration reserve with automatic activation (aFRR), could be provided by physical units with a regulation capacity greater than 1 MW. Detailed information about how this reserve is calculated and traded can be found in [125].

(iii) **Tertiary reserves** are activated according to the highest loss of production or load a power system must probably deal with. Generally, this reserve is a mandatory service remunerated and traded in market environments. MARI (Manually Activated Reserves Initiative) is the platform used in Portugal to find the most cost-efficient frequency restoration bids that meet the energy balance needs [83]. According to MARI, this reserve, currently called frequency restoration reserve with manual activation (mFRR), could be provided by physical units with a regulation capacity greater than 1 MW. The minimum total upward reserve is calculated considering the maximum loss of production directly caused by a simple fault in an element of the electrical power system, increased by 2% of the load forecasted, by 10% of the wind energy production forecasted, and by 5% of solar photovoltaic production forecasted. On the other hand, the minimum total downward reserve is defined considering the maximum loss of pumping units or consumption of storage units directly caused by a simple fault in an element of the electrical power system, increased by 2% of the load forecasted, by 10% of the wind energy production forecasted, and by 5% of solar photovoltaic production forecasted. This reserve can follow scheduled activations (SAc) or direct activations (DAc) with minimum delivery times of 5 and 6 to 19 minutes from the activation signal, respectively.

(iv) **Replacement reserve** is also important for the operation of the electrical power system when an event leads to energy imbalances capable of depleting the previously mentioned regulation reserves, thus, the restoration reserves are delivered between 15 to 60 minutes [124], [125].

Considering the intermittent nature and uncertainties around RES generation, it becomes noticeable that increases in its penetration levels simultaneously with the reduction in generation from fossil fuel as those mentioned in Section 1.2, highlight the need for integrating into the power network additional physical units that aim to provide frequency regulation services [52]. In Portugal, different types of units participate in the regulation market providing system services to the power system, e.g. hydro, pumping hydro, thermal, solar, and loads, which are organized in balancing areas[128].

As this research is oriented towards profit-making strategies, the tertiary reserve is the second service to be provided by batteries. Therefore, regulation market data recorded by REN for 2019, 2022, and 2023 are taken as the signal to which battery operation must respond. This choice is made by considering the aspects summarized below:

(i) Batteries replicate the behavior of PSH units in the Portuguese regulation markets.

(ii) Detailed information about PSHs participating in tertiary reserve is shown in Appendix C. Analyses revealed that PSHs were activated in 20.8%, 26.7%, and 21% of the 8760 periods that comprised years 2019, 2022, and 2023 respectively, being downward reserve activated 80.9%, 74%, and 62.7% of the times, respectively. These activations represented around 10% of the bids the PSHs made.

(iii) At least, for 83% of the activations the storage unit provided up to 6% of its maximum historical cumulative capacity, while in 80% of successive activations (two or more consecutive periods) the storage unit provided up to 30%. Moreover, only for 5% of downward and 3% of upward activations, this type of storage provided more than 10% of its maximum historical cumulative capacity in a single activation, and only for 5% of downward and 2% of upward activations provided more than 70% of its maximum historical cumulative capacity in consecutive activations.

(iv) Appendix C revealed that as the share of energy generated from RES has increased, the activation profile of upward reserve has predominately taken the profile described by solar PV generation for both single and successive activations profiles. Nevertheless, the energy activated has been reduced, and requirements greater than 10% and 70% of its maximum historical cumulative capacity in single and successive activations respectively, are almost non-existent.

(v) Moreover, Appendix C revealed that as the share of energy generated from RES has increased, the activation profile of the downward reserve has changed its form tending to take a uniform distribution over the day. About the energy activated, this has also become almost non-existent for requirements greater than 10% and 70% of its maximum historical cumulative capacity in single and successive activations, respectively.

(vi) Although tertiary reserve (mFRR) can be traded in a market environment, the strategy developed in this work is not based on making price/energy bids. On the contrary, historical price and energy data from REN are modeled as described in Section 4.3.

All these facts point out valuable information about the characteristics a storage technology must fill (e.g. capacity, C-rates, RTE vs. commitments) to participate in the regulation market and the availability required to replicate downward (by charging batteries) or upward activations (by discharging batteries) from PSH. Therefore, batteries providing simultaneously tertiary reserve and price/energy arbitrage services comprise the second strategy assessed by considering regulation market data and the electricity market prices recorded by REN and OMIE, for 2019, 2022, and 2023.

4.3 Scenarios Generation Models for Market Prices

The electricity market and the regulation market described interesting behavior that must be properly modeled to consider most of the facts that influenced the behavior of those markets as previously described in Section 4.2. Given the price and energy signals obtained from these markets influence on BESS's response when assessed operation strategies such as price/energy arbitrage and simultaneously price/energy arbitrage and tertiary reserve, it is crucial to approach detailed models, not only about the devices but also about uncertainties surrounding the operation process[4], [34], which directly refers to the prices of both markets.

In the scope of this research work, BESS is a price taker and forecast models for the electricity and regulation market are not addressed. The price scenarios database is constructed from historical data of each market accounting for significant uncertainties that influence optimal BESS operation [22]. Once uncertainties in the data price/energy also lead to uncertainties in the BESS revenue model, the scenario generation model for market prices developed in this work considers reproducing the historical from electricity and regulation markets.

According to the aspects identified from the literature review, it was reported in Section 3.3 that one of the methods widely used to handle uncertainties surrounding the planning and operation problem is related to probabilistic methods. Similarly to [34], [44], [53], [54], [76] a stochastic method like the Monte Carlo is used here to generate a set of samples of the random variables, in this case, prices/energy from electricity and regulation markets.

4.3.1 Preprocessing historical data from electricity and regulation markets

Data preprocessing plays a significant role in improving the reliability of analytics. It ensures that data properly treated is ready for the subsequent stages, e.g. exploration, modeling, interpretation, and use. For this reason, before generating scenarios, it is suitable to analyze the raw historical data to identify what aspects may influence the battery behavior (e.g. variation in electricity and regulation market prices) to characterize and model them. Similarly to previously approached in [6], [16], [53], [54], seasonal variability is a criterion used to identify patterns in data. In addition, daily price volatility is also considered because it contains useful information that allows the data to be explained and thus reproduced. Flow charts in Figure 4-2 summarize the steps to separately analyze the 8760 periods that comprise each year of the historical data from electricity and regulation markets. The preprocessing of the raw data considers the following steps:

(i) Start the process by grouping the daily price curves (each one represented by 24 periods) based on the season in which they were recorded. Seasonality is chosen because the availability of sources like hydropower[52], influences market prices.

(ii) The previous step results in the creation of four sets of curves of daily prices per type of market, which are individually analyzed to select the maximum daily price reached by each curve.

(iii) Once the maximum prices are identified, every set of values per season per market is normalized to organize each data set in a 10-bar histogram to define whether its shape describes a known probability distribution pattern.

(iv) The question about which probability distribution best fits the data cannot be answered without analyzing the patterns revealed by each set given some of the key aspects to be considered to decide what distribution could be used are related to the likelihood of extreme values for the data, relative to the mid-value, and the potential to represent outliers.

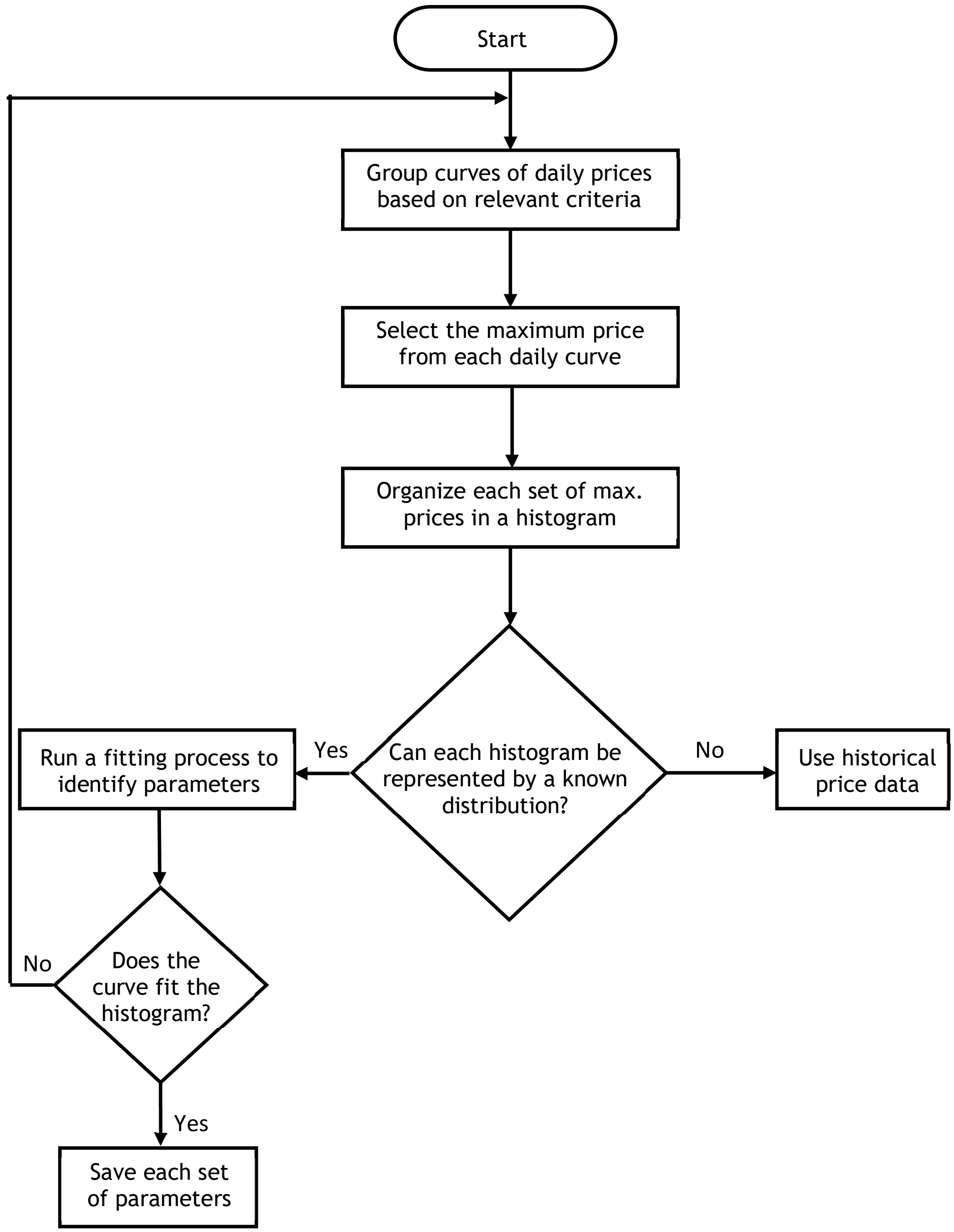


Figure 4-2. Scheme approached to identify the distributions described by historical data from market prices.

(v) A fitting process is followed to identify the parameters that describe the histogram it could be explained by a known probability distribution function. Otherwise, the raw historical data should be used.

(vi) Given there is an error associated with the fitting process [112], it is necessary to verify that the parameters obtained from it explain the histogram indicated in (iii), then, if the fitted distribution curve fits the histogram, the parameters that describe the curve fitted are saved. Otherwise, it is important to consider adding relevant criteria to regroup the curves of daily price as proposed in (i).

This preprocessing stage is important to ensure that input data is analyzed as required by the aspects/factors that influence the variation in the electricity and regulation market prices since the histogram's shapes depend on the data grouping criteria.

4.3.2 Stochastic scenarios generation model

When a process describes a random behavior, it could be said the dataset obtained from it could be characterized by stochasticity. Reproducing a set of random values requires a method that properly represents the facts and uncertainties contained in the dataset [4].

Similarly to previously proposed in [4], [32], [53], [54] and as mentioned in Section 3.3, in the scope of this research work, a Monte Carlo sampling approach is the method used to manage the uncertainties surrounding the BESS operation process, in this case, those related to the electricity and regulation market. Therefore, price scenarios must be generated to assess BESS behavior and to obtain a more reliable revenue stream.

For the price scenarios used here, samples are generated from the probability distribution identified in the previous section. Therefore, as a random value from a probability distribution function is equally likely to be at any cumulative probability, random numbers can be generated for the variable by sampling from a distribution [111].

Considering the criteria used for grouping data in the preprocessing stage, the charts in Figure 4-3 summarize the steps to generate random numbers that represent the probability distribution of each season over a year and the probability distribution of a market price to reach a specific value regarding the season. Figure 4-3a shows the process followed to generate random numbers that explain the distribution of each season over a year. This process can be followed as described below:

(i) Over a year the seasons have the same probability of occurrence and the days that comprise each season are represented by the random numbers, α. Then, the probability distribution of a season through a year is obtained from a uniform distribution $U\ (0,1)$, which means that every set of days represents a season with the probability of occurrence equal to 25%, see Figure 4-3a.

(ii) Then, from a uniform distribution $U\ (0,1)$ a set of numbers α are generated. As a year comprises 365 days, the stop criterion is met when the set of numbers contains 365 numbers α.

(iii) The 365 numbers α generated are verified given, as expected, these numbers must describe a uniform distribution $U\ (0,1)$. Nevertheless, considering there is always an error associated with the creation of random data [112], [129], an error of up to $\pm$ 0,2% is accepted for the probability of occurrence of each season.

(iv) If the set of numbers α per meets the error criterion, the numbers α are saved.

Figure 4-3b shows the process followed to generate random numbers that explain the probability of distribution of a market price to reach a specific value regarding the season. This process can be followed as described below:

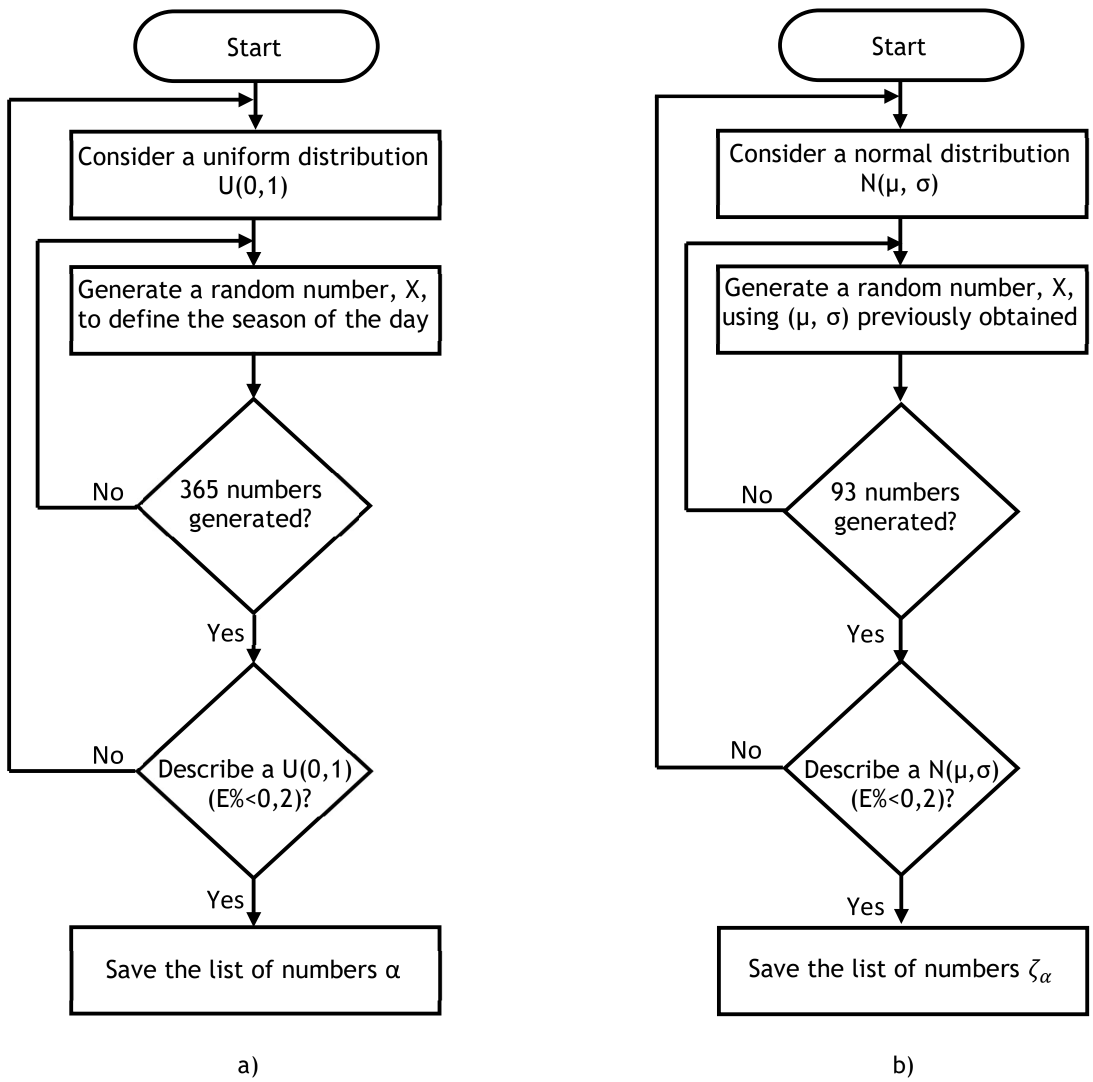


Figure 4-3. Flowchart followed to generate the random numbers for the season α (a) and the daily price per season ζ_α (b).

(i) In the scope of this work, the process followed in the previous Section revealed that normal distributions could explain the histograms constructed with the raw historical data. Therefore, the fitting step is run by considering a Gaussian Least-Square fitting process according to the methodology proposed in [112], [130]. The parameters mean, μ, and variance, σ^2, that explain each probability distribution fitted are the starting point of the generation process of random numbers, ζ_α, which represents the probability of occurrence of a specific maximum daily price regarding the season.

(ii) Then, from a normal distribution $N\ (\mu, \sigma)$ a set of numbers ζ_α are generated per season. As the set of numbers α generated allows an error of about $\pm\ 0{,}2\%$, each list of numbers ζ_α could contain 93 numbers. Then, this is the stop criterion for the generation of numbers ζ_α.

(iii) Every list of 93 numbers ζ_α generated is verified given, as expected, these numbers must describe a normal distribution $N\ (\mu, \sigma)$ with data distributed as follows: 68%≈μ±σ and 95%≈μ±2σ. Nevertheless, considering there is always an error associated with the creation of random data [111], [129], a total error of up to $\pm\ 0{,}2\%$ for data concentrated in μ±σ is accepted for the probability of occurrence of a specific maximum daily price regarding the season. In addition, it is ensured that each list contains numbers ζ_α < μ-2σ and μ+2σ <ζ_α.

(v) When each set of numbers ζ_α met the error criterion, the list of numbers is saved.

Lastly, considering that a large list of numbers could increase the reliability of the model but also its complexity and a short list of numbers has the opposite effect [39], a price scenario reduction is carefully applied before starting the final stage of the scenario generation model proposed here. Therefore, considering the numbers ζ_α, 12-bar histograms are constructed. Then, each bar is represented by the most typical maximum daily price, which means that every range of probability will be expressed by a typical maximum daily price selected from the historical data.

The final stage is to build the price scenarios database. For this, α and ζ_α are then selected and compared to their respective cumulative probability function obtained as indicated in [111], [112] and shown in Section 3.3.5. This aims to determine which season, and day will be used for gathering information. Hence, a daily scenario can be extracted from a historical database as described below:

(i) The list of numbers α and ζ_α are sequentially read. Therefore, the season is identified in its cumulative function as indicated by the number α.

(ii) Next, the maximum daily price per season is identified in its respective cumulative function as indicated by the number ζ_α.

(iii) Once the maximum daily price is identified, its correspondent daily curve is obtained from the historical database and inserted in the price scenario database.

(iv) The scenarios generation model is repeated for raw historical data for 2019, 2022, and 2023.

By following this selection process, the database is not grouped by season, it has the season dispersed throughout the year instead. The desired effect is to produce a larger sampling data dispersion over what would be achieved with a classical grouping of season data.

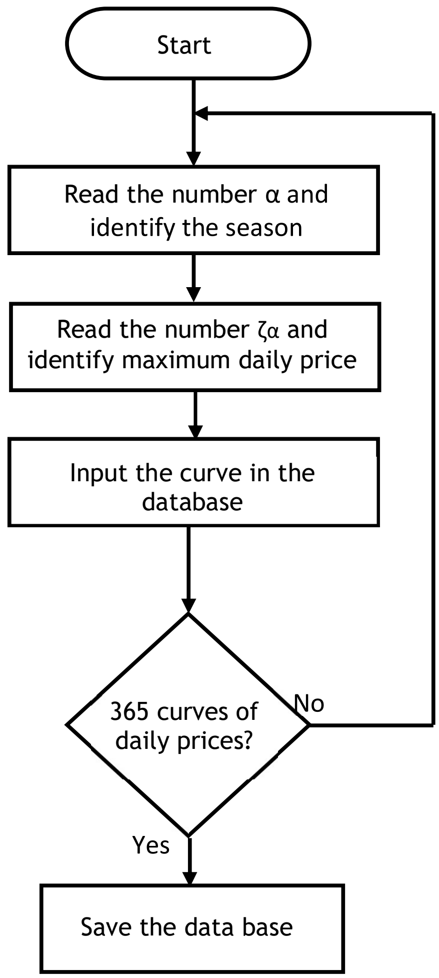


Figure 4-4. Flowchart followed to generate the database scenario.

4.4 Strategies for Battery Energy Storage Operation

Optimal battery operation is an interesting topic to be focused on given the relevance of the performance parameters influencing its behavior and revenue stream. BESS operation is characterized by several potential applications [11], [31], [44], [51] as those mentioned in Chapter 2. Although some battery technologies are qualified to provide profit-making-oriented services, they vary in energy and power capacity, cost, lifecycle, and RTE, among other technical and non-technical parameters. Moreover, according to the services to provide and the technical constraints of the network to which it is integrated, the battery technological requirements could be different [5].

As mentioned in Section 4.2, in the scope of this work, battery performance is assessed under two profit-making-oriented strategies, namely, price arbitrage or Strategy A, and simultaneously price arbitrage and tertiary reserve or Strategy B. Similarly to [22], [53], here is considered that battery deployment should be made in the first year of the planning period, therefore, annualized assessments of battery behavior and revenue stream are performed.

4.4.1 Battery performance parameters

In Section 2.2 the technical and non-technical battery parameters are reported and defined. Moreover, in Section 2.3, Table 2.1, typical values for some of these parameters have been reported. Aiming to assess the performance and revenue model of batteries that operate under profit-making-oriented strategies, parameters like energy and power capacity, useful storage energy, self-discharge, DOD, SoC, DC-DC/AC-AC RTE, lifecycle, calendar life, and C-rates take relevance in this work.

Specifically, RTE is an important parameter that must be properly modeled since, as shown in Figure 2-1, when integrated into the DN BESS needs a power converter and a step-up transformer, and both devices have energy losses associated with their operation. Authors in [55] pinpoint the relevance of considering the AC-AC RTE (efficiency measured at the connection point to the DN) for a more real-life analysis given it considers the total energy losses around the battery charge/discharge process. On the other hand, authors in [11] indicate that charging and discharging strategies together with adherence to manufacturers' recommendations (e.g. charge/discharge power limits, DOD, minimum SoC, and cycles/day) must be considered to face some technical challenges of BESS deployment such as energy/power output, efficiency, and lifetime. Even, authors in [16] indicate that the C-rates should not be too high because it would mean higher battery temperature during the charge/discharge process, affecting its lifespan negatively [16].

Concerning DOD, authors in [22] indicate that a suitable value for DOD is 80%, and authors in [16] found that a DOD equal to 80% is the optimal value to be considered given battery (specifically, Li-Ion) operation at this DOD resulted in a lower degradation and higher lifetime. Regarding charging and discharging rates, authors in [76] found that the revenue stream increases as the C-rates increase, nevertheless, authors in [22] explain that C-rates should not be too high in some battery technologies given high C-rates lead to high temperatures in the storage bank which results in a reduction in the battery lifespan.

As mentioned in Chapter 3, a profitable BESS integration into the DN should consider BESS investment cost and deal with the risk related to the revenue stream by its operation. Although optimal BESS operation is frequently considered a subproblem of the BEES planning problem [53], [89], the former has been gaining more attention given detailed battery models are needed to identify how their performance parameters influence its behavior and revenue stream, and how could be offered valuable information to decision-makers about investment opportunities.

4.4.2 Price arbitrage strategy or strategy A

Price/Energy arbitrage is a trading strategy with which batteries charge or discharge in response to a signal, as mentioned in Section 2.4. In the case of price arbitrage, price is the signal. Since profitability from batteries that respond to price signals could be influenced by price fluctuations [4], in addition to a more detailed model of the storage device that considers the performance parameters, it is crucial to properly model the price samples to determine reliable charge/discharge battery decisions.

As mentioned in Section 3.4, one of the battery models widely used in the literature to represent battery behavior is similar to the one used in the operation of hydropower stations, where the SoC at each period interacts with its adjacent periods (before and after) and the energy that could be injected to the network or stored from it. The formulation that represents this assumption is called the balance equation. Equation 3-19 presents the formulation of the balance equation for an ideal battery model (where energy losses from the charge/discharge process are not considered) and Equation 3-20 for a non-ideal battery model.

In the scope of this research work, for strategy A, the optimal battery operation aims to minimize the operation costs of batteries that respond to price signals according to the objective function formulation reported in Equation 4-1.

$$\min B_{op\_em} = \sum_t^T \left(E_{pr\_t} * Ebl_t - E_{pr} * Ebg_t\right) \qquad (4\text{-}1)$$

Where:

E_{pr_t}, corresponds to electricity prices at time t, up to the horizon time, T.

Ebl_t corresponds to energy coming into BESS in the charging phase (as load).

Ebg_t, corresponds to energy moving out BESS in the discharging phase (as generator).

The objective function in Equation 4-1 is subject to the equality provided by the balance equation (Equation 4-2) and the inequalities described from Equation 4-3 to Equation 4-5.

$$SoC_t = -\delta S + SoC_{(t-1)} + n_c n_{in}\, Ebl_t - \frac{Ebg_t}{n_{out}} \qquad (4\text{-}2)$$

$$0 \leq Ebl_t, Ebg_t \qquad (4\text{-}3)$$

$$SoC_t^{min} \leq SoC_t \leq SoC_t^{max} \qquad (4\text{-}4)$$

$$Ebl_t, Ebg_t \leq S * \gamma \qquad (4\text{-}5)$$

In the equality reported in Equation 4-2, the state of charge, SoC_t, at any t, is equal to its previous state SoC_{t-1} plus the energy coming into the BESS in the charging stage, minus the energy moving out the BESS in the discharging stage and the loss of energy capacity due to battery self-discharge, δ. Specifically, n_c, n_{in} and n_{out}, represent the battery efficiency, and the network interface technology efficiency to and from the battery, respectively. In the case of the ideal battery model, n_c, n_{in} and n_{out} are considered equal to 1 or 100% and δ is considered equal to 0 or 0%.

The inequality reported in Equation 4-3 indicates that energy coming into or moving out of BESS must be non-negative. In Equation 4-4, the minimum SoC_t, at any t, is defined according to the battery technology since these technological devices should not be totally discharged [6] while the maximum SoC_t, at any t, usually is defined by the battery capacity. Nonetheless, lower values could be selected for non-flow technologies if they contribute to extending the battery EoL [2]. Then, the SoC_t, at any t, could take values between SoC_t^{min} and SoC_t^{max}. Finally, in Equation 4-5, the maximum energy coming into or moving out of the BESS, at any t, is obtained by multiplying the battery size, S, and C-rate, γ, which is defined by the technological interface.

Following this optimization process, Ebl_t and Ebg_t at any t, the total operation cost (or revenue stream) up to the horizon time, T, and the lifespan of batteries, are determined.

4.4.3 Simultaneously price arbitrage and tertiary reserve or Strategy B

Similar to price/energy arbitrage, ancillary and system services are potential services BESSs may provide to ensure flexible, safe, and reliable electrical power network operation. These services, mainly focusing on supporting frequency regulation, voltage control, grid forming, and Blackstar, might yield additional revenue opportunities for BESS and ESS [30] and consumers qualified to provide them [82], as long as regulatory barriers are overcome. Therefore, their modeling is also relevant for identifying potential business opportunities. In the Iberian Peninsula, these services also followed the evolution of the power network structure, hence, there are specific markets to execute their transactions.

For strategy B, the optimal battery operation aims to minimize the operation costs of batteries that simultaneously respond to price arbitrage and tertiary reserve according to the objective function formulation reported in Equation 4-6.

$$\min B_{op\_erm} = \sum_t^T E_{pr\_t} \left(Ebl_t - Ebg_t\right) + \sum_t^T \left(E_{pr\_down\_t} * Edn_t - E_{pr\_up\_t} * Eup_t\right) \qquad (4\text{-}6)$$

Where:

$E_{pr\_up\_t}$, corresponds to price to upward tertiary reserve at time t, up to the horizon T.

$E_{pr\_\mathrm{down}\_t}$, corresponds to price to downward tertiary reserve at time t, up to T.

Edn_t, corresponds to energy activated as a downward reserve (charging phase) at the connection point with the DN.

Eup_t, corresponds to energy activated as an upward reserve (discharging phase) at the connection point with the DN.

The objective function in Equation 4-6 is subject to the equality provided by the balance equation (Equation 4-7) and the inequalities described from Equation 4-8 to Equation 4-10.

$$SoC_t = -\delta S + SoC_{(t-1)} + n_c n_{in}\, Ebl_t - \frac{Ebg_t}{n_{out}} + Edn_t - Eup_t \quad (4.7)$$

$$0 \le Ebl_t, Ebg_t, Edn_t, Eup_t \quad (4.8)$$

$$SoC_t^{min} + Eup_t \le SoC_t \le SoC_t^{max} - Edn_t \quad (4.9)$$

$$Ebg_t + Eup_t,\ Ebl_t + Edn_t, \le\ S * \gamma \quad (4.\ 10)$$

In the equality reported in Equation 4-7, the state of charge, SoC_t, at any t, is equal to its previous state SoC_{t-1} plus the energy coming into BESS in the charging stage and the energy activated as a downward reserve, minus the energy moving out BESS in the discharging stage, the energy activated as an upward reserve and the loss of energy capacity due to battery self-discharge, δ. Specifically, n_c, n_{in} and n_{out}, represent the battery efficiency, and the network interface technology efficiency to and from the battery, respectively. In the case of the ideal battery model, n_c, n_{in} and n_{out} are considered equal to 1 or 100% and δ is considered equal to 0 or 0%.

The inequality reported in Equation 4-8 indicates that energy coming into or moving out of BESS must be non-negative. In Equation 4-9, the minimum SoC_t, at any t, is defined according to the battery technology since these technological devices should not be totally discharged [6] while the maximum SoC_t, at any t, usually is defined by the battery capacity. Nevertheless, the values that SoC_t could take at any time t are dependent on the commitments of BESS in providing tertiary reserve.

Finally, in Equation 4-10, the maximum energy coming into or moving out of the BESS, at any t, is obtained by multiplying the battery size, S, and C-rate, γ, which is defined by the technological interface.

Following this optimization process, Ebl_t and Ebg_t, at any t, the total operation cost up to the horizon time, T, and the expected of batteries are determined.

4.5 Numerical Simulations

The operation models proposed here address the challenge of assessing the impacts of battery parameters on its behavior, revenue streams, and lifespan. A tool that considers non-ideal battery models and uncertainties surrounding the process will provide valuable and reliable information to different stakeholders, but mainly for small-scale ones, about investment opportunities when planning BESS integrated into the DN.

In this section, the profit-making-oriented operation strategies detailed in Section 4.4 are assessed by considering non-ideal battery models in addition to electricity and regulation market data for three years with different market behaviors between them, aiming to pinpoint the relevance of both, markets behavior and battery performance parameters to achieve the objectives of the stakeholders and to identify the efforts BESS owners must perform to provide services to the DN.

Results are discussed based on a sensitivity analysis carried out considering energy and power capacity, useful storage energy, self-discharge, DOD, SoC, DC-DC/AC-AC RTE, lifecycle, calendar life, and C-rates are the parameters that take the main relevance in this study. Table 4.1 reports the parameters used for battery technologies here assessed.

Table 4.1. Battery performance parameters.

Parameter[a,b]	*Li-Ion*	*Lead-Acid*	*VRFB*
Estimated Installation cost ($/KWh)[b]	340.5	458.8	486.9
Estimated Recycling cost ($/KWh)[b]	0.0	25.69	50.87
DC-DC/AC-AC RTE (%)	92-96 / 85-92	80-85 / 70-85	70-80 / 65-75
DOD (%)	85-100	55-85	80-100
Self-discharge (%)	<0.3	<0.4	<0.2
Lifecycle[c]	4500	2000	12000
Calendar Life (years)	5-15	5-15	10-20
C-rates (%/period)	10-90		

[a.] Adapted from [3]-[5], [55].
[b.] Average values to 2030 reported for batteries of 1MW/2-4h.
[c.] Calculated as the number of times the battery has entered the state of charge at 80% of DOD.

4.5.1 Historical data from electricity and regulation market prices

Before processing the electricity and regulation market prices data, the historical information collected from OMIE public records for the Portuguese market [120] and REN public records [59] for the tertiary reserve market were analyzed to identify relevant facts and differences between years that help to understand and explain the results provided by the optimization tool for the BESS operation.

Appendix D summarizes the analysis of historical data on the electricity and regulation market over the years 2019, 2022, and 2023. Figure D-1 shows how the price behavior in the regulation market compared to the price behavior in the electricity market has changed over the years. Considering a physical unit that could trade in both markets, it could be highlighted that, in 2019, prices in regulation markets were more attractive than prices in the electricity market given the former were frequently higher for the upward and lower for the downward reserve than the latter. On the other hand, in 2022 and 2023 the prices in the regulation market were more concentrated within the profile described by the electricity prices which could be understood as a loss of attractiveness for the physical unit. These aspects show how it is necessary to properly model the market prices given they are input data to the optimization tool for the BESS operation.

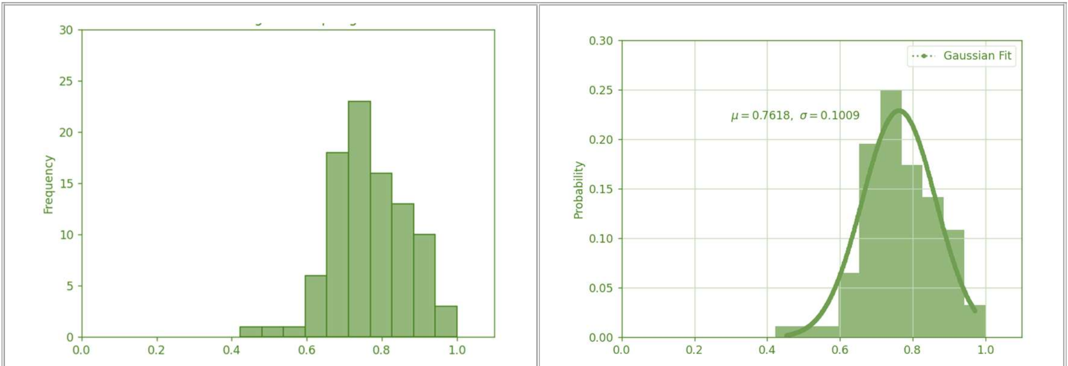
4.5.2 Creation of the electricity and regulation market prices database

The electricity and regulation market databases were created following the procedure described in Section 4.3. The preprocessing of the historical data started by grouping the curves of daily prices (represented by 24 periods) by season as indicated in Figure 4-2 and ended with the sets of histograms constructed with the maximum daily prices data.

After preprocessing market prices, it was identified that normal or Gaussian distributions can explain the histograms of electricity prices. In contrast, the regulation market prices could not be explained by a distribution probability function, which led to considering that the price and energy data to add to the final database scenarios generated are a perfect foresight of the historical data.

Figure 4-5 shows an example of the fitting process run for the histogram obtained for the maximum electricity prices of the spring of 2022. Figure 4-5a shows the 10-bar histogram constructed from the normalized values of maximum electricity prices, in which the sizes of the bars represent the frequency of an interval of prices in the set of historical data. Figure 4-5b shows that the probability distribution that fits the histogram is a normal distribution with mean and standard deviation of 0.7618 and 0.1009, respectively.

As normal distributions explained each histogram of normalized maximum daily prices, the parameters mean, μ, standard deviation, σ, and variance, σ^2, obtained from the fitting process were saved per season per year. With this information, the list of random numbers α and ζ_α were generated per year per season by following the steps proposed in the flowcharts shown in Figure 4-3. Finally, the database scenarios per year were created following the flowcharts presented in Figure 4-4.

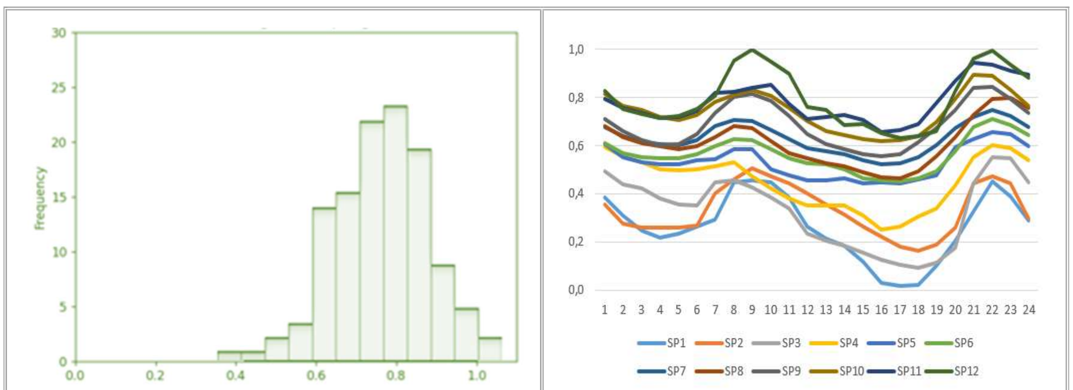


a) Histogram for spring of 2022

b) Distribution fitted for spring of 2022

Figure 4-5. Illustrative example of the fitting process run for the histogram of spring of 2022.

Figure 4-6a shows an example of the 12-bar histogram constructed with the list of numbers ζ_α generated to explain and manage the uncertainties surrounding the daily prices in the electricity market in the spring of 2022. As noted, the set of numbers ζ_α considers the occurrence of maximum daily prices out of the interval of historical data compared to Figure 4-5a. Since the scenario generation model proposed in this work considers the price scenario reduction, each bar in the 12-bar histogram is defined by a curve whose maximum daily prices correspond to the most common values in the interval. This means that for the cumulative density function of each histogram, a range of probability is represented by a typical maximum daily price selected from the historical data. Figure 4-6b shows the curves of daily prices for the spring of 2022 considered to build the database scenarios for 2022.



a) Spring's histogram generated from random numbers ζ_α

b) Set of curves of spring of 2022 to be used to build the prices database

Figure 4-6. Illustrative example of scenario's reduction and curves of daily prices to be used.

Once the scenario reductions are applied for all datasets, the final stage of the stochastic scenario generation model is followed as indicated in the flowchart shown in Figure 4-4 to obtain the databases of electricity prices for 356 days or 8760 periods.

The model proposed for explaining data and managing uncertainties from market prices is repeated 15 times aiming to generate 15 databases per year. Figure 4-7 shows, over 120 periods, an example of the 15 electricity price databases generated for 2022.

Scenarios generated for 2022 consider the most probable (≈95% of maximum daily prices are in μ±2σ) maximum daily prices as follows: values between 70 and 410 €/MWh in winter, 195 and 280 €/MWh in spring, 145 and 240 €/MWh in summer, and 120 and 230 €/MWh in fall. Nonetheless, scenarios generated also consider less probable maximum daily prices as follows: smaller than 17 €/MWh and greater than 480 €/MWh in winter, 120 €/MWh and 320 €/MWh in spring, 105 €/MWh and 300 €/MWh in summer, and 85 €/MWh and 275 €/MWh in fall.

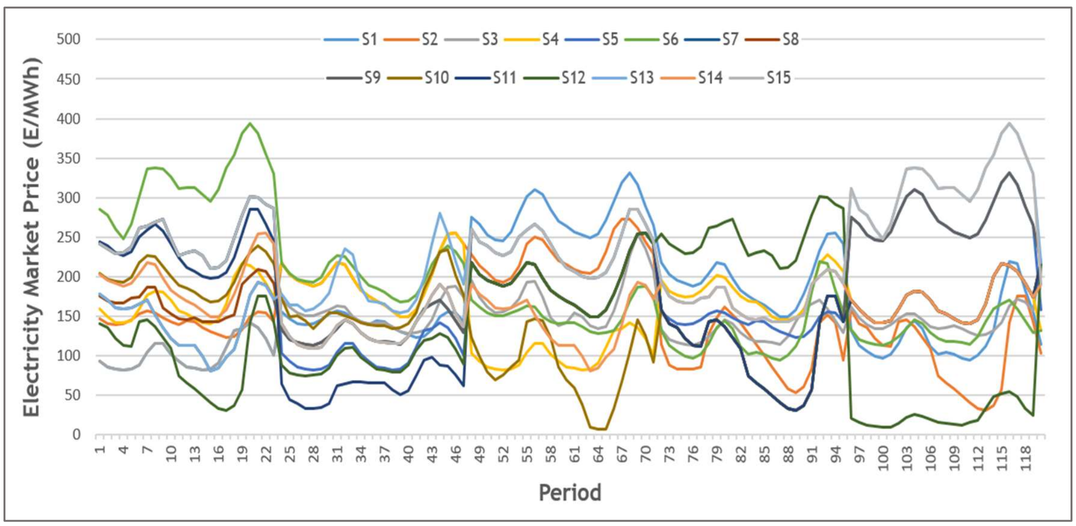


Figure 4-7. Examples of 15 electricity market price scenarios generated for the year 2022 from historical data.

By following this process, the database is not grouped by season, the season data is dispersed throughout the year instead, which not only guarantees a larger sampling dispersion condition, represents the volatility and uncertainties found in the electricity market, but also ensures the evaluation of a wide range of values in addition to the minimum and maximum prices. Finally, it is relevant to pinpoint that each database of regulation market data follows random behavior imposed by the electricity market to ensure correspondence with the real historical data.

4.5.3 Analyzing price arbitrage potential for non-ideal battery models

To assess and analyze this strategy, also called strategy SA, 15 databases of electricity prices per year and two battery models as indicated below, are considered to optimize BESS operation:

(i) An ideal battery model described in Section 4.4, whose AC-AC RTE is 100%.

(ii) Non-ideal battery models are described in Section 4.4, whose AC-AC RTE is 85%.

(iii) DOD is set at 90% for both models. Therefore, the useful storage energy and the minimum SoC are 90% and 10% of its nominal capacity, respectively.

(iv) C-rates are set at 50%/period for both models. Therefore, the batteries may demand or supply 50% of their capacities per period.

Following the procedure described in Sections 4.5.2 and considering the complementary information reported in Table 4.1, simulations were carried out to analyze BESS behavior at each period, the revenue stream, and the lifespan of the batteries.

Figure 4-8 shows a comparative example of battery operation over 120 periods in response to price signals from the database S1 for electricity market prices generated for 2022. As noted, the battery modified its charge/discharge behavior when its technical parameters were considered. For example, in the $day_{(n+1)}$, the optimal decisions of the non-ideal battery model considered not charging the batteries in the second half of the day and keeping the battery at minimum SoC whereas the ideal model recorded some discharge cycles in the same period. A similar behavior can be seen in the $day_{(n+3)}$ where the optimal decisions of the non-ideal battery model considered not discharging the batteries at all in noon and saving energy to be discharged later, whereas the ideal model, again, recorded some discharge cycles in the same period.

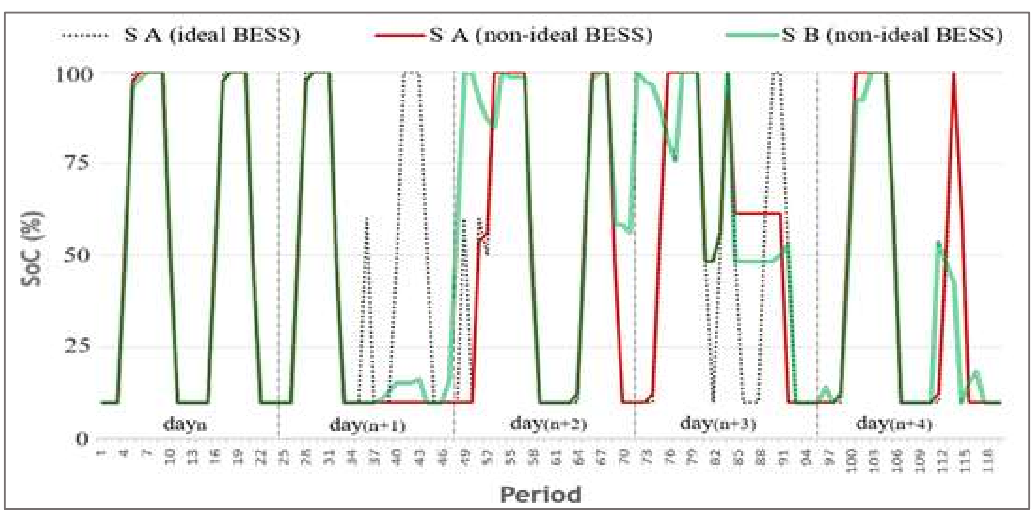


Figure 4-8. Examples of an ideal and non-ideal battery operation under strategy SA.

In addition, it can be seen that the differences in the optimal decisions between models (responding to the same price signals) may influence the annual cycles and the annual battery operation costs (or annual revenue stream) because reductions in charge/discharge cycles mean a lower number of transactions of buying/selling energy.

To verify and quantify the impacts of battery models on the annual cycles and operation cost, a wide range of C-rates values (from 10%/period to 90%/period) were considered to carry out simulations for the ideal and non-ideal battery models that respond to price signals from the database scenarios.

Figure 4-9 shows an example of variation in the number of annual cycles and operation cost (or revenue stream) for different battery models when scenario S1 for electricity market prices for 2022 was considered. Annual cycles were calculated following the rainflow cycle counting method indicated in [131]. The variations were determined regarding the number of annual cycles and the annual operation cost obtained for an ideal battery modeled with the fastest technological interface (C-rate) given they represent the maximum values achieved when strategy SA was assessed. Hence, the figures are expressed as a percentage of these reference values.

In Figure 4-9a, for a specific C-rate, it is noticeable that as the performance parameters of batteries are modeled and the AC-AC RTE is lower, there is a reduction in the annual cycles compared to the behavior recorded for the ideal battery model.

Specifically, comparing non-ideal battery models (65%≤ AC-AC RTE ≤95%) to the ideal model (AC-AC RTE = 100%), the annual cycle variations are more representative for higher C-rates (50-90 %/period) than for medium (30-40 %/period), low (20 %/period), or very low C-rates (10 %/period). Comparing the starting and ending points at each C-rate curve, it could be seen that the annual cycles decrease from 90% to 20% for higher C-rates (this is from 2.62 to 0.56 cycles/day), from 75% to 15% for medium C-rates (which means from 2.16 to 0.43 cycles/day), from 60% to 14% for low C-rate (this is from 1.45 to 0.38 cycles/day), and from 35% to 11% for very low C-rates (which means from 0.87 to 0.31 cycles/day). This highlights how relevant it should be for decision-makers to consider more reliable information about the annual cycles given charge/discharge cycles directly influence battery lifespan, frequency of battery replacement/augmentation, and the replacement cost modeled in the planning level of a BESS project to be integrated into the DN.

On the other hand, Figure 4-9b illustrates how wide the range of variation in annual cycles could be for a storage project according to different C-rates. As noted, the range of variation is reduced as the AC-AC RTE is lower, which occurs because the energy lost in the charge/discharge process affects the SoC of the battery taking more relevance in the optimization process.

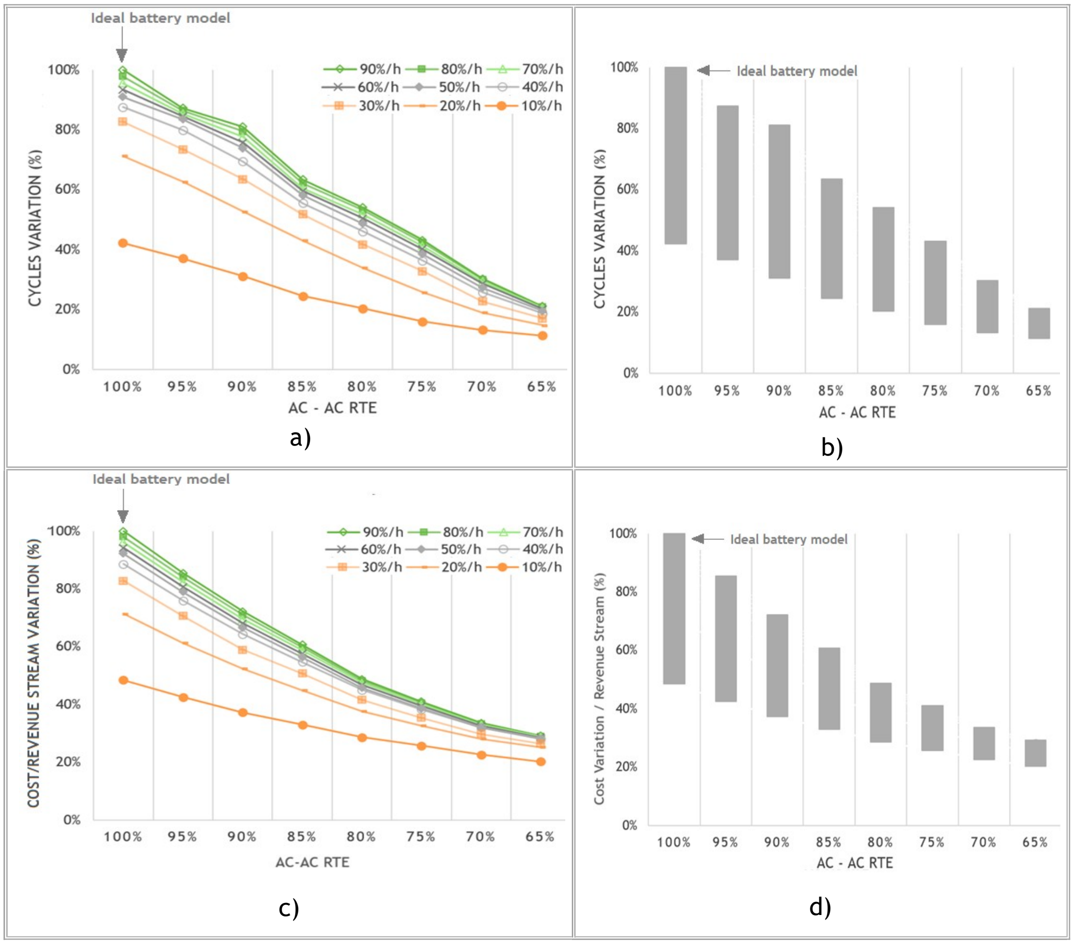


Figure 4-9. Example of annual cycle variation and operation costs (or revenue stream) for non-ideal batteries modeled for different C-rates.

In Figure 4-9c similar to the aspects identified from Figure 4-9a for a specific C-rate, as the performance battery parameters are modeled and the AC-AC RTE is lower, there is a reduction in the annual revenue stream from battery operation compared to the amount recorded by the ideal model. Specifically, when non-ideal battery models (65%≤ AC-AC RTE ≤95%) are compared to an ideal one (AC-AC RTE=100%), the annual revenues decrease from 90% to 30% when higher C-rates are considered, from 78% to 28% when medium C-rates are considered, from 60% to 24% when lower C-rates are considered, and from 42% to 20% when very low C-rates are considered. This pinpoints how important it should be for decision-makers to consider reliable information about revenue stream in the planning level of an optimal planning of a BESS to be integrated into the DN given the revenue stream is responsible for amortizing repayment of the loan and upfront investment costs on the storage projects.

Figure 4-9d illustrates how wide the range of variation in revenue streams could be for a storage project according to different C-rates. As noted, the range of variation is also reduced as the AC-AC RTE is lower, which occurs because an important percentage of energy coming into the BESS in the charging process is used to “feed” the losses. This also challenges the optimization process to make better decisions to minimize the operation cost given more energy must be moved into the BESS to keep it sufficiently charged.

When simulations were carried out for the ideal and non-ideal battery models regarding price signals from the electricity market prices database for 2019 and 2023, similar results to those shown in Figure 4-9 were obtained.

After analyzing the potential of batteries providing price arbitrage services (Strategy SA), it is confirmed that when planning BESS integrated into the DN to provide this service, non-ideal battery models should be considered to optimize battery operation given the battery performance parameters significantly influence the optimal charging/discharging decisions, the operation cycles, and revenue stream from battery operation. This means that, at least, the terms $C_R(x)$ (Replacement cost) and $C_{RS}(x)$ (Operation cost or revenue stream) in the objective function expressed in Equation 3-5 are influenced by the outputs of the optimization process applied to schedule the batteries operation.

4.5.4 Analyzing price arbitrage potential regarding electricity price behavior

Given that battery operation under strategy SA was assessed considering databases of electricity prices for three years with different market behavior and these databases are inputs for the optimization tool of the BESS operation, it is essential to analyze how the behavior of electricity market prices influences BESS charging/discharging decisions, the revenue stream, and the lifespan of the batteries. This analysis was carried out considering two battery models as indicated below:

(i) An ideal battery model described in Section 4.4, whose AC-AC RTE is 100%.

(ii) Non-ideal battery models described in Section 4.4, whose AC-AC RTE are between 65% and 95%.

(iii) DOD is set at 80% for both models. Therefore, the useful storage energy and the minimum SoC are 80% and 20% of its nominal capacity, respectively.

(iv) C-rate is set at 80%/period for both models.

(v) The calendar life of batteries is defined as 15 years. As shown in Table 2-1 this is a common time for different battery technologies.

Figure 4-10 shows an example of the annual cycles and operation cost (or revenue stream) of different battery models in response to market prices whose characteristics were defined in Section 4.2. In Figure 4-10a can be seen the most efficient battery models (85%≤ AC-AC RTE ≤95%) recorded more annual cycles as the electricity prices and volatility were higher. For lower AC-AC RTE (between 65% and 75%) batteries recorded higher annual rates regarding mid values of electricity prices and volatility. Figure 4-10b shows the battery lifespan comparison between an ideal and a non-ideal model (AC-AC RTE 90%) calculated considering the annual cycles shown in Figure 4-10a. Compared to calendar life, the lifespan determined from lifecycles is first met for both models, which means the storage bank must be replaced/augmented and these costs should be considered in the BESS planning stage. Therefore, considering non-ideal battery models avoids underestimating the lifespan and overestimating the replacement costs.

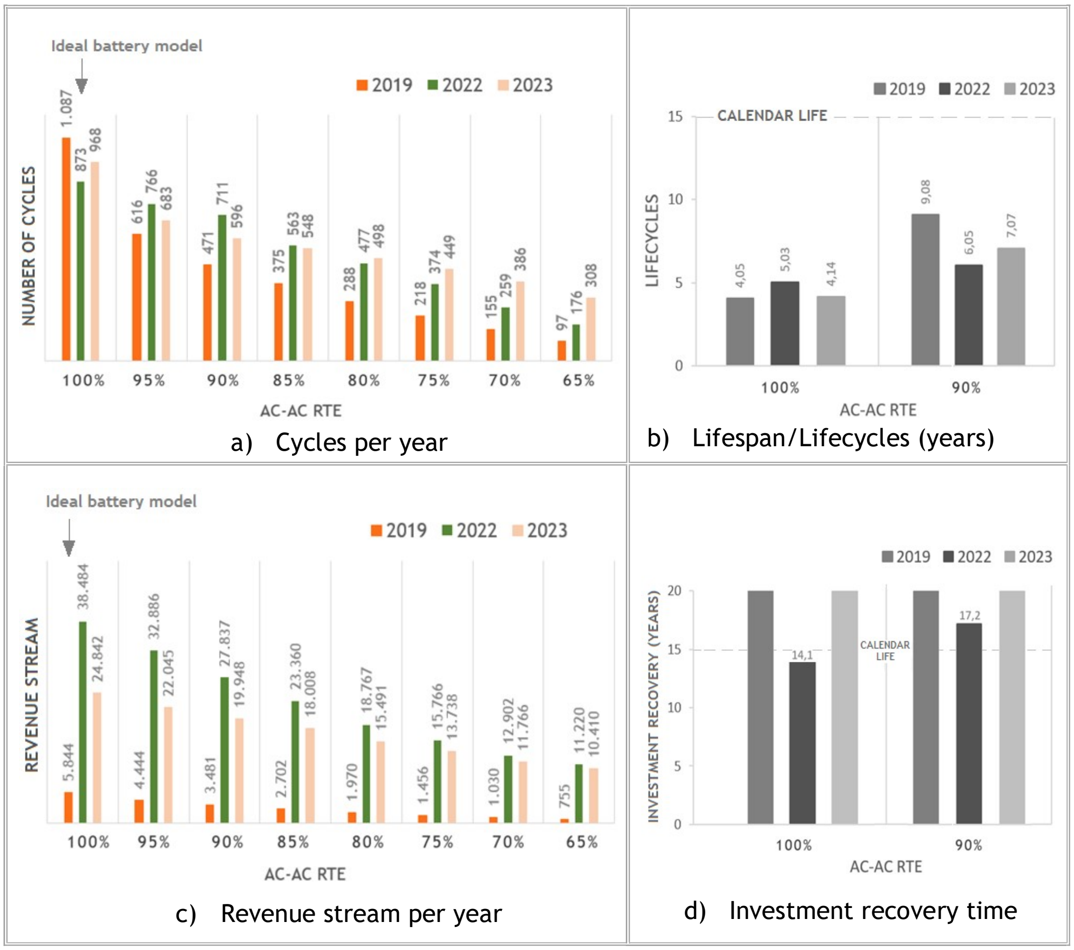


Figure 4-10. Examples of annual cycles and operation cost (or revenue stream) of batteries that respond to electricity prices with different behaviors.

It can be estimated from Figure 4-10c that the revenue streams for 2019 and 2023 are about 15% and 65% of those reported for 2022, respectively. Then, the highest revenue stream (or lower operation cost if considering their negative form) was obtained when market prices recorded the highest volatility. This finding has been previously reported in the literature, nevertheless, here it is also confirmed that, even for a year with the highest historical volatility, the revenue stream from Strategy SA does not lead to the recovery of the investment in BESS projects before meeting the battery calendar life. This comparison is shown in Figure 4-10d, in which the investment recovery time is estimated using Equations 3-5 to 3-7 and taking the terms $C_I(x)$, $C_{O\&M}(x)$ and $-C_{RS}(x)$ into account to simplify the calculation.

After analyzing the potential of batteries providing price arbitrage services (Strategy SA) regarding different behaviors of electricity market price, it is confirmed that prices modeled to assess the profit-making-oriented services influence not only the revenue stream from battery operation but also the battery lifespan. Hence, it is noticeable that assumptions about electricity prices need to be carefully considered to avoid over/ underestimations of revenue stream and replacement cost (terms $C_{RS}(x)$ and $C_R(x)$in the objective function expressed in Equation 3-5) provided to the BESS planning stage.

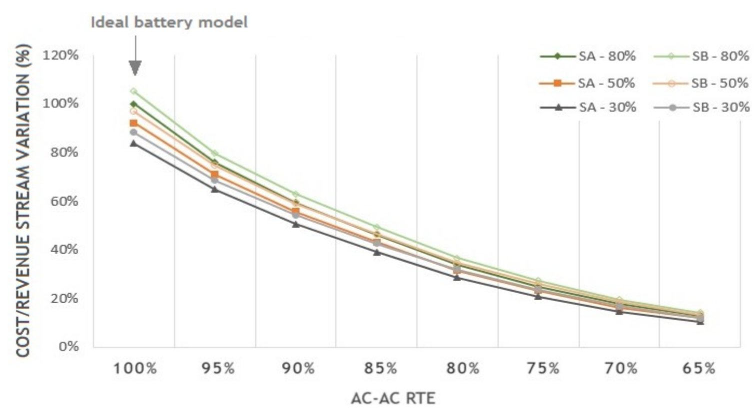
4.5.5 Analyzing simultaneous price arbitrage and tertiary reserve provision

To assess and analyze this strategy, also called strategy SB, 15 databases of electricity and regulation market prices per year and two battery models as indicated below, are considered to optimize BESS operation:

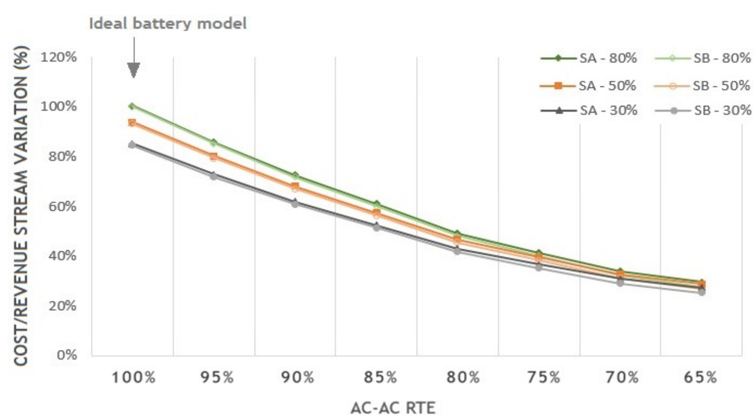
- (i) An ideal battery model described in Section 4.4, whose AC-AC RTE is 100%.
- (ii) Non-ideal battery models are described in Section 4.4, whose AC-AC RTE is 85%.
- (iii) DOD is set at 90% for both models. Therefore, the useful storage energy and the minimum SoC are 90% and 10% of its nominal capacity, respectively.
- (iv) Tertiary reserve provision follows the profiles described in Appendix C for the PSH

Figure 4-8 also shows a comparative example of non-ideal battery behavior over 120 periods in response to price signals from the database S1 for electricity and regulation market prices generated for 2022. As noted, compared to strategy SA, batteries operating under strategy SB modified their behavior even more when the tertiary reserve provision was added. For example, in the day$_{(n+1)}$, batteries operating under Strategy SB are required to provide a downward reserve in the second half of the day (over some successive periods), meaning that batteries are charged at rates and paid at prices defined by the provided tertiary reserve, while in the same period batteries operating under strategy SA are kept at rest (at minimum SoC). A similar behavior can be seen at the end of the day$_{(n+2)}$ when batteries operating under Strategy SB are charged to be ready to provide upward reserve at the beginning of the day$_{(n+3)}$, while in the same period batteries operating under strategy SA are kept at rest again.

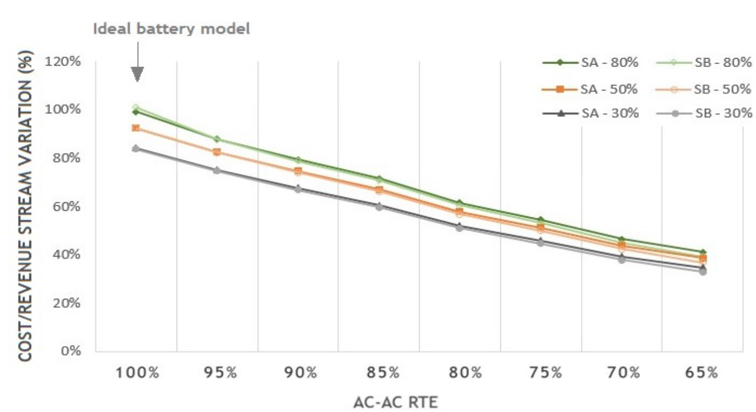
As expected, these differences occur because batteries must be available to provide tertiary reserve according to requirements from the TSO. To verify and quantify the impacts of the strategy SB on the cycles and operation cost, different C-rates values (i.e., 30, 50, and 80%/period) were considered to carry out simulations on non-ideal battery models (DODs set at 80%) that respond to price signals from database scenarios. Figure 4-11 shows an example of the annual operation cost for batteries operating under price arbitrage strategy (SA) and simultaneously price arbitrage and tertiary reserve.



a) Revenue stream variation for 2019



b) Revenue stream variation for 2022



c) Revenue stream variation for 2023

Figure 4-11. Example of annual operation costs (or revenue stream) of batteries operating under strategies SA and SB.

Figure 4-11a shows that strategy SB could be more interesting for battery operation than strategy SA given that, the revenues under SB increased between 4% and 7% regardless of the C-rate and the AC-AC RTE, which occurs because the regulation prices are slightly more attractive than electricity prices in 2019 (see Figure D-1, Appendix D). Nevertheless, Figure 4-10c shows the increase is not as attractive compared to the revenue stream from batteries operating under strategy SA for signals with high prices and volatility.

Figure 4-11b and Figure 4-11c show that there are no solid advantages in providing tertiary reserve simultaneously to price arbitrage given the revenue stream under SB only increased between 1% and 1,5% for more efficient battery models (85%≤ AC-AC RTE ≤95%) which occurs because regulation prices are within the profile described by the electricity prices in 2022 and 2023, as shown in Figure D-1, Appendix D. In contrast, the revenue stream for less efficient models (65%≤ AC-AC RTE ≤75%), regardless of the C-rate, meant reductions between 1.5% and 2.8% compared to strategy SA.

4.5.6 Model robustness

Robustness is frequently used to measure the ability of a model to withstand assumptions and perform reliably despite changes in input data [111]. The optimization tool for the operation of BESS considers market prices as an input, therefore modeling and managing price uncertainties plays an important role regarding the optimization process and the outputs from each battery model.

As described in Section 4.3, the electricity market prices were modeled based on a stochastic approach whose probability of occurrence of maximum daily prices defined the shape of probability functions to generate the price scenarios per season. Admitting the stochastic generation model should provide database scenarios comprised also of uncertain values of daily prices, the robustness is assessed based on the risk of obtaining a non-satisfactory solution (far away from an optimum) after a single run of the optimization tool. Similarly to previously described in [53] and [76] a quadratic dispersion metric, analog to variance, is used to determine the distribution of values of revenue stream or operation cost in the set of optimal solutions compared to the best solution.

Equation 4-11 indicates how the quadratic dispersion of revenue data is calculated [111]. Then, using Equation 4-12 a percentage measure of the dispersion is calculated.

$$Dispersion^2(€^2) = \sum_s^S (C_{RS_s} - C_{RS_{BS}})^2/(S-1) \qquad (4.11)$$

$$Dispersion(\%) = Dispersion(€)/C_{RS_{BS}} \qquad (4.12)$$

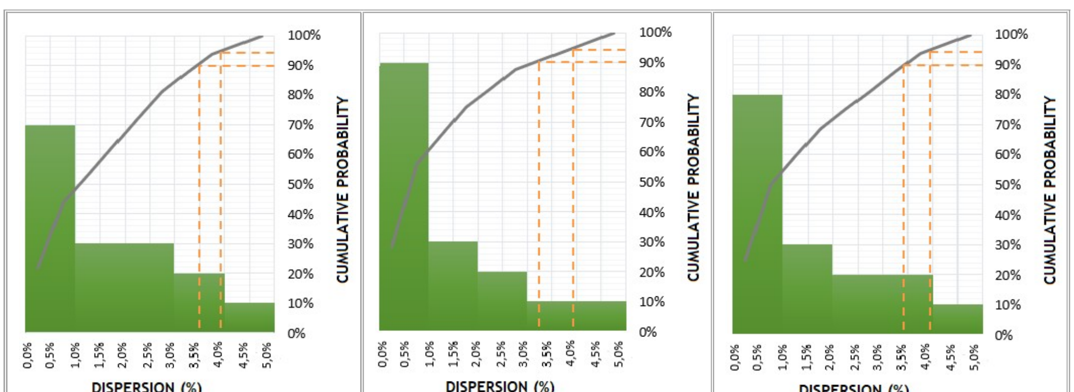
Where: S represents the number of price scenario databases used as input data which also corresponds to the number of optimal solutions. C_{RS_s} represents the revenue stream obtained after running the optimization tool using the database S. And $C_{RS_{BS}}$ represents the best revenue stream or operation cost in the set of optimal solutions.

Given that dispersion in data could be explained by a probability distribution function, a 5-bar histogram, and its cumulative density function are constructed. Finally, the risk of obtaining a non-satisfactory solution is estimated based on the percentual distance of an optimal solution from the best one.

Hence, the robustness is evaluated using 15 price scenarios databases generated per year as input for the optimization tool that considered different battery models operating under strategy SA at different C-rates, which means each battery model operating at a specific C-rate provides 15 revenue stream results from price arbitrage. The highest dispersion per year was obtained when non-ideal battery models with DOD = 80%, C-rate = 80%/period, and AC-AC RTE = 95%, were evaluated. For these cases, the comparison resulted in a dispersion of 2.5% in 2019, 2.1% in 2022, and 2.3% in 2023.

Figure 4-12 shows examples of the cumulative function constructed from results to assess the robustness of the optimization tool. Figure 4-12a shows the cumulative function for 2019, which reveals that the estimated probability of having a result (in a single run) distanced from more than 3.92% of the best value is 5%, and from more than 3.45% is 10%. Figure 4-12b and Figure 4-12c show that the estimated probability of having a result distanced more than 3.88% and 3.93% of the best value is 5%, and more than 3.29% and 3.47% is 10% for 2022 and 2023 respectively.

These are convincing results about the robustness of the model, which performs well within a confidence interval of 95%. As this is run offline, the assessment of the optimization tool for different price scenario databases is allowed.



a) Dispersion for 2019 b) Dispersion for 2022 c) Dispersion for 2023

Figure 4-12. Model robustness assessment based on cumulative density functions that estimate the risk of obtaining a non-satisfactory solution.

4.6 Conclusions

This chapter approached the problem of the optimal battery operation in the scope of small-scale BESS investors that aim to provide profit-making-oriented services such as price arbitrage (strategy SA) and simultaneously price arbitrage and tertiary reserve (strategy SB) when integrated into the DN. BESS operation is addressed as a problem decoupled from the planning stage to identify how the electricity and regulation market prices and the battery performance parameters influence its lifespan, revenue stream, and other aspects that feed the planning stage.

The success of solving the BESS operation problem is strongly related to the formulation of the optimization problem as well as the definition of the cost function that better represents the revenue model. In the absence of incentives, subsidies, or a regulatory framework that remunerates storage activities, decision-makers should describe the BESS operation problem as closely as reality to provide more reliable information to the planning stage. This means considering detailed models not only about the devices but also about uncertainties surrounding the operation process.

An optimization tool for BESS operation under strategy SA and SB is proposed considering it covers a diversity of non-ideal battery models defined by performance parameters such as energy and power capacity, useful storage energy, self-discharge, DOD, SoC, DC-DC/AC-AC RTE, lifecycle, calendar life, and C-rates, and a variety of market prices mainly defined by volatility in prices. After running numerical simulations for this tool, the following findings obtained via sensitivity analyses can be pinpointed:

(i) Battery operating to provide profit-making-oriented services requires both market prices and their performance parameters to be properly modeled since when comparing their performance assessment to the one obtained from an ideal model, it is evident that the latter overestimates the revenue stream and the replacement cost of the storage bank as well as underestimates the battery lifespan. These over/underestimations are more critical as battery models are less efficient.

(ii) Non-ideal battery models operating to provide simultaneous profit-making-oriented services such as price arbitrage and tertiary reserve are not economically competitive compared to a single service like price arbitrage. Even when batteries responded to price signals with the highest historical volatility recorded the results were the same. Therefore, adding tertiary reserve to the revenue model of batteries without a remuneration scheme is not competitive compared to other storage technologies that already participate in regulation markets.

(iii) The non-competitivity of strategy SB over SA cannot be interpreted as a positive fact for strategy SA because batteries providing solely price arbitrage service do not generate the revenue stream needed to cover the investment cost required to integrate this storage technology into the DN. Even when batteries responded to price signals with the highest historical volatility recorded, the results were the same. Therefore, it is recommended that, under the current technical, economic, and regulatory framework, strategy SA be considered a complementary service to be provided to the DN.

(iv) As market prices play a crucial role in the battery operation assessment because its responses to the price signal are affected by the behavior of prices modeled, the Monte Carlo method offered a suitable probabilistic approach to not only model price behaviors but also manage market uncertainties given that, from seasonal grouping criteria, prices could be represented by distribution functions comprised of certain and uncertain values with an estimated probability of occurrence associated. Therefore, it is verified that the tool proposed here successfully deals with different battery models, market price behaviors, and price uncertainties. The statistical robustness achieved confirms the reliability of the methods used.

In sum, these findings are of paramount importance for decision-makers because they provide insights into the relevance of modeling battery performance parameters, market price behaviors, and uncertainties. Moreover, they put up valuable information to policymakers and regulators to realize incentives or subsidies that consolidate batteries such as a technology with an attractive economic competitivity to be integrated into the power network to provide profit-making services.

The following chapter approaches the BESS planning and operation when integrated into DNs with RES already operating. Specifically, the problem is approached from the perspective of a small-scale investor who not only expects to provide profit-making-oriented services to the DN but also a technical-support-orientated service to be defined by the DSO according to its technical needs.

Chapter 5

Planning Methodology for Supporting Investment Decision-Making in Small-Scale BESS

5.1 Overview

The challenges brought by sustainable development and the energy transition needs have changed the perspective on how electrical power networks should be planned and operated [11], [42] because it is no longer enough to supply consumers at a minimum cost. As explained in previous Chapters, the distribution and transmission network are the backbone of the power network, therefore, as the generation sources are moving to renewable technologies and the consumers are being empowered [14], the network is expected to move from a centralized and passive to a decentralized and active one.

It is crucial to clarify that is not just one path that leads to a successful energy transition and the decarbonization process given that devising solutions for the challenges the electrical power network is facing is a complex task when the interests and perspectives of several stakeholders/players (e.g. researchers, organizations, governments, utilities, solutions providers, policy-makers and, consumers) must be harmonized according to their roles and responsibilities [30], [56]. Moreover, the disparity between the accelerated RES adoption, the need for a more flexible power system, and the delays in defining a regulatory framework for technological solutions such as ESS could lead to suboptimal outcomes not only for investors in adopting ESS technologies but also for operators about operating them into a power network in which they are also responsible by maintaining a reliable, economic and safe operation [19].

Previous chapters have mentioned how ESSs such as BESS can cover a broad spectrum of benefits and how the regulatory, economic, environmental, market, and pricing, among other difficulties or barriers, have been restricting the widespread deployment of these technologies [3]–[5]. Highlighting that one of the main barriers refers to the absence of subsidies, incentives, or a regulatory framework that remunerates flexibility and storage services, nowadays, turning BESS integration into the DN a reality is mainly determined by the planning and operation strategies approached by planners and decision-makers.

Authors in [11] and [31], stated that the misusing and mislocation of ESS into the DN can reduce the reliability, and degrade power quality while also affecting voltage profiles. Therefore, under a power network transformation [13], [15] and the need for widely deployed BESS before 2030 [17], [30], some doubts about the planning and operation of the DN with BESS, such as the ones listed below, should be clarified to find a way to carefully devise strategies to adapt this process to the current DN status and the uncertainties surrounding the process:

(i) How to shape a suitable future for a DN in which cooperation between stakeholders/players' perspectives is required to ensure the network's sustainability, reliability, flexibility, and safety?

(ii) What strategies could be approached to manage uncertainties surrounding the planning and operation process and the complexity of the DN models regarding the integration of technological solutions such as batteries?

(iii) Considering the problem can no longer be seen from a singular perspective, how could multiple perspectives be harmonized to make investment decisions that allow stakeholders/players to represent their interests and objectives while the decision-making process is devised as accessible to a broader range of stakeholders/players as possible?

For this, it is essential to admit that planning tools are needed to define business models for BESS (in the form of an optimization problem) that allow planners and decision-makers to deal with more realistic load and generation profiles, network models, and BESS models while BESS operation, sizing, selection, and investment cost should be addressed thoroughly, and the optimal location, concentrated or distributed, should entirely be decided by the planning tool [22], [31], [44], [54], [87].

When small-scale BESS investors are interested in getting involved in the energy transition, the decarbonization process, and shaping a more decentralized and active electrical power network, managing all these aspects while attending to different technical, social, environmental, regulatory, or economic criteria enlarges even more the problem. Hence, the main objective of this Chapter is to devise strategies for BESS planning and operation and a decision-making process with the potential of finding a final decision made for more than one decision-maker, which means finding an economically feasible decision from the BESS owner's perspective that is also technically feasible from the DSO/DISCO perspective when the latter evaluates additional criteria technical-support-oriented. Therefore, here it is considered that:

(i) An attractive planning tool should be able to decouple the operation problem, the planning problem, and the decision-making process to thoroughly manage each stage. Concerning BESS, decoupling the planning process is advantageous given that the strategies defined for each stage can be properly assessed to identify their impacts on the whole process while providing valuable information to decision-makers, regulators, and policy-makers.

(ii) The data inputs into the planning tool should be carefully modeled to better deal with the uncertainties associated with them. Since batteries follow a charge/discharge process according to the signals defined by the application/service to provide, as assessed in Chapter 4, input data influence the battery behavior and the expected revenue stream from its operation. Monte Carlo is the probabilistic method used here to model load, generation, and market price data behaviors and manage uncertainties.

(iii) The tool must identify the most suitable locations for BESS. This means that the tool should be able to evaluate and decide between a concentrated or distributed integration.

(iv) The combinatorial nature of the planning problem should be represented given BESS planning into the DN leads to selecting the sizing, location, technology, and network interface while BESS operation is thoroughly dependent on the application/services to be provided. A hybrid approach based on Evolutionary Particle Swarm Optimization (EPSO) at an upper-level (sizing, location, network interface, and technology selection) and Linear Programming (LP) at a lower level (battery operation over time) is used for solving the problem proposed in this Chapter, considering that most of the buses in the DN are potential locations for BESS integration.

(v) Non-ideal battery models defined by technical and non-technical parameters such as energy/power capacity, useful storage energy, self-discharge, DOD, C-rates, SoC, DC-DC/AC-AC RTE, lifecycle, and calendar life take relevance in this work. In addition, AC networks are modeled to avoid simplification related to energy losses and voltage profiles, which are crucial when planning the integration of assets with an active behavior like batteries.

(vi) The tool also should provide insights into a decision-making process in which two decision-makers can decide how to integrate BESS into the DN. BESS is versatile enough to simultaneously provide profit-making-oriented and technical-support-oriented services; however, it is not always easy to define suitable metrics and harmonize both types of criteria when the BESS owner differs from the DSO.

Considering that several stakeholders/players have the potential to shape the power network's future, the methodology followed in this chapter proposes a planning tool that intends to deal with the DN operational constraints and suggests basic but essential procedures for planning and operating BESS into the DN in the absence of incentives, subsidies or a regulatory framework that remunerate the flexibility and storage services, while providing valuable information to BESS investor, decision-makers, regulators, and policy-makers about the feasibility and profitability of a business model for BESS. Therefore, this Chapter aims to support the decision-making process instead of exploring several optimization methods and techniques to simply find an optimum. Since the planning process is run offline, the decision-making strategy to find a feasible solution is more challenging than reducing the computational effort when the BESS planning and operation problem is solved using optimization methods and techniques with proved robustness.

5.2 BESS Owned by Small-Scale Investors

The sustainable energy transition and the decarbonization process have inevitably changed the electrical power network structure and influenced the growth and rise of new business models. A transformation like this implies moving from a centralized and passive network structure with unidirectional power flows (from generation to consumers) to a decentralized structure in which bidirectional power flows are frequent at all voltage levels given that distributed resources are being increasingly integrated into the distribution network by independent stakeholders/players and consumers are being encouraged to take a more active role (e.g. self-consumers, prosumers or an energy community) [22], [46], [70], [98]. As a result of these changes, flexibility has risen as a critical challenge the electrical power network should overcome [19], [30].

The idea that small-scale players have the potential to thoroughly contribute to shaping the future of the electrical power network has emerged since their involvement is essential to ensure that decisions related to economic, technical, social, and environmental aspects are successfully supported [48]. However, regulatory frameworks and incentive schemes are necessary to devise feasible and profitable business models. From the investor perspective, IEPs, RECs, and Aggregators can fulfill what in this research work is considered a small-scale investor given their role/impacts on the electrical power network:

(i) **Independent Energy Providers or Producers**, also identified as IEPs, are stakeholders/players that own and operate facilities to provide energy but do not operate as a public utility. They often develop projects backed by power purchase agreements (PPA). An IEP could be a corporation, cooperative (e.g. rural solar or wind energy producers), privately held facility, or a non-energy industrial concern that can inject their surplus energy into the network. The surplus energy can be sold to DISCOs or consumers not only to increase its passive income but also to ensure its surplus is not wasted [125].

(ii) **Renewable Energy Communities**, also identified as RECs, are legal entities of members/shareholders around the RES projects they own and have developed. The members could be buildings sharing a PV system in a common rooftop, neighborhoods/villages with PV plants in the vicinity, or a mix of consumers, local industries, and private/public service facilities that own/share energy assets, share their surpluses with other REC members, and provide energy projects and procurement common interest-related [132]. For this reason, the member's addition into a REC is mainly determined by the member's proximity to the RES projects [35]. REC's main purpose refers to providing social, environmental, or economic benefits to shareholders or the local area where REC operates, instead of financial profits. Therefore, RECs produce and consume renewable energy, but also can share, store, or sell/buy it [98].

(iii) **Aggregator** can be defined as a stakeholder that offers services to aggregate energy produced from different generator agents and acts toward the wholesale market as one entity. It also includes the local aggregation of the demand [109]. Therefore, this stakeholder may combine small consumers into a single purchasing unit to trade with retailers. They may provide a wide range of services to small consumers such as the management of distributed resources and consumer engagement. An aggregator is a supportive stakeholder to the consumers that can also provide flexibility to the DN, given small consumers are not allowed to participate in the markets directly.

5.2.1 Business and revenue model proposal

Chapter 2 and Chapter 3 have mentioned how supportive BESS can be when integrated into the DNs due to its technological characteristics. The attractiveness of providing an application/service over another could depend on the BESS owner's objectives and the regulatory framework, nevertheless, regardless of the service provided the business model should be profitable for the stakeholders involved in the BESS project [68]. Currently, although there is no defined incentives scheme or regulatory framework for flexibility and storage activities, it is essential to encourage small-scale stakeholders/players to shape the electric power network landscape. In this Section IEPs, RECs, and Aggregators (under an individual or integrated role) are considered potential BESS owners, therefore, the general perspective of the business and revenue model proposed could be applied to all of them. Nevertheless, some RECs' particularities such as consumer involvement [48] and energy management [132], the financing possibilities for distributed resources and energy efficiency projects [98], and their potential to mitigate the standoff between economic growth and environmental sustainability withstand the need to give them more attention.

The model considers storage assets to be owned by a REC to provide flexibility and storage services to other stakeholders/players regardless of the internal REC management, which means that BESS operation does not attend to internal REC needs or complement RES operation. Instead, BESS is operated to minimize its operation cost or increase the revenue stream as high as possible by mainly attending profit-making-oriented operation strategies. Therefore, an aggregator is required to intermediate with other stakeholders in providing flexibility and storage services under a structure DSO-Aggregator-REC [93].

The idea of decoupling BESS operations from internal REC needs is related to:

(i) The need for REC to ensure its availability in providing flexibility and storage services to stakeholders while DSO reduces the need for additional coordination with TSO due to local imbalance. Moreover, an integrated BESS-REC operation (for mainly preserving REC commitments) may make the way energy is shared among members and how members are economically compensated even more complex [98], and reduce the opportunity to interact with DSO and other stakeholders whether REC only grows behind-the-meter [56].

(ii) The importance of REC participation in the planning, operation, and management of the power network [132], as well as promoting the consumers' participation in decision-making processes [48]. Moreover, REC may push forward the consolidation of local energy markets to trade flexibility and other storage services [93].

(iii) The REC's potential to extract financial profit from storage services and invest it in social projects that improve the REC's self-sufficiency, integrate vulnerable members to the REC, or other projects that aim to mitigate energy poverty and promote socio-economic development [47].

It could be expected that a BESS owned by a REC ensures a democratic and inclusive sustainable energy transition and decarbonization process since the involvement of REC members in the investment decisions related to electrical infrastructure may increase the overall benefit perceived by the REC members, gain public acceptance, as well as may increasing the pressure to dismantle the regulatory barriers. A BESS owned by a REC could be interesting from an environmental perspective given it is expected that environmental burdens associated with the location of the assets and visual or auditory pollution are already harmonized with the economic objectives.

5.3 Methods and Techniques for Planning BESS into DN

Nowadays, optimal battery planning is an interesting topic to be focused on given that distributed resources like energy storage systems have been recognized as a key solution to achieve sustainable development and energy transition in electrical power systems [11], [30], [31], [43]. As mentioned in Chapter 2 and Chapter 3, batteries may provide several services defined by their economic and performance parameters, and the revenue and business models established by the BESS owner. These facts prove that the planning problem can no longer be seen from a singular perspective in which, at a minimum cost, the decision-maker determines the sizes of a set of assets and their locations to supply the current and future energy demand. Currently, decision-makers need to find some harmony between the perspectives of the stakeholders/players in designing distribution networks that meet different criteria [61].

In this section, the algorithms that could be used to solve the BESS planning problem proposed in this research work are not discussed. As mentioned in Section 3.3, in the last decades, methodologies have evolved into a wide variety as the computational capacities improve and researchers and decision-makers devise solutions according to the electrical network's needs. In [11] and [99] authors provide a detailed review of the optimization models and tools widely used while authors in [44] explain each type of algorithm based on a generic flowchart.

The method and techniques approached in this research work consider the complexity of planning BESS into the distribution network since it is relevant for decision-makers to provide solutions that deal with:

(i) Uncertainties, and a more realistic network and configuration models.

(ii) The inherent relationship between models and algorithms.

(iii) The combinatorial nature of the BESS planning problem.

(iv) The capability of decoupling the planning process to reliably solve the problem.

Therefore, inspired by the promising results of a metaheuristic method for the planning problem and a probabilistic method for uncertainty management [53], [54], [76], the Evolutionary Particle Swarm Optimization (EPSO) and the Monte Carlo method are introduced as robust solvers for planning BESS into the DN.

5.3.1 EPSO for BESS Planning

EPSO combines Evolution Strategies (ES) and Particle Swarm Optimization (PSO) concepts. EPSO is a self-adaptive evolutionary algorithm in which the operation "recombination" in PSO is replaced by an operation called "particle movement". The effectiveness of this hybrid is explained by EPSO developers based on the fact that "particle movement" is more effective than "recombination" in generation solutions to find the optimum of a function, in addition to the self-adaptive characteristics of EPSO, which makes it non-dependent on external definitions of weights/parameters [110], [133], [134]. Nevertheless, before talking about EPSO it is suitable to refer to PSO.

PSO relies on a different concept. This algorithm imitates the social or collective behavior of animal swarms or bird flocks by considering moves/advancements in a space of search motivated by three factors: habit, memory, and cooperation [135]. It implies that, at a given iteration, there are a set of solutions called "particles". From one iteration to the following, each particle X_i moves or advances according to the movement rule defined in Equation 5-1. As V_i represent the velocity of the particle X_i, the new V_i^{new} is determined as indicated in Equation 5-2.

$$X_i^{new} = X_i + V_i^{new} \tag{5-1}$$

$$V_i^{new} = Dec(t) w_{i0}\left(X_i - X_{(i-1)}^p\right) + Rdn_1\, w_{i1}(b_i - X_i) + Rdn_2 w_2\left(b_g - X_i\right) \tag{5-2}$$

Where:

$X_{(i-1)}^p$ represents the particle position in the previous iteration.

b_i represents the best point found by the particle in its past life.

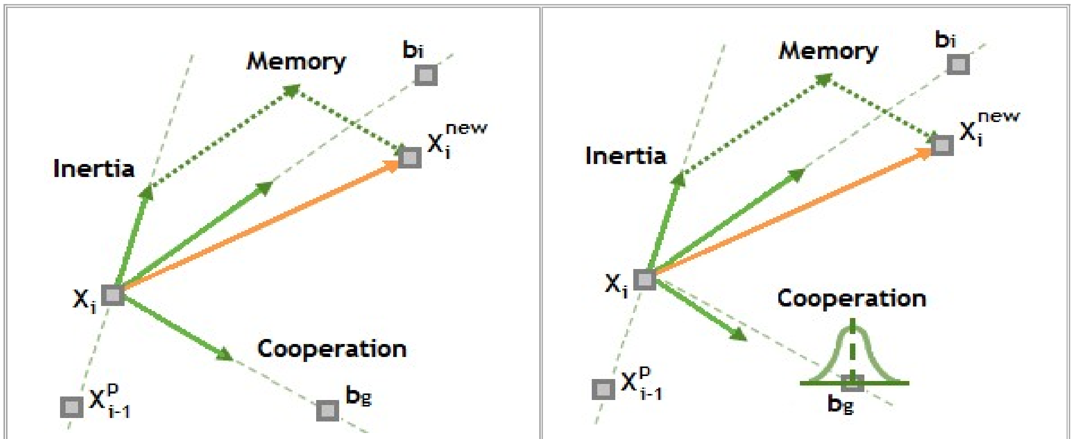
b_g represents the best global point found by the swarm of particles in their past life.

w_{ik} represent weights fixed at the beginning of the process.

Rdn_x are random numbers sampled from a uniform distribution in $U\ (0{,}1)$.

$Dec(t)$ correspond to a function decreasing with the progress of iterations to progressively reduce the importance of the first term of the Equation 5-2.

As noted, $V_i^{new}$is defined by three factors. The first term, inertia or habit represents the particle following the path along its previous movement direction. In the second term, memory influences the particle to return to the best position found during its life. Finally, the last term, cooperation/information exchange induces the particle to move closer to the best point found by all the particles in its family. Figure 5-1a illustrates how a particle moves in the space of search in iteration i, under the PSO concept.



a) Particle movement in PSO b) Particle reproduction in EPSO

Figure 5-1. Abstract graphic about how the particle is generated for the next generation.

For using PSO, several parameters must be defined by the user, then, it is essential to tune the algorithm for practical problems carefully. For instance, the function $Dec(t)$ should be carefully defined given that reducing rapidly the inertia in an early stage of the process could be risky for the algorithm because it could be trapped in some local minimum. Moreover, the factors Rdn_x are not sensitive to the evolution of the process.

Considering the opportunities for improvement, EPSO introduces the self-adaptation power of ES to the exploration power of PSO. The operator "particle movement" introduced by EPSO contributes to the increase of the value of the progress rate towards the optimum. According to the vocabulary used in the ES community, the variables in an EPSO formulation are identified as object and strategic parameters, which correspond to the X variables and the weights w, respectively. Thus, the particle movement follows the movement rule defined in Equation 5-3 and Equation 5-4.

$$X_i^{new} = X_i + V_i^{new} \tag{5-3}$$

$$V_i^{new} = w_{io}^* V_i + w_{i1}^* (b_i - X_i) + P w_{i2}^* (b_g^* - X_i) \tag{5-4}$$

Where:

w_{ik}^* represent the strategic parameters "weights" defined according to Equation 5-5.

b_g^* represents the global best point randomly distributed according to Equation 5-6.

P is a communication factor used to provide information to the particles about b_g.

This formulation is similar to PSO given the movement is guided by terms like inertia, memory, and cooperation. Nevertheless, the weights and the best global undergo mutation as indicated in Equation 5-5 and Equation 5-6, respectively, where τ and τ' are learning parameters that affect the amplitude of the Gaussian distribution (either fixed or treated also as strategic parameters, therefore, subject to mutation. Moreover, $N(0,1)$ represent a normal distribution with mean 0 and variance 1.

$$w_{ik}^{*} = w_{ik} + \tau N(0,1) \tag{5-5}$$

$$b_{g}^{*} = b_{g} + \tau' N(0,1) \tag{5-6}$$

The b_g modification is supported by two facts: a) when the current $b_g$is already the global optimum, there are no relevant modifications regarding b_g^*.However, b) when the optimum hasn't yet been found, it may be in the neighborhood, therefore, it should not aim exactly at the current b_g. This proposal is especially relevant for the latter stages of the process, where the search is focused on a certain region. Figure 5-1b illustrates how a particle moves in the space of search in iteration i, under the EPSO concept.

Concerning iterations, EPSO considers a set of alternatives to the solution called particles. Every particle created comprises object and strategic parameters $[X, w]$, which follows the EPSO scheme indicated in [110], [133], [134] and Figure 5-4 to find a solution that, regardless of the initialization, probabilistically ensures it is optimal or is near it (slight deviation). The planning strategy for battery sizing, location, network interface, and technology selection is presented in Section 5.4, in which the EPSO particle that aims to solve the planning problem is defined.

5.3.2 Linear programming for battery operation

In this Chapter, linear programming is responsible for solving the problem of battery operation, which considers the performance parameters influencing its behavior, lifespan, and revenue stream given that, from the small-scale investors' perspective, there are essential more real analyses about battery operation.

As defined in Chapter 4, the technical and non-technical battery parameters like energy and power capacity, useful storage energy, self-discharge, DOD, SoC, DC-DC/AC-AC RTE, lifecycle, calendar life, and C-rates must take relevance to assess batteries operating under profit-making-oriented strategies. Then, considering that in this Chapter batteries respond to price signals, the operation model to be used refers to the one formulated in Section 4.4 for non-ideal batteries.

5.3.3 Distribution network modeling

One of the most important steps in the planning process is determining a suitable network modeling for the problem approached. As shown in Figure 3-1, this is the starting point for the problem formulation given the model chosen is responsible for simplifying or approximating it to the real problem. Since the complexity of modeling the DN is related to the quantity and quality of the data, the limitation of the solution methods, and the computational power [34], [99], planners and decision-makers must detailly evaluate what aspects are the most relevant to designing the problem formulation and what aspects could be analyzed after finding a solution because the introduction of latter may increase the complexity of the problem.

The most common aspect to be considered to define the model for planning the DN is related to the load and generation modeling, how dynamic the model is (planning horizon), what technical or quality parameters should be measured (e.g. losses, reliability, etc.), and how the configuration is (e.g. radial, weakly-meshed, or meshed). Although an AC model of the DN may denote a higher computational effort, in the scope of this work, DNs are represented under an AC model as described in Section 3.3 given it is relevant to avoid questionable simplification about network parameters (e.g. losses, voltages profiles, etc.) when planning the integration of assets with active behavior like batteries. Therefore, special attention is given to some parameters like feeder/branch loadability, busses voltage profiles, and power losses.

5.3.4 Uncertainties management

Uncertainty management is an important challenge that decision-makers must face [87] when planning the DN because input parameters such as load and generation profiles directly influence the planning process [34]. Even though planners and decision-makers do not control future values or behaviors of network parameters, from the investors' perspectives, it could be suitable that decision-makers find a way to manage the uncertainties while avoiding camouflaging them behind generalized assumptions [99] and dense mathematical formulations.

Information reported in Section 3.3 indicates that one of the methods widely used to handle uncertainties surrounding the planning problem is the probabilistic one. Similarly to [34], [44], [53], [54] a stochastic method like the Monte Carlo is used in this section to generate a set of samples of the random variables. Therefore, the stochastic scenario generation model proposed in Section 4.2 is also followed. Lists of numbers ρ_{α} are generated to build a database scenario of energy generated at the DN from distributed resources given their profiles are explained by normal distributions (Figure 4-3b) after being seasonally grouped (Figure 4-2).

Concerning the load both, commercial and residential profiles are considered in this work. After preprocessing load data according to seasonal criteria as shown in Figure 4.2, data revealed that uniform distribution could explain it. Therefore, Figure 5-2 shows the process followed to generate random numbers that indicate the probability of distribution of each load profile per type of load per season.

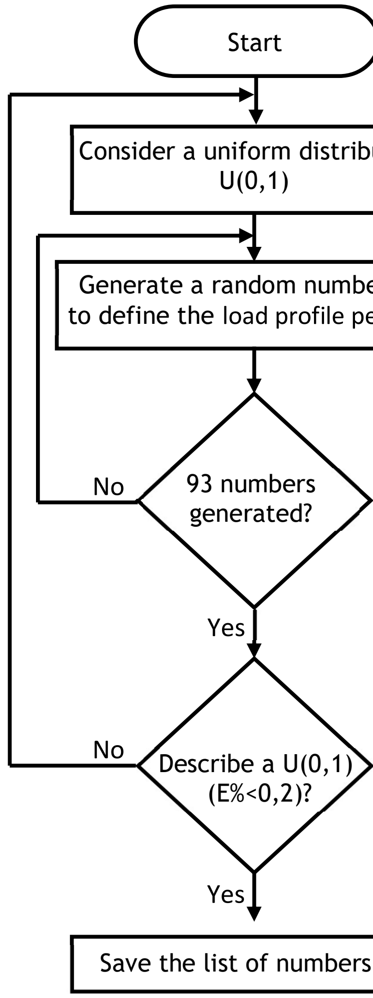


Figure 5-2. Flowchart followed to generate the random numbers L_α for the daily load profile.

(i) From a uniform distribution $U\ (0,1)$, a set of numbers L_α are generated. As the set of numbers α generated to represent the season (Figure 4-3a) allows an error of about $\pm\ 0{,}2\%$, each list of numbers L_α could contain 93 numbers. Then, this is also the stop criterion for the generation of numbers L_α.

(ii) Every list of 93 numbers L_α is verified given, as expected, they must describe a uniform distribution $U\ (0,1)$. However, considering there is always an error associated with the creation of random data [111], [129], an error of up to $\pm\ 0{,}2\%$ is accepted for the probability of occurrence of each load profile.

(iii) If the set of numbers L_α met the error criterion, the list of numbers L_α are saved.

(iv) Similar to those indicated in Section 4-2 for data explained by normal distributions, a load scenario reduction is carefully applied for data load according to the load level, namely minimum, medium, and maximum. Considering each list of numbers L_α, $L_{\min\_\alpha}$, L_{med_α}, and $L_{\max\_\alpha}$ represents the probability of occurrence of a specific load profile per type of load per season defined by a typical minimum, medium and maximum load profile selected from the historical data.

(v) Lastly, following the flowchart shown in Figure 4.4, with the list of numbers L_α, ρ_α, and ζ_α, the load, generation from RES, and market price databases are built. As noted, using the selection process proposed, the databases are not seasonally grouped, seasons/days are dispersed throughout the year instead. With it, the desired effect of producing a larger sampling data dispersion over what would be achieved with a classical grouping of season data.

5.4 Strategies for Battery Energy Storage Planning and Operation

To optimally plan BESS into the DN, battery sizing, location, network interface selection, and technology selection are considered. As indicated in Section 5.2, the problem is solved from the perspective that REC is the BESS owner, and batteries operate following profit-making-oriented strategies. Similarly to [43] and [53], the optimal BESS planning and operation is solved following a bi-level optimization approach as shown in Figure 3-1. In this approach, an interconnected and iterative scheme considers an upper-level where potential solutions or decisions are generated and a lower level where the battery operation is simulated and evaluated as indicated by the objective function and for the time horizon. Hence, there is continuous feedback between levels until the optimization reaches the stop criteria. As mentioned in Section 3-1, the advantage of this scheme is related to the capability of decoupling the planning and operation problems [94].

5.4.1 Sizing, location, network interface, and technology selection strategy

EPSO is the powerful algorithm responsible for solving the planning problem located at the upper-level of the bi-level optimization.

Similar to [53], the particle composition is defined by battery size and its C-rate as object parameters, and its size is determined according to the number of potential locations, N, for BESS. Therefore, for the battery size, S, and the C-rate, γ, the particle size can be set as $2N$ because, for each potential location or bus n, there are two objective parameters, S_n and γ_n. The particle structure is shown in Figure 5-3.

S_1	γ_1	S_2	γ_2	...	...	S_n	γ_n	S_N	γ_N

Figure 5-3. Particle structure for EPSO.

The fitness function to be evaluated by EPSO is shown in Equation 5-7. This considers the minimization of the sum of a set of costs as indicated below:

$$Min: OF_{BESS} = [\, C_I(x) + C_{O\&M}(x) + C_R(x) - C_{RD}(x) - C_{RS}(x) + C_P(x) \,] \tag{5-7}$$

The investment cost required to integrate BESS into the DN, $\boldsymbol{C_I(x)}$, the annual O&M cost of the BESS, $\boldsymbol{C_{O\&M}(x)}$, the replacement/augmentation cost of the battery storage bank over the project life, $\boldsymbol{C_R(x)}$, the recycling and disposal cost of material at BESS EoL, $\boldsymbol{C_{RD}(x)}$, the revenue stream from BESS operation, $\boldsymbol{C_{RS}(x)}$, and the penalization cost, $\boldsymbol{C_P(x)}$, which is applied when a solution generated do not ensure voltage limits, assets loadability, or technical losses are between standard values. More detailed information about each term is presented in Section 3.3.

As noted, the fitness function to be evaluated by EPSO slightly differs from Equation 3-5 given that to make it more realistic it does not consider any subsidies or incentives, $\boldsymbol{C_{S/I}(x)}$, a REC owner can receive by investing in BESS. Regarding an environmental approach, this is represented by the economic criterion defined by the recycling and disposal process for BESS due to three facts:

(i) Identifying a criterion that can be used regardless of the battery technology and service provided;

(ii) Introducing an environmental objective that aims to identify the CO_2 emissions from battery operating at the DN to optimize it, not only implies dealing with a multicriteria approach but also increasing the computational effort required to solve the problem, which could be non-compensated by the CO_2 contributions made by a BESS operating under profit-making-orientated strategies compared to strategies technical-support-oriented [108];

(iii) As REC promotes the BESS project, it is assumed REC participants previously approved BESS's potential locations. Therefore, the definition of additional criteria based on environmental aspects such as visual/auditory pollution and land uses is not considered a concern that should be harmonized with the technical criteria defined in Equation 5-7.

According to [55], the recycling and disposal costs depend on the recoverable metal in them. Specifically, for NMC batteries, the cost is estimated at $0 since the recycling and disposal costs are offset by the income from metals recouped. Contrary to the NMC battery, the LFP type contains fewer amounts of recoverable metal, which means it currently experiences recycling costs for the battery owner. As for lead-acid batteries, there are a few more mature recycling processes and supply chain routes given this battery technology is used in automotive or marine industries. Concerning VRFB, the recycling process is focused on the vanadium found within the electrolyte due to the restrictions on vanadium production methods and its use.

The BESS planning problem formulated in Equation 5-7 is subject to the same AC power flow constraints expressed in Equation 3-10 to Equation 3-15. Moreover, Equations 5-8 and Equation 5-9 present two operation conditions penalized with a high contribution to the penalization cost, $\boldsymbol{C_P}(\boldsymbol{x})$, given Equation 5-8 ensures that the reverse power flow, R_{pf}, will not exceed 20% of the substation/feeder rating, $R_{s/f}$ to which BESS is integrated, whereas Equation 5-9 ensures that the power flow from the substation to the first bus along the feeder to which BESS is integrated will not exceed 85% of the feeder rating.

$$R_{pf} \leq 0.2R_{s/f} \tag{5-8}$$

$$P_{0j} \leq 0.85P^{max} \tag{5-9}$$

Similarly to [22] and [53], this work considers that battery deployment should be made in the first year of the planning period, therefore, annualized costs are performed according to the annuity factor expressed in Equation 3-7.

5.4.2 Operation strategy

As indicated in Section 5.3.2, linear programming is the technique responsible for solving the operation problem located at the lower-level of bi-level optimization. From the findings reported in Chapter 4, price arbitrage will be the profit-making-oriented strategy followed by BESS. Three electricity market price behaviors are considered for battery operation according to the aspects identified and described in Section 4.2.1. 2019 could be understood as a “pessimistic price scenario” for a BESS project whose revenue streams solely depend on the electricity price gap given the former is inversely proportional to the latter (this year's gaps were the lowest over the last 5 years) whereas 2023 and 2022 could be understood as optimistic and very optimistic electricity price scenarios, respectively. The definitions proposed for each year consider as the price gap is higher, the price arbitrage strategy is more attractive.

A set of curves of batteries operating at a wide range of different C-rates are generated per year per technology to provide the planning level information such as battery behavior, that should be assessed under a multiperiod power flow scheme.

5.4.3 Decision-making process based on a conditional decision set

The decision-making process is a complex task that is not often possible to follow under a very detailed model, then, planners and decision-makers usually devise strategies that allow them to mitigate the problem's complexity and find an optimal solution in the scope of the planning framework [24], [31], [99]. As shown in Figure 3-1, nowadays, this complexity could be enlarged when the planning process involves more than one stakeholder/player since each will surely provide planning objectives that would like to be properly represented and harmonized in the decision to take [2], [48]. Considering there is no clear regulatory framework for BESS projects, it may be difficult for the DSO/DISCOs to apply a remuneration scheme to these projects by the potential services they may provide.

As indicated in Section 5.2, the planning problem is approached here from the perspective of a BESS owned by REC. It is known that batteries follow an operation strategy profit-making-oriented, and their sizing, location, network interface, and technology selection are planned by ensuring the technical parameters of the DN are kept within standard values. Although there were no considered deferring DN upgrades, reducing congestion, or other technical-support-oriented strategies from a multicriteria perspective, the planning methodology proposes a strategy that supports the decision-making process in choosing not only an economical decision for the BESS owner perspective but also one that is technically feasible for the DSO as well.

The strategy aims to create a conditional decision set. A conditional decision set refers to a set of feasible decisions from the perspective of the BESS owner, therefore, the set comprises the most attractive candidates for a final decision [54], [90]. Under a real-life planning environment, the approval of BESS integration into the DN is surely dependent on the technical concept issued by the DSO/DISCOs, they may analyze the conditional set provided by the BESS owner according to additional technical criteria such as an extended DN model, mid-term planning horizon, optimistic/pessimistic load growth rates, or a specific technical need the DN should fulfill, to determine the most feasible “final decision” for both.

This is an interesting decision-making approach given both the BESS owner and the DSO/DISCOs can estimate the economic and technical consequences that will bring each decision if it is taken. Moreover, this approach reduces the possibility of regretting the “final decision” since the BESS owner can quantify a certain loss of attractiveness in the final decision compared to the optimal solution. Authors in [90] and [114] proposed a risk-averse strategy for DN expansion planning under a multicriteria approach, in which the decision is taken by minimizing the regret felt by a decision in all possible futures.

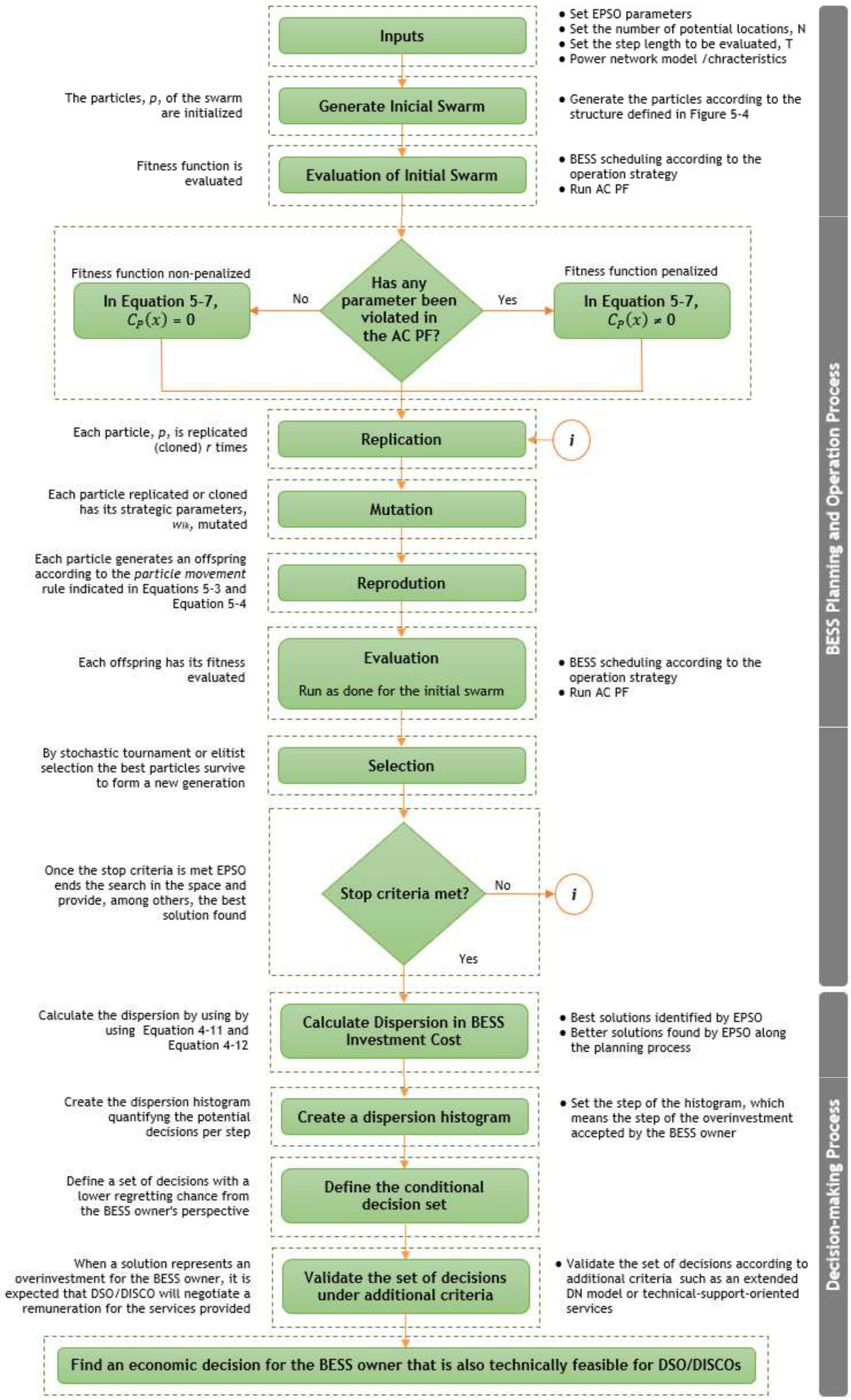


Figure 5-4. Methodology for BESS planning and operation, and decision-making process.

In the scope of this work, the loss of attractiveness is defined as an unwanted additional investment that represents each decision regarding the most economical (the optimal solution) but that is accepted from the perspective of the BESS owner. Then, the conditional decision set is comprised of potential decisions that represent for the BESS owner an accepted overinvestment aiming to ensure that DSO/DISCOs, after evaluating the integration of the BESS project, find in the conditional set a technically feasible decision for them as well. When the final decision represents an overinvestment for the BESS owner, it is expected that DSO/DISCOs will negotiate a remuneration by the additional criteria evaluated given that the methodology pursues to create win-win situations for different stakeholders.

To create the conditional decision set, firstly, it is proposed to determine the distribution of investment cost that represents the decisions generated along the planning process compared to the optimal solution based on a quadratic dispersion metric, analog to variance [54], [111]. Dispersion is calculated by using Equation 4-11 and Equation 4-12. Then, a dispersion histogram is constructed to quantify the decisions in each range of dispersion and provide BESS owners with more reliable information about the decisions contained in the conditional set and the maximum loss of attractiveness they represent. The histogram step depends on the loss of attractiveness accepted from the perspective of the BESS owner. Figure 5-4 shows the methodology proposed for the BESS planning and operation, and decision-making process.

5.5 Numerical Simulations

The planning methodology proposed here addresses the challenge of providing a set of conditional decisions made from the perspective of a small-scale investor that owns BESS, namely a REC. A tool that considers non-ideal battery models and uncertainties surrounding the planning and operation problem will provide valuable and reliable information to different stakeholders, but mainly for REC members, about investment opportunities and economic return when planning BESS integrated into the DN following a conciliatory process between the small-scale investor and the DSO/DISCOs.

As defined in Section 5.4 batteries will follow a profit-making-oriented operation strategy given BESS owners consider extracting financial profits from storage services and invest them in social projects aiming to mitigate energy poverty and promote socio-economic development. Therefore, as mentioned in Section 5.2 considering storage as a decoupled service may encourage consumers' participation in shaping the future of the electrical power network while promoting a strong interaction with DSO and other stakeholders, and not just grow behind-the-meter.

Results are discussed based on identifying the relevance of small-scale investors optimally planning and operating BESS into DNs and providing a decision-making process in which the DSO/DISCOs participate in determining the final decision.

5.5.1 Case study for validation of the methodology

Two test systems are used here to validate the planning and decision-making methodology proposed, namely the CIGRE MV Distribution Network Benchmark and the IEEE 33-bus system. The case study that each one brings is defined below. Nevertheless, more details are reported in Appendix E while Figure E-1 shows the network configuration.

(i) **CIGRE MV Distribution Network Benchmark:** This network has a total peak power consumption of 11.88 MVA for commercial loads and 34.29 MVA for residential loads. In normal operating conditions, this test system operates on radial topology. Some modifications were proposed to adapt this network to the test subject: (a) REC comprises consumers connected to feeders 1 (F1) and 2 (F2), which represent a peak power consumption of 1.54 MVA and 3.69 MVA for commercial and residential loads, respectively; (b) REC owns distributed PV generation that represents 25% of its maximum load installed; and (d) both commercial and residential loads are considered as balanced.

(ii) **IEEE 33-bus system:** The original configuration is modified according to the one specified in [136] (given those authors demonstrated it improves the voltage profile while reducing the technical losses), nevertheless, under the modified configuration the radial topology is ensured. Consumers connected to the feeder and branches comprise a REC whose peak power consumption is 1.93 MVA and 2.73 MVA for commercial and residential loads, respectively. This represents approximately 70% of feeder loadability.

5.5.2 Creation of the load, PV generation, and electricity prices database

The load, PV generation, and electricity market prices databases were created following the procedures described in Section 4.3 and Section 5.3. As expressed in Section 4.3, seasonal variability is the criteria used to group data and identify patterns.

Concerning electricity prices, data from 2019, 2022, and 2023 were considered to represent pessimistic (2019), optimistic (2023), and very optimistic (2022) scenarios for the revenue stream of a BESS operating according to price signals.

Residential and commercial load profiles for 2023 were considered to represent load behavior while PV generation curves were generated based on data from real PV plants. Therefore, the database scenarios are generated from E-REDES public records for the

Portuguese Distribution network operator [137], OMIE public records for Portugal's real-time electricity price [120], and from a PV station situated in Évora, Portugal [138].

Figure 5-6 shows an example of the load, PV generation, and electricity price curves to be used to construct the databases for 2022 after applying the scenario reduction according to the previously defined in Section 4.3.

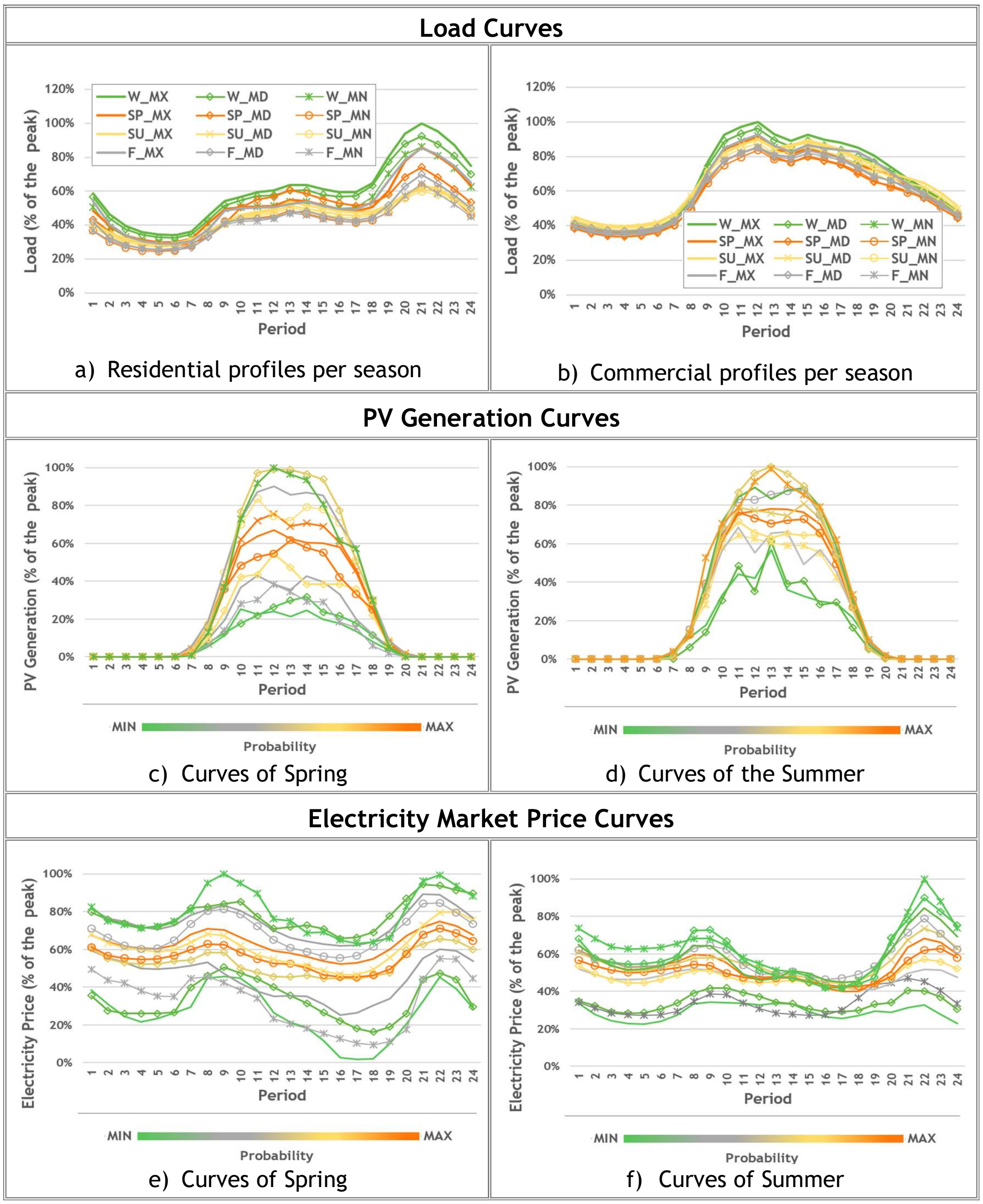


Figure 5-5. Illustrative examples of load, PV generation, and daily price curves used to construct the databases for 2022.

Once the load, PV generation, and electricity price curves are defined the stochastic scenarios databases are constructed according to the flowchart shown in Figure 4-4 to obtain the databases of electricity prices for 356 days or 8760 periods. This process is repeated 20 times to consolidate 20 packs of databases for every test system. Figure 5-7 shows an example of the electricity prices, PV generation, and load scenarios generated for the CIGRE MV DN over 10 days with data from 2022. As noted, the database is not grouped by season, the season data is dispersed throughout the year instead, which guarantees a larger sampling dispersion condition.

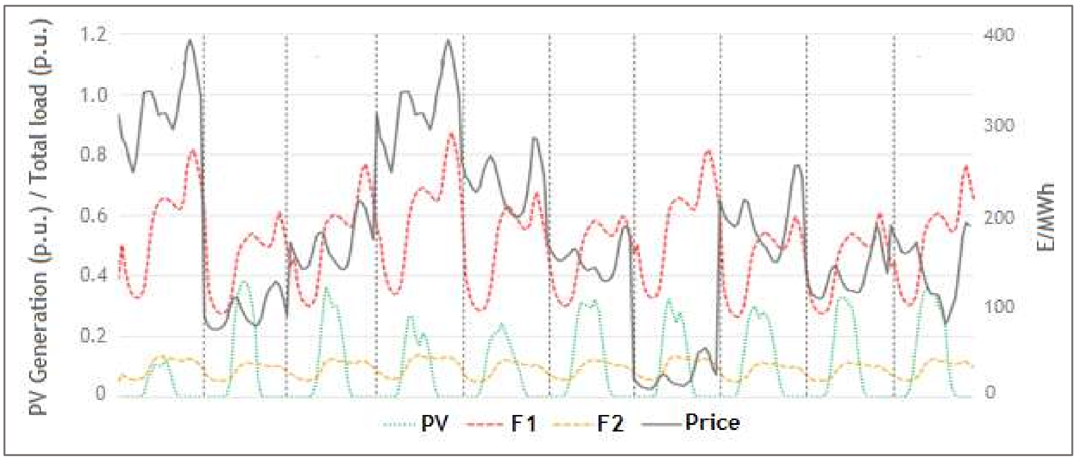


Figure 5-6. Illustrative examples of database scenarios created for the CIGRE MW Distribution Network Benchmark over 10 days.

5.5.3 BESS operation

Section 5.4 explains that the planning and the operation problems are decoupled into two levels to be solved separately. For a small-scale investor or a RECs that owns a BESS to be operated integrated into the DN, the operation strategy must be based on non-ideal battery models and series-time of electricity price to represent the impact of the performance parameters and price levels and volatility on the battery behavior, revenue stream, and battery lifespan given this information is transmitted to the planning level.

This Section does not show illustrative examples of how battery behaviors, revenue stream, and lifespan are influenced by battery parameters and the electricity prices given Chapter 4 approaches this problem in detail. Figure 4-8, Figure 4-9, and Figure 4-10 provide those examples, and results are discussed throughout Section 4.5 for different electricity market price behaviors and battery technologies. For this reason, this Section states that only non-ideal battery models are considered to create a set of curves that determine the BESS behavior regarding price arbitrage application to be provided to the planning level along the iterative process followed to planning BESS.

5.5.4 BESS sizing, location, network interface, and technology selection

Determining the optimal size, location, network interface, and battery technology selection is relevant for a REC or a small-scale investor because at least the amortization of the loan payment and the upfront investment costs in BESS should be ensured.

BESS planning is started according to the flowchart shown in Figure 5-4. The EPSO particle was defined to preserve the structure shown in Figure 5-3. Then, preliminary analyses were carried out to set the size of the EPSO swarms and thus, have a high exploring capacity in the problem domain while avoiding compromising the overall computational time. 40-particle swarms (for 100 runs of the optimization model) were chosen to perform the planning optimization tasks.

Moreover, current installation costs reported in Table 2.1 and estimated installation costs to 2030 reported in Table 4.1 were considered to identify if the overall investment in BESS integration can stand out as a limitation for the business model. For both current and estimated costs to 2030, it is confirmed that even under the very optimistic electricity market price scenario (2022), installation costs are not suitable for a small-scale investor to invest in a BESS project to operate it integrated into the DN because revenue stream is not attractive enough to recover the investments. For these reasons, breakeven cost scenarios for battery installation cost were identified to find the point where the BESS integration becomes feasible for REC.

Table 5-1 shows the reduction required in BESS installation cost, $RC_I(x)$, defined by the breakeven cost calculated for each price scenario of the electricity market. As noted, the reduction in BESS installation costs required is currently between 68% and 91%. Even more worrying is the fact that estimated installation costs to 2030 will still not be enough, therefore, for battery-based business models to thrive, these costs will need to be 50% to 90% lower than estimated if there are considered electricity prices could fluctuate between the three scenarios considered. Specifically, the breakeven cost identified in this study for Li-Ion battery technology was similar to the value estimated in [139] to 2050.

Table 5.1 Reductions required in BESS installation cost regarding different price scenarios.

Electricity Price Scenario	*Cost Reduction Needed*	
Very Optimistic (year 2022)	Current	68.4% < $RC_I(x)$ ≤ 71.8%
	Estimated to 2030	57.3% < $RC_I(x)$ ≤ 66.2%
Optimistic (year 2023)	Current	76.5% < $RC_I(x)$ ≤ 78.9%
	Estimated to 2030	69.1% < $RC_I(x)$ ≤ 74.6%
Pessimistic (year 2019)	Current	89.3% < $RC_I(x)$ ≤ 91.2%
	Estimated to 2030	86.1% < $RC_I(x)$ ≤ 89.6%

This confirms that without incentives, subsidies, or regulatory frameworks that remunerate the storage activities, the revenue model based solely on price arbitrage does not provide the financial support required to invest in this BESS business model. For this reason, the planning methodology proposed considers the breakeven costs calculated.

With the size of the particle swarm, the EPSO particle structure, the BESS installation cost ($RC_I(x)$), and the set of curves of batteries operating at a wide range of different C-rates defined, the optimal planning process is run (for 100 iterations of the optimization model) as indicated in Figure 5-4 for both, the CIGRE MV DN and IEEE 33-bus system modified. Considering that almost 85% of the buses along the feeder are available locations for BESS integration. Table 5-2 shows an example of the most economical solution found for each test system when the very optimistic electricity price scenario was considered as the price signal for battery operation.

Table 5.2 Examples of the most economical decisions found, and the final decisions selected from the conditional decision set after analyzing additional criteria.

Test System	*Most Economical Decision*				*Final Decision after DSO/DISCOs Analyze Additional Criteria*			
	Bus	*MWh*	*C-rate*	*Technology*	*Bus*	*MWh*	*C-rate*	*Technology*
CIGRE MV DN	5 7 8 10 13 14	0.8 0.5 0.4 0.3 1.0 0.5	0.6 0.8 0.5 0.3 0.7 0.8	Li-Ion Li-Ion Li-Ion VRFB Li-Ion Li-Ion	3 5 8 13 14	0.6 0.7 0.5 0.9 0.6	0.7 0.6 0.3 0.8 0.6	Li-Ion Li-Ion VRFB Li-Ion Li-Ion
IEEE 33-bus system	5 8 9 18 21 22 24	0.4 0.6 0.3 0.5 0.4 0.5 0.4	0.4 0.5 0.6 0.7 0.7 0.6 0.7	VRFB Li-Ion Li-Ion Li-Ion Li-Ion Li-Ion Li-Ion	6 8 10 18 20 22 23	0.5 0.5 0.5 0.5 0.3 0.4 0.4	0.5 0.4 0.6 0.6 0.7 0.8 0.5	Li-Ion VRFB Li-Ion Li-Ion Li-Ion Li-Ion Li-Ion

As noted in Table 5-2 for the CIGRE MV DN, distributed solutions were privileged over concentrated ones, even when the first and last bus of the feeders were enabled as possible locations. The total capacity of the distributed BESS represents 56% of the maximum REC load, nevertheless, their C-rates differ between them. Similar results were obtained for the IEEE 33-bus system given that the solution found also privileged distributed battery integration with different C-rates, nevertheless, in the main feeder the batteries were always located near the substations. In this case, the total capacity of distributed BESS represents 79% of the maximum REC load. The definition of BESS capacities regarding the respective REC loads is done to provide a reference on the expected behavior of BESS as a load (charging process) or generator (discharging process).

During the planning process, it was identified that for the CIGRE MV DN the BESS capacity was constrained by the maximum allowed feeder loadability. In the case of the IEEE 33-bus system modified, it was restricted by the minimum voltage profile allowed at each node. Concerning the most economical solutions, Li-Ion batteries at high C-rates were the most selected technology given their high AC-AC efficiency and suitable lifecycle. Only one VRFB battery at medium C-rates was selected, and the Lead-Acid battery was not selected because its lower lifecycles cause a high frequency of replacement, which increases the replacement, recycling, and disposal costs.

Simulations under the optimistic and pessimistic electricity price scenarios packages revealed similar results given that distributed solutions were also privileged over concentrated ones, no batteries were located in the first bus of both networks, and Lead-Acid technology was not selected either.

5.5.5 Model robustness

As mentioned in Section 4.5.6, the robustness of a model is useful to measure its ability to withstand assumptions and perform reliably despite changes in input data [111]. Therefore, robustness is assessed by admitting that it could be useful to quantify the risk of having a non-satisfactory solution after a single run of the planning model.

Similar to [53], this is done by running the planning model for 100 simulations of the same case studies (with random initialization of variables) and comparing the cost results of each solution regarding the most economical solution achieved to calculate a quadratic dispersion analog to variance and determine the distribution of values of investment cost.

Equation 4-11 and Equation 4-12 are used to explain data by a probability distribution function (a 10-bar histogram), and its cumulative density function, whose shapes are similar to those shown in Figure 4-12. Results reveal that, under a very optimistic electricity price scenario, the estimated probability of having a result (in a single run) distanced from more than 3.75% and 3.58% of the most economical solution is 5%, and from more than 2.91% and 2,95% is 10% for the CIGRE MV DN and the IEEE 33-bus-system modified, respectively.

Considering the planning tool proposed is run offline, the results about the robustness of the model are convincing given it performs well within a confidence interval of 95%. Concerning the optimistic and pessimistic electricity price scenario, the planning model also performs well within a confidence interval of 95%.

5.5.6 Defining the conditional decision set for supporting the decision-making process

The most economical solution reported in Table 5-2 was determined by ensuring that DN parameters are within standard values given that the BESS owner recognizes that battery integration into the DN must respect them.

As indicated in Section 5.4.3, the final decision about a BESS project could result from a conciliatory process with DSO/DISCOs given they are responsible for defining how it will interact with/affect the DN operation since batteries lead to both a behavior as a "generator" and behavior as "load". DSO/DISCOs can also evaluate BESS integration for additional criteria or technical-support-oriented strategies.

For instance, if DSO/DISCO considers network reliability an additional criterion, the most economical solution should be evaluated into the DN under contingency scenarios. Although, this special criterion implies that the feeder capacity is now constrained by its capacity under contingency [8], accounting for contingency scenarios to plan for a safety capacity would take relevance as the feeder failure rate and impacts on the consumers (energy not supplied) increase.

However, in the scope of this work, reliability is an additional criterion assessed. For this, seven scenarios were defined as crucial to evaluating the solution:

- E0, normal configuration at maximum load period considering BESS operation;
- E1, total load transfer at maximum load period without considering BESS operation;
- E2, total load transfer at medium load period without considering BESS operation;
- E3, total load transfer at minimum load period without considering BESS operation.
- E4, total load transfer at maximum load period considering BESS operation;
- E5, total load transfer at medium load period considering BESS operation;
- E6, total load transfer at minimum load period considering BESS operation;

For this purpose, the CIGRE MV DN uses switch S1 located between buses 8 and 14 (see Figure E-1a, Appendix E) to transfer the load between F1 and F2 and reduce the energy not supplied as a result of scheduled or unscheduled power outages. Regarding the IEEE 33-bus system modified, the tie lines between buses 7 and 20, and 24 and 28 (see Figure E-1b, Appendix E) are used to transfer the load from the branches to the main feeder.

The results after evaluating reliability as additional criteria are reported in Table 5-3. As noted, scenario E5 is the most critical for both the CIGRE MV DN and the IEEE 33-bus system modified because under-voltages were identified at the end of the feeders (values between 0.87 p.u. and 0.89 p.u were recorded). Concerning loadability, feeders in the CIGRE MV DN recorded overloads between 100% and 103% and transformers upstream recorded an overload of about 106%. In fact, from the simulation for 8760 periods, scenario E5 stood out 63 times and 57 times for the CIGRE MV DN and the IEEE 33-bus system modified, respectively. As for scenario E1, warnings about proximity to the under-voltage limits were identified 59 times for the IEEE 33-bus system modified, however, as recorded in scenario E4 these warnings were cleared when the BESS operation was considered.

Table 5.3. Results after evaluating the most economical solution under additional criteria.

Test System	*Operation Scenarios under Normal and Contingency Conditions*						
	E0	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*
CIGRE MV DN	Nv	Nv	Nv	Nv	Nv	Uv, Ol	Nv
IEEE 33-bus	Nv	W	Nv	Nv	Nv	Uv	Nv

Nv, Non-violations; Ol, Overload; Overload Ov, Overvoltage; Uv, Undervoltage; W, warnings.

In summary, when the DSO/DISCO evaluates additional criteria for the most economical solution, some network parameters occasionally violate the standard values, therefore, the acceptance or rejection of the most economical solution will depend on the DSO/DISCO perspective. If the most economical solution is not accepted by DSO/DISCO, then, other potential solutions in a set of good-quality solutions could be evaluated by DSO/DISCO. For this reason, the conditional decision set rises as an interesting approach for a decision-making process in which two decision-makers, the BESS owner and the DSO/DISCO contribute to making a final decision under a conciliatory process.

As proposed in Section 5.4.3 and according to the flowchart in Figure 5-4, a set of conditional decisions is constructed with the best solutions found at each iteration. In this case, the BESS owner will accept overinvestment or a loss of attractiveness up to 5%. Therefore, a 5%-step dispersion histogram is constructed. Results indicate that up to 3 additional solutions could be analyzed for the CIGRE MV DN, and up to 2 for the IEEE 33-bus system modified. This means that under the decision-making process proposed, the BESS owner may provide more than one potential solution to the DSO/DISCO.

After evaluating each conditional decision set for the additional criteria, the DSO/DISCO finds a final decision. The results of these final decisions are reported in Table 5-2 for each test system. For the CIGRE MV DN, the final solution leads to an overinvestment of about 3,8% for the BESS owner and a reduction of about 2.9% in the total capacity of BESS. Concerning, the IEEE 33-bus system modified, the final solution leads to an overinvestment of about 4,6% and a reduction of about 0.3% in the total capacity of BESS.

Similarly, the final solutions reveal that battery locations changed, nevertheless, dispersed battery integrations at different C-rates were still privileged over concentrated ones. Concerning the battery technologies, Li-Ion batteries at high C-rates were the most selected, only one VRFB battery at medium C-rates was selected, and the Lead-Acid battery was not selected either.

As indicated in Section 5.4.3, this decision-making process is interesting for the BESS owner and the DSO/DISCO because they can estimate the economic and technical consequences of a solution, which reduces the possibility of regretting the "final decision" from both stakeholders. In addition, the conciliatory stage of the decision-making process considers the BESS owner could be compensated by the additional benefits/services DSO/DISCO is extracting from BESS integration into the DN. This stage is pinpointed as "conciliatory" given that the absence of incentives, subsidies, or a regulatory framework that remunerates the storage activity makes it hard to estimate an economic compensation beyond one defined by cost savings due to the operation of the network.

However, some benefits can be extracted from BESS integration into the test systems. Figure 5-7 and Figure 5-8 show examples of the feeder profiles for the CIGRE MV DN (feeder 1) and the IEEE 33-bus system modified respectively, after integrating the final solution reported in Table 5-2.

As noted, for both test systems, the period in which peak load occurs is modified due to the BESS operation and the fact that peak load and the maximum electricity price occurs at the same period of the day. Even at this period, BESS operation leads to load values falling to values less than those recorded at valley periods, which means that BESS capacity satisfies the load locally. It is pinpointed that this accentuated drop is related to the high C-rate selected for the batteries. On the other hand, the peak load is moved to periods of low electricity prices given for those periods the batteries are charging. Finally, in most cases, BESS operation and the PV generation profiles do not overlap given the lower electricity prices do not simultaneously to PV generation.

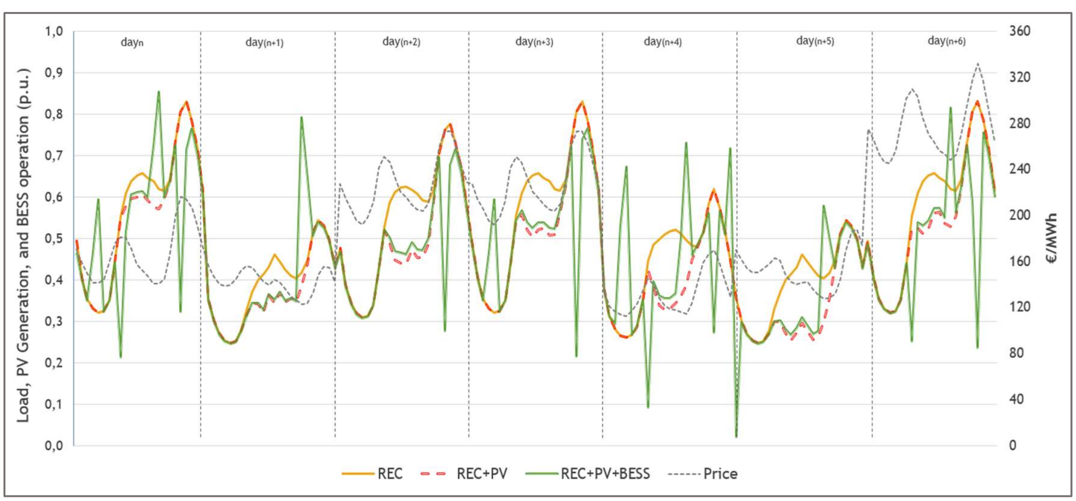


Figure 5-7. Feeder profile (green line) over 7 days after integrating distributed BESS into the CIGRE MV Distribution Network Benchmark.

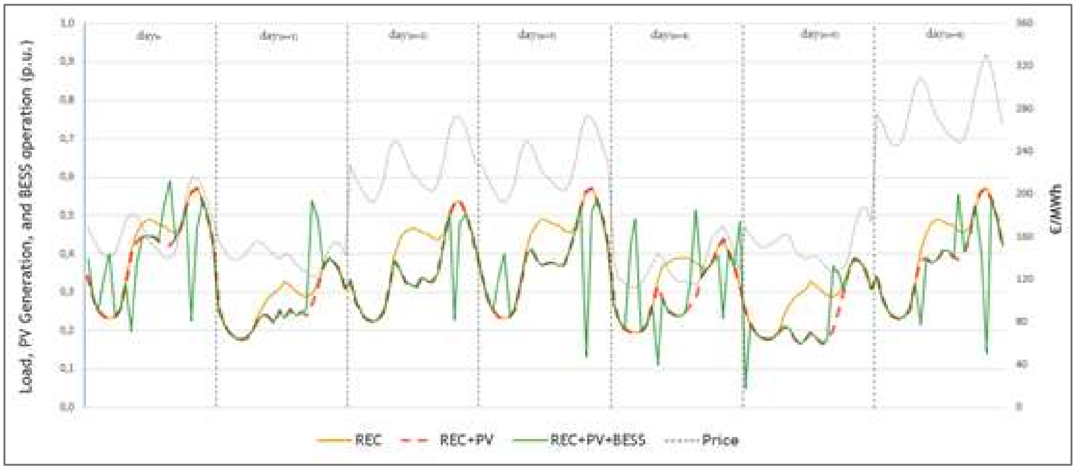


Figure 5-8. Feeder profile (green line) over 7 days after integrating distributed BESS into the IEEE 33-bus system modified.

5.6 Conclusions

This chapter approached the problem of the optimal planning and operation of batteries in the scope of small-scale BESS investors that aim to integrate BESS into the DN operating under a profit-making-oriented strategy, namely price arbitrage. Although the small-scale investor is a REC that considers a business model for BESS independent from internal REC management, it is expected that the REC manager ensures a democratic and inclusive involvement of the REC members in the investment decisions and the management of financial profits extracted from the storage activities to invest them in social projects that aim to mitigate energy poverty and promote socio-economic development.

The planning methodology follows a bi-level scheme, in which battery operation (battery behavior) is solved separately from the battery planning (battery size, location, network interface, and technology selection) to subsequently solve the latter by adopting an iterative process. In addition, a decision-making process is devised by considering a final decision should be selected under a conciliatory process in which the solution is economically beneficial for the BESS owner and technically beneficial for the DSO/DISCO.

The operation problem is solved at the lower level using a Linear Program formulated to consider more realistic models of the devices and the electricity market prices. Therefore, battery technologies are defined by their performance parameters (i.e. energy and power capacity, useful storage energy, self-discharge, DOD, SoC, DC-DC/AC-AC RTE, lifecycle, calendar life, and C-rates) and electricity prices generated under a stochastic perspective based on the Monte Carlo method are considered.

At the upper-level, Evolutionary Particle Swarm Optimization (EPSO) is responsible for solving the planning problem, which aims to minimize a set of objectives formulated under an economic nature to size, locate, and select the network interface and technology of batteries while fulfilling the constraints defined for an AC network operation.

After running numerical simulations for two cases studied in networks with radial configurations, the BESS planning tool proposed provides the most economical solutions for each case study, from which are extracted the following findings:

(i) The installation costs are the main drawback for battery deployment. Even for the estimated cost by 2030, the business model is not profitable for small-scale investors. Therefore, breakeven points were calculated (considering three electricity price scenarios) to identify the installation costs that make the business model profitable. The breakeven points revealed that estimated costs by 2050 in the literature are those currently needed, meaning installation costs must fall by 55% to 90%.

(ii) Planning with the breakeven cost identified reveals that distributed battery was mostly privileged over a concentrated location. On the other hand, a mix of network interfaces and technologies is selected, instead of a single technology. The most preferred technology was Li-Ion whereas Lead-Acid was not found in the most economical solutions provided by the planning tool.

(iii) The profiles of battery operation into the network (as a load or as a generation) do not overlap with PV generation profiles, which reinforces the potential of BESS in pushing forward the consolidation of local energy markets to trade storage services.

(iv) Although the planning objective is formulated from the BESS owner's perspective, the planning tool provides a solution that ensures the network parameters are within standard values during BESS operation.

As is known, the most economical solutions identified by the planning tool are obtained from a planning process with confirmed robustness. However, considering DSO/DISCO could evaluate the integration of BESS under additional technical criteria (e.g. an extended DN model, optimistic/pessimistic load growth rates, among others), a decision-making process based on a conditional decision set is approached. For this, the BESS owner admits a loss of economic attractiveness (an overinvestment) regarding the most economical solution as the condition to create a set of economically feasible decisions to provide them to the DSO/DISCO for their evaluation. This loss of attractiveness intends to reduce the possibility of economically and technically regretting a decision.

Simulations run from the DSO perspective revealed that when the most economical solution was evaluated by adding reliability criteria at the level feeder, some network parameters were violated several times. Assuming that for the DSO/DISCO this is a highly relevant finding because, in the periods in which violations were recorded, the failure rate of the feeder is representative. Then, the DSO could evaluate other potential solutions in the conditional decision set until it finds an economically feasible solution from the BESS owner's perspective that is also technically feasible from the DSO/DISCO perspective.

The merit of this approach lies in the fact that the decision-making process allows the participation of more than one decision-maker on the final decision, to promote an economically and technically conciliatory process devised in a way that is accessible for the understanding of different stakeholders/players, mainly for those who today are considered as one with the greatest potential to shape the electrical power network of the future, the small-scale players.

Chapter 6

Conclusions and Future Work

This concluding chapter renders an overview of the contributions this research work brings. Moreover, answers to the research question stated in Chapter 1 are conferred and newly emerging open questions and future research paths are discussed.

6.1 Overview

The efforts in devising solutions for the DN planning and operation problems from different perspectives are an opportunity to strategically design electrical power systems that integrate energy storage technologies, namely battery energy storage, to face the new challenges that the massive and accelerated integration of RES brought. It is essential to pinpoint that these challenges will increase as actions related to the sustainable transition and decarbonization increase given they are the main ones responsible for promoting RES integration into the DN as an environmentally friendly solution to replace highly polluting generation sources (i.e. oil, natural gas, and coal).

Traditionally, the complex nature of the DN makes researchers and planners approach planning and operation problems that aim at clarifying or solving a specific, or a group of topics, mainly considering that DSOs play the main role since they are responsible for ensuring a reliable and safe operation of the DN. Nonetheless, in the current context, it is necessary to approach comprehensive methodologies that embrace not only the planning and the operation problem but also the decision-making process that should be run when more than one player is taking relevance in designing the electrical power network. For this reason, this work proposes a methodology to embrace several complex aspects related to the DN planning and operation problem. In particular, the planning and operation of BESS when integrated into the DN.

The methodology proposed here is devised to represent the purpose of small-scale investors in getting involved in the planning and decision-making process since, nowadays, they are recognized for their potential role in shaping the future of the electrical system. Hence, the methodology is accessible to a broader range of stakeholders/players.

6.2 Key Findings and Conclusions

This research provides a solution to the complex problem of planning and operating BESS integrated into the DN with RES already integrated, able to deal with the uncertainties surrounding the process and the devices, and from the perspective of the small-scale investors. A hybrid approach between Evolutionary Particle Swarm Optimization and Linear Programming is responsible for solving the optimization problem that represents the BESS planning and operation when integrated into the DN.

Although this hybrid approach performs well and with the robustness required, the research dissertation also aims to remove barriers perceived by the stakeholders/players with the greatest potential to push forward investments in storage assets, the small-scale investors, about the decision-making process. For this reason, this research states that more than focusing on how fancy and complex the optimization models and methods could be, it is crucial to understand that the optimization stage is included within a planning process in which may participate more than one stakeholder/player.

This is what this research provides, a methodology in which the investment decision in BESS is obtained from a decision-making process that allows the participation of more than one decision-maker aiming at developing it based on a conciliatory perspective and an optimization tool that considers the conceptual basis of planning and the current need of the power network to capture its essence. In this context, principle research upshots are presented to address the question outlined in Chapter 1 and rewritten below:

"What would be a suitable technical and economic model for planning and operating BESS into the DN with RES already integrated, able to deal with uncertain scenarios related to energy demand, RES generation, and market prices, and to provide valuable information to small-scale investors about the profitability of the storage activity?"

The findings and conclusions that support the answers to the question consist of the consolidated conclusions from the literature review of the problem, the planning and operation problem formulation, the specification and development of the planning and operation framework, and the validation through the case studies.

Can batteries become a real technological solution to face the challenges the sustainable transition and decarbonization have brought to DNs?	The choice of batteries as the storage technology considered in this research is beyond the fact they stand out as a trending topic. As reported in Chapters 2 and Chapter 3, from an academic and technological perspective, batteries are a relevant asset to address the planning and operational challenges the DNs are facing. They can offer a wide range of services at different time scales, which renders them a highly versatile technological solution. However, their deployment is restricted by the lack of incentives or regulatory frameworks that define remuneration schemes by the storage activities, the installation costs of the BESS, and the need for control and communication systems. While additional barriers exist, these are the ones that have caused the greatest concern among investors because investing in batteries means making high-risk investments irrespective of the business models or battery technologies considered. In Chapter 5 it is established that, at present, for a business model based on price arbitrage, BESS installation costs should fall between 55% and 90% to at least reach its breakeven point just before batteries reach its EoL. This means installation costs estimated in the literature by 2050 are those needed today. Understanding that regulators and policymakers are the links to change the general perception of batteries from " a technology with potential" to "a technology with applications consolidated", Some actions are expected to be taken soon and thus the deployment of BESS would become a reality.
Can profitable business models for BESS be formulated from the perspective of small-scale investors?	Chapter 3 explains what an effective business model should embrace: (i) the role of the investor within the market, (ii) its value proposition, and (iii) the revenue model. Based on the facts that batteries can provide a wide range of services, different stakeholders/players may invest in storage assets and participate in markets, and that every business (existing or emerging) must align itself with sustainable development commitments, a large portfolio of opportunities is described from the perspective of different battery owners. However, when profitability is assessed such a portfolio is almost non-existent if the revenue stream is uniquely responsible for amortizing repayment of the loan and

upfront investment costs. Considering that small-scale investors in storage assets want to formulate business proposals, Chapter 4 studied operation strategies profit-making-oriented, namely price arbitrage as single services and price arbitrage and tertiary reserve as simultaneous services, to determine their relevance in generating revenue streams. As these strategies are highly dependent on price signals an elevated temporal resolution for data was required.

In Chapter 4 it is proven that the price signal must be modeled considering probabilistic models such as the Monte Carlo method to capture the subtleties of price behavior and the uncertainties surrounding them. Moreover, it is demonstrated that depending on the price gap is highly risky for an investor because, even for the largest price gap recorded in the last 5 years, the revenue stream could not find the breakeven point, nor counterbalance the installation costs. In the other hand, it is confirmed that there is no economic advantage in providing simultaneous services such as price arbitrage and tertiary reserve given there is no tradeoff between the regulation market price and the storage unit commitment even when batteries follow the same profiles as other ESS technologies like PSH which is a mature technology that already participate in regulation markets.

How can the challenges of BESS planning and operation be addressed from the perspective of small-scale investors, while adopting a more realistic approach?

This research recognizes the planning process from the understanding that, currently, several actors can contribute to the design of the DN and the markets if their participation favors and ensures that DN operation conditions are within the standard values. As described in Chapter 3, this research resumes the essence of the planning process admitting that planning the electrical network planning is a matter of decision-making and not only the optimization process.

Chapter 5 provides a methodology for the planning process that contemplates decoupling the planning, operation, and decision-making problems to:

(i) adequately model the operation of the battery under a high temporal resolution to determine operation decisions;

(ii) implement evolutionary methods to explore the search space in useful time and thus solve the problem of sizing, locating, network interface and battery technology selection under a more realistic network environment; and

(iii) define a decision-making process based on a conciliatory approach in which the BESS owner admits that it can be made a decision that leads to an overinvestment regarding the optimal solution if it would favor the integration of BESS into the DN under the scenario in which DSO evaluates additional criteria to verify the possibility of extracting technical-support-oriented benefits from the storage activity.

In Chapter 5 it is proven that the absolutist perspective imposed on the optimal solution is abandoned to replace it with a more conciliatory perspective in which the decision-making process promotes the participation of more than one decision-maker to reduce the possibility of regretting the “final decision”. That is, finding an economical solution from the owner's perspective that is also technically feasible from the DSO/DISCO perspective. This is why the methodology attempts to capture the essence of a real-life process to formulate it as accessible as possible to the understanding of broader stakeholders without compromising the rigor to which the optimization process must be subjected

Considering there is enough quantifiable information about input parameters and that they are expressed under an elevated temporal resolution, how can uncertainties surrounding them be managed?

The influence of uncertainties on planning and operational decisions indicates that deterministic models cannot be well admitted for solving a problem that involves an active asset such as a battery. In Chapter 4 and Chapter 5, the Monte Carlo method and scenarios techniques are responsible for providing reliable probabilistic models for the load, PV generation, and energy market price.

For this, before running the Monte Carlo method daily profiles were seasonally grouped to preprocess 365 profiles expressed in 24 periods. Once data is grouped, normalized, and probabilistically organized, PDFs patterns are identified by running a fitting process that aims to define the curve that explains each group. Then, to ensure random behavior conditioned by the parameters of the fitted curves, a set of daily profiles for each season is generated with a probability of occurrence associated as indicated in Figure 5-5. Finally, a scenario comprised of 365 daily profiles, each divided into 24 periods, is generated to ensure random behavior imposed by the PDF that represents the probability of finding a daily profile that refers to a season of the year.

Adopting the scenario generation model ensures larger sampling dispersion condition and supports the management of associated uncertainties. In addition, ensure that a limited set of scenarios can be generated from the same set of raw data available.

Can a BESS profit-making-oriented operation model for BESS be formulated in a way that provides reliable information to the planning problem?

As reported in Chapter 3, batteries can be electrochemical, electrical, and mathematically modeled. In optimization problems, mathematical models are well accepted. Considering the influence of BESS operation when integrated into the DN, in Chapter 4 it is proven that battery performance parameters play a crucial role in identifying battery behavior and ensuring the reliability of the information provided to the planning problem.

After analyzing three market prices scenarios, it is demonstrated that revenue stream and operation cycles are overestimated when ideal battery models are used, which influences planning tasks. For example, for non-ideal battery models operating under a price arbitrage, reductions between 60% and 10% in revenue streams and between 70% and 30% in operation cycles were determined, which occurs because the optimal operation decisions are naturally conditioned by BESS efficiency. Regarding the provision of simultaneous services, it is also proven that providing simultaneous services such as price arbitrage and tertiary reserve does not increase revenue streams, therefore, “provides simultaneous services to increase revenue stream" cannot be stated as a rule.

Adopting the battery operation model and the price scenarios generation model proposed here provides reliable information to planners, decision-makers, and investors about the feasibility of the revenue model given it is proven that the battery revenue stream and lifespan are dependent on both battery performance parameters and the market prices, and thus, under a non-prohibitive batteries installations cost scenario, the profitability of the business model can vary according to the market conditions.

How can BESS be adequately integrated into the DN planning and operation problem, to obtain benefits from the perspective of small-scale investors?

BESS integration into the DN needs to address the characteristics of the network and the devices. Both may ensure an adequate quantification of the impacts and benefits of the problem approached. Therefore, modeling the distributed generation resources and load already integrated and the DN under an AC model is essential for an adequate assessment of the parameters of the network behavior. Then, the optimal battery size, location, network interface, and technology selection are achieved by fulfilling both network and batteries.

It is demonstrated that a hybrid approach based on Evolutionary Particle Swarm Optimization (EPSO) at an upper-level (sizing, location, network interface, and technology selection) and Linear Programming (LP) at a lower level (battery operation over time) provides the robustness required to solve the BESS planning problem when integrated into the DN with distributed PV generation already integrated. Analyses demonstrated that hybrid formulation between this powerful evolutionary programming and linear programming achieves the optimal solution within a confidence interval of 95%.

It is also demonstrated that distributed batteries were mostly privileged over a concentrated location. Concerning battery technology selection, a mix of network interfaces and technologies was selected, instead of a single option. Nevertheless, Li.-ion remained the most common technology chosen.

6.3 Perspective of Future Research Opportunities

This section outlines pathways for future research given the potential evolution of the methodological framework. The subject addressed in this research was somehow ambitious. Although a few aspects were not treated as deeply as expected, it was a conscious choice that aimed not to overshadow the basic essence of the research. The main directions for future subjects are suggested as follows:

(i) First of all, it is almost mandatory to refer to the **Multicriteria Decision Methods**. It would be possible to extend the research by including extra chapters exploring how to make decisions in the presence of multiple objectives which, at least, represent the criteria and perspective of two stakeholders/players. As known, these multiple objectives are usually conflicting, thus, the decision is strongly dependent on the preferences of the decision-maker who would solve the conflict within a framework of understanding and mutual comprise. Although Multicriteria Decision Methods are well-mature, the inclusion of such chapters would change the focus of this research because, even without a multicriteria formulation, the methodology proposed for the BESS planning and operation and the decision-making process ensures a framework of understanding and mutual comprise between two stakeholder/players with different objectives, namely economic and technical, providing the advantage that the methodology is accessible to a broader range of stakeholders/players and that the decision could be made for more than one decision-maker.

(ii) The developed planning and operation framework is based on an exhaustive but robust iterative process to explore space search. For this, the planning problem was decoupled from the operation problem to follow a bi-level scheme in which the decisions related to the battery operation, namely charge and discharge decisions, were defined in the lower level, whereas in the upper-level battery size, location, network interface, and technology selection were identified. The advantage of decoupling is represented in the possibility of separately **redefining the** planning and **operation problem**. For example, the battery operation problem could be redefined whereas the planning framework remains as currently defined because the operation tool aims to define the batteries' charge and discharge decisions as a response to a price signal when the operation strategy considered price arbitrage services, and simultaneously a price and load signals when the operation strategy considered simultaneously price arbitrage and tertiary reserve services. However, batteries can provide several applications /services, and then, the operation problem can be reformulated to identify optimal decisions when batteries respond to other signals given that the main objective of this tool is to construct a set of curves that represent optimal charge and discharge decisions, to be provided to the upper-level through the iterative process. On the other hand, **redefining the planning problem** while the operation problem remains as currently defined provides the advantage of considering other methods and techniques to explore the search process for the optimal solution, which could be done by investigating how to improve the algorithms or analyzing the possibility of providing the responsibility of the search process to other methods/techniques to compare it with the one proposed here. Although the essence of this work is the accessibility of the decision-making process to a broader range of stakeholders, it cannot be omitted how important the method and techniques in the search for an optimal solution are.

(iii) Since one of the most relevant challenges of integrating BESS into the power network is related to the adequate representation of battery behavior, **improvements in battery models** could be proposed. This is an important subject to avoid over/underestimation of battery performance, battery lifespan, and revenue streams, and even refine the understanding of the feasibility and profitability of some business models. More accurate battery models to represent the dependence between parameters and some feedback from the industries that have been working on accelerating the knowledge curve about BESS, e.g. future works will be focused on a more detailed battery model that considers different C-rates for the charge and discharge process, the idle/rest time required by some battery technologies after the charge or discharge process, and the capacity degradation effect (represent the dependence between battery SoH and EoL). These modifications to the battery models will provide more accurate information, mainly about the battery revenue model given that without remuneration schemes, presently, the revenue stream the responsible for amortizing repayment of the loan and upfront investment costs.

(iv) Carry out **additional research on the planning and operation procedures currently used by DISCOs in different countries** to better understand the problems that planners and decision-makers are facing to achieve the sustainable transition of their power systems. Identifying their needs would help improve the methodology approached here and even would help to suggest some improvements to the whole process. It is crucial to identify the relevance of planning for contingency or emergency conditions given this type of planning model, which aims to improve reliability, is strongly related to the network conditions and DISCOs criteria. This is the main reason why this research considered reliability as an additional criterion given that accounting for contingency conditions to planning implies that the MV Substations/feeders' capacity is now constrained by their capacity under contingency. Then, contingency scenarios should be modeled according to the relevance of the feeder failure rate/periods and impacts on the consumers (energy not supplied).

The subjects previously pinpointed are far from being thorough given it could be highly possible some of them are being under study, which could be good news for stakeholders/players, planners, and decision-makers because in the absence of incentives, subsidies, or a regulatory framework that remunerate storage activities, batteries are far away to be widely deployed into the power system. Finally, it should be stated that, although the methodology devised proposed a robust tool for the BESS planning and operation into the DN and the conciliatory process intended to represent a better understanding for a broad of stakeholders/players, mainly those with the greatest potential to push forward investments in storage assets, it is still necessary tools that represent the reality of the energy assets process integration to better conditioning the reasoning of the decision-makers.

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APPENDIX A

CLASSIFICATION OF ESS REGARDING THE FORM OF STORING THE ENERGY

This appendix reports on the characteristics that make the different ESS suitable for storing energy. However, it also highlights the challenges they must still overcome concerning the form they store the energy [3], [5], [11], [33], [64], [65].

Table A - 1. Classification of ESS regarding the form of storing energy.

ESS	*Type*	*Advantage*	*Challenge*	*Capacity*	*Calendar life*
Mechanical	Compressed Air (CAES)	- Mature technology - Small sizes than PSH with potential locations widespread - Long-term discharge periods - Lower levelized cost of electricity - Unlimited cycle life	- Finding potential locations for the storage tank - Efficiency improvements - Becoming more environmentally friendly - High capital investment	5MW up to 1GW	40-50 years
	Flywheel (FES)	- Early commercialization stage - Adequate power density - High efficiency - Reduced maintenance cost - Unlimited cycle life	- Energy density improvements - Short-term storage periods - High capital investment - Frictional forces affect FES efficiency	0,1MW up to 20MW	15-20 years

Appendix A: Classification of ESS Regarding the Form of Storing the Energy

ESS	*Type*	*Advantage*	*Challenge*	*Capacity*	*Calendar life*
	Gravity Storage	- Demonstration stage - Adequate efficiency - Reduced environmental Impacts - High energy density - Unlimited cycle life	- Finding potential locations that fill geological requirements - Huge space requirements - High capital investment - The levelized cost of electricity is related to the discharge period	Up to 25MW	30-35 years
	Pumped Hydro (PHS)	- Mature technology - Wide utility-scale uses - Lower levelized cost of electricity - Up to 10h of storage per 24h - Unlimited cycle life - Adequate efficiency	- Suitable geographic features - Available area for installation - Habitat species conservation - Efficiency improvements - High capital investment - Long construction periods	0.1 up to 5GW	50-60 years
Electrical	Super and Ultracapacitor	- Technology in the advanced developing stage - Suitable for short-term applications - High cycle life and RTE	- Lower energy density - Contain toxic and corrosive components - High self-discharge	Up to 0.05MW	10–20 years
	Superconducting Magnetic Energy	- Technology in the commercializing stage - High cycle life and RTE - Suitable for short-term applications	- High investment cost - High self-discharge - Lower energy density	0.1 up to 10MW	20–30 years

Appendix A: Classification of ESS Regarding the Form of Storing the Energy

ESS	Type	Advantage	Challenge	Capacity	Calendar life
Chemical	Hydrogen	- Technology in the advanced developing stage - Wide utility-scale uses High energy density and cycle life - Suitable for long-term applications - Range of cells regarding the type of application	- High investment cost - Low RTE - Expensive catalysts or processing are often required - Suitable geographic features	Up to 60MW	~20 years
Electrochemical (Batteries)	Sodium-Sulfur (NaS	- Relatively Mature technology - Suitable cycle life, Discharge time, RTE and DOD - High energy density - Suitable for utility-scale BESS applications - Low maintenance requirements	- High investment cost - Self-discharge significantly increases as corrosion in insulators occurs. - High-temperature requirements for its operation (>300°C) - Contain hazardous materials that become combustible when combined with water	0.05 up to 8MW	10–20 years
	ZEBRA	- Materials are fully recyclable - Suitable cycle life, Discharge time, RTE and DOD - Higher energy density than NaS technology - Suitable for utility-scale BESS applications - Low maintenance requirements	- High investment cost - Complex manufacturing process - High-temperature requirements for its operation (>300°C) - Self-discharge increases as required by parasitic heating during idle/resting times	Up to 3MW	8-15 years
	Lead-Acid	- Mature technology - Lower investment cost - Suitable response time, Discharge time and self-discharge	- Limited energy density - Short cycle life - Intensive maintenance requirements - Contain materials that make it a non-sustainable technology	Up to 20MW	5-15 years

Appendix A: Classification of ESS Regarding the Form of Storing the Energy

ESS	Type	Advantage	Challenge	Capacity	Calendar life
	Lithium Ion (Li-ion)	- Promising and faster-rising technology - Lightweight and high energy density - Long cycle life and high efficiency - Suitable response time, Discharge time and self-discharge	- High investment cost due to raw materials cost - Need a protection circuit for its safe operation - Thermal runways may lead to environmental concerns - Cycle life is dependent on the temperature	Up to 0.1MW	5-15 years
	Nickel-Cadmium (Ni-Cd)	- Reliable and Mature technology - High energy density - Some materials are being replaced with less toxic ones (e.g. metals) - Suitable response and self-discharge	- Expensive raw materials - Contain materials that make it a non-friendly and non-sustainable technology - Lower cycle life - Memory effects	Up to 40MW	10-20 years
	Vanadium Redox Flow (VRFB)	- Most mature battery flow technology - Long cycle life (considered unlimited) - Suitable for utility-scale BESS applications - Suitable response time, cycle life and self-discharge	- High investment cost - Limitation regarding energy density - Complicated manufacturing process - Potential leakage of electrolytic solutions reduces the RTE	0.03 up to 3MW	10-20 years
	Zinc-Bromine (Zn-Br)	- Technology with advanced development stage - Capable of operating in extreme conditions - Energy/power capacity can individually be scaled up - DOD up to 100%	- Charging efficiency issues - Higher parasitic losses during idle/resting time reduces the RTE - risk associated with highly toxic vapors from bromine leakage	0.05 up to 2MW	5-10 years
	Zinc-Air (Zn-Air)	- Technology in the developing stage - Promising and technically feasible technology - Potentially the least expensive option among metal-air batteries	- Requires more research and efforts to accelerate its maturity stage - Limited marketability due to its lower RTE - Mitigates CO_2 impacts from the air on the cathode and electrolyte - Technology in the developing stage	0.01 up to 1MW	>1 year

Appendix A: Classification of ESS Regarding the Form of Storing the Energy

ESS	*Type*	*Advantage*	*Challenge*	*Capacity*	*Calendar life*
	Iron-Chromium (Fe-Cr)	- Promising technology given its low investment cost and lower toxicity of the electrolyte - Long cycle life	- Technology in the developing stage - Require more research and efforts to accelerate its maturity stage - Limited marketability due to its important loss of capacity	1 up to 10MW	10-15 years
Thermal	Latent Heat	- High energy density - Energy is collected and stored as heat directly - High efficiency - Most phase change materials are non-toxic, with long cycle life - Suitable for being used with solar-thermal power	- High investment cost - Most phase change materials have low thermal conductivity, which results in slow charge and discharge rates - Placed R&D to find new materials and topologies to increase the specific energy - Technology in the developing stage	0.01 up to 1MW	10-30 years
	Sensible Heat	- Technology in the commercializing stage - Most common materials are concrete, cast ceramics, and molten salts - Unlimited cycle life - Suitable self-discharge	- Storage medium is the main concern and defines the storage capacity - Lower efficiency	0.01 up to 10MW	10-30 years
	Thermochemical Heat	- Technology in R&D stage - Higher energy density compared to sensible and latent heat - Unlimited cycle life - Suitable self-discharge	- High investment cost - Lower efficiency in heat transfer between materials	0.01 up to 1MW	10-30 years

APPENDIX B

BESS PLANNING AND OPERATION: OBJECTIVES, UNCERTAINTIES MANAGEMENT, NETWORK MODELING, AND SOLUTION METHODS

This appendix summarizes the available data on planning objectives and constraints, network modeling, uncertainty management, and solution methods for solving the optimal planning problem, collected from the literature reviewed.

Table B - 1. Summary of the reviewed works on BESS planning and operation in the DN.

ESS Technology	*BESS-owner*	*Application*	*Planning Objectives*	*Uncertainties Modeled*	*SoC limits*	*C-rates analyzed*	*Cycling aging considered*	*RTE considered*	*Network Model*	*Solution Methods*	*Test System*	*Ref.*
NE	DISCO	Smoothing voltage fluctuations	S L	Wind generation	NE	NE	NE	NE	Probabilistic AC PF	Weibull PDF Point estimate method Hybrid multi-objective PSO	IEEE 9, 14, 30, 57, and 118-bus	[1]
1, 2, 3, 5,	IEP/A DISCO	Arbitrage Curtailment reduction Loss minimization	S L T	NE	NE	N	Y	70% to 77%	AC OPF	Cost/benefit analysis	Rural DN with 41-bus	[2]
3	DISCO	Peak shaving Voltage support Reliability (ENS)	S L	Load Wind generation	10% - 100%	Y	Y	75%	Probabilistic AC PF	Point estimate method Tabu search PSO	DN-connected 21-node MG	[6]
4	DISCO	Voltage control, Peak shaving Loss reduction	S L	NE	NE	Y	Y	NE	AC PF	Genetic Algorithm PSO	IEEE 33-bus	[16]

Appendix B: BESS Planning and Operation: Objectives, Uncertainties Management, Network Modeling, and Solution Methods

ESS Technology	*BESS-owner*	*Application*	*Planning Objectives*	*Uncertainties Modeled*	*SoC limits*	*C-rates analyzed*	*Cycling aging considered*	*RTE considered*	*Network Model*	*Solution Methods*	*Test System*	*Ref.*
4	DISCO	Smoothing voltage fluctuations Loss reduction	S L	Load PV generation	NE	Y	Y	Y	AC OPF	MILP Hierarchical clustering method (load) Beta PDF (PV generation)	33-bus radial DN 141-bus radial DN	[22]
2,3	DISCO	Wind power curtailment reduction (It is assumed BESS is only charged by the wind power)	S L	Load Wind generation Micro-turbine	20% - 80%	20%	Y	75% 77%	Multiperiod AC OPF	Monte-Carlo embedded differential evolution algorithm	IEEE 15-Bus	[32]
2, 4	DISCO	Load following/leveling Loss reduction	S L	Load PV and wind Market prices	ΔSoC 70%	NE	Y	80% 85%	AC PF	Forecasting models Fuzzy Particle Swarm Optimization	IEEE 15-Bus	[37]
1, 2, 5	DISCO	Price Arbitrage Upgrade Deferral Loss reduction	S L	Load Wind generation	70% - 77%	N	Y	Y	Probabilistic AC PF	Rayleigh PDF Linear Programming Genetic Algorithm	IEEE 33-bus	[39]
1	MG	Load following	S	Wind generation PV generation	Up to 100%	N	Y	Y		Weibull PDF Sources sizing algorithm Battery sizing algorithm	DN-connected MG system	[45]
NE	DISCO	Price arbitrage	S L T C-rate	Load PV generation Electricity Price	NE	Y	N	100%	DC OPF	Monte-Carlo Method Linear Programming EPSO	CIGRE MV DN 15-bus	[53]
NE	IEP/A	Price arbitrage	S L T C-rate	Load PV generation Electricity Price	Up to 100%	Y	N	100%	DC OPF	Monte-Carlo Method Linear Programming DEEPSO	CIGRE MV DN 15-bus	[54]
NE	DISCO	Load leveling Loss reduction	S	Load PV generation	NE	N	N	Y	Forward-Backward Sweep PF	Genetic Algorithm	IEEE 33-bus	[71]
4	DISCO	Peak shaving Voltage regulation	S L		15% - 85%		Y	Y	AC PF	Cost/benefit analysis	Radial GE DN model 16-bus	[75]
NE	IEP/A	Load following Price arbitrage	S		NE	Y	N	75% to 82%		Dynamic Programming	DN-connected Wind+Storage	[95]

1, Sodium-Sulfur; 2, Lead-Acid; 3, Zinc-Bromine; 4, Lithium-Ion; 5, Vanadium- Redox; Y, Yes; N, Not; NS, non-specified; MG, Microgrid; A, Aggregator; IEP, Independent Energy Provider; REC, Renewable Energy Community; S, Size; L, Location; T, Technology selection.

APPENDIX C

ANALYSES OF HISTORICAL DATA OF HYDRO PUMPING UNITS PARTICIPATING IN THE TERTIARY RESERVE IN PORTUGUES MARKET

This appendix summarizes analysis and findings from historical data of pumping storage hydro units that provided tertiary reserve to the Portuguese electrical power system in 2019, 2022, and 2023.

Behavior analysis of hydro pumping units that provide tertiary reserve services is relevant to identifying what a BESS must deal with and how the energy it will provide to the electrical power network could be influenced by its technological parameters.

Figures C–1a, C–2a, and C–3a, and Figures C-1e C–2e, and C–3e show the upward and downward reserve activation profile per hour, respectively, which were determined as a percentage value of the times the pumping units were activated at each period. As a complement, Figures C-1b, C-2b, and C-3b, and Figures C-1f, C-2f, and C-3f show the profile of the range of upward and downward energy activated per hour, respectively, which was determined as a percentage value of the times a range of energy values was activated regarding the historical largest energy reserve calculated from the sum of the energy reserves activated during two or more successive periods between 2019 and 2023. In general, the upward and downward reserve profiles of activations per hour followed slightly similar behaviors every year.

Specifically, the upward reserve profile recorded for 2019 (Figure C-1a) shows that the more frequent activations occurred between periods 2 and 6 during the third and fourth quarters. While 91.5% of the times the upward reserve activated represented up to 6% of the historical largest energy reserve calculated, only 3% represented more than 10% of that historical value (Figure C-1b). Figure C-1e shows that similar to the upward reserve, the more frequent activations of the downward reserve occurred between periods 2 and 6 regardless of the quarter under analysis, however, between periods 15 and 19 important percentages of activations were also recorded. 83% of the downward reserve activations represented up to 6% of the historical largest energy reserve calculated. In contrast, only 6,5% represented more than 10% of that historical value (Figure C-1f).

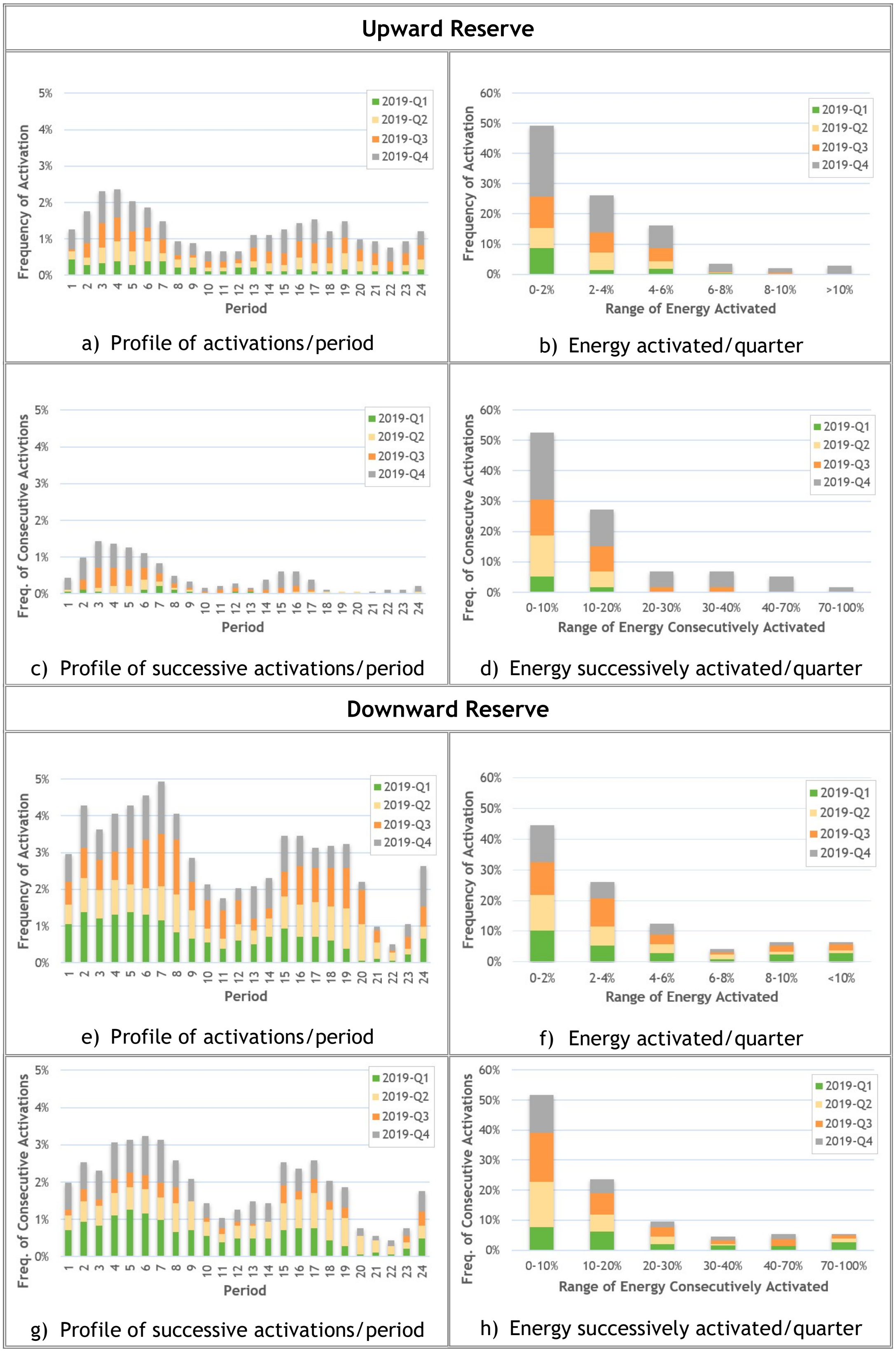


Figure C - 1. Characterization of pumping unit's participation in tertiary reserve in 2019.

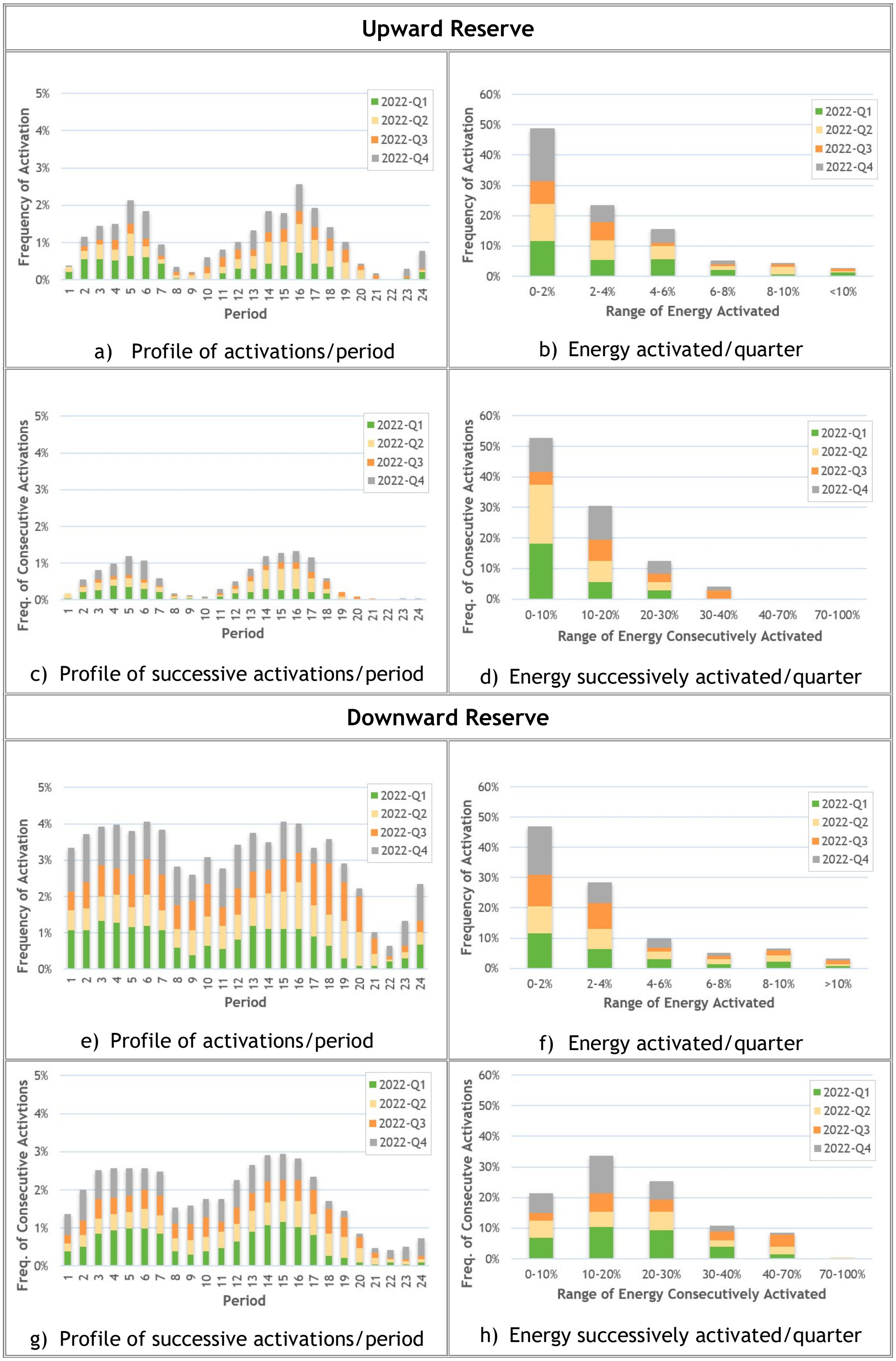


Figure C - 2. Characterization of pumping unit's participation in tertiary reserve in 2022.

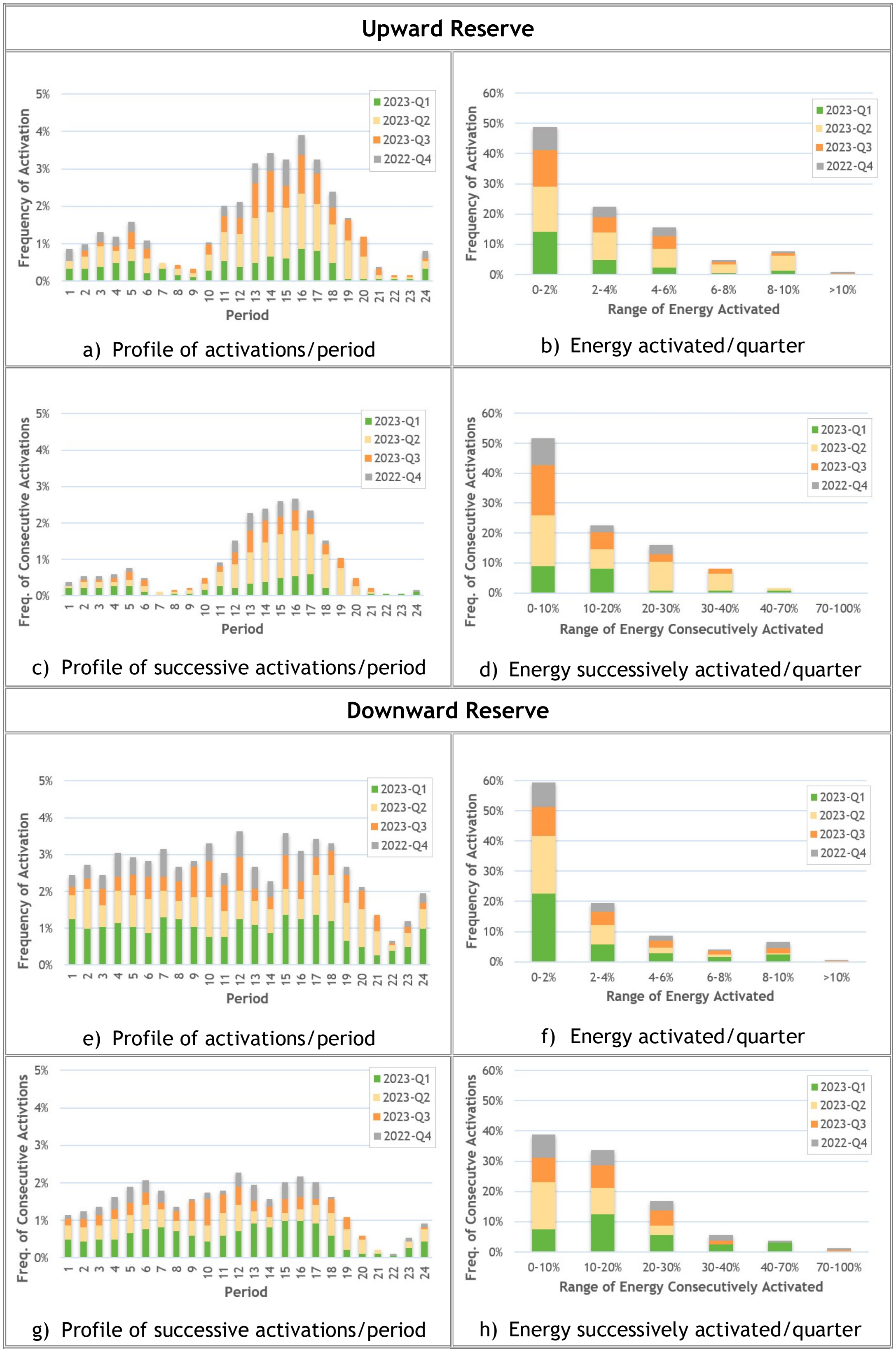


Figure C - 3. Characterization of pumping unit's participation in tertiary reserve in 2023.

The upward reserve profile of activation per hour recorded for 2022 (Figure C-2a) shows that the more frequent ones occurred between periods 3 and 6, and between periods 13 and 18 regardless of the quarter under analysis. 87.5% of the upward reserve activations represented up to 6% of the historical largest energy reserve calculated. But, only 2.5% represented more than 10% of that historical value (Figure C-2b), which occurred in the first quarter. Figure C-2e shows the downward reserve profile of activation per hour was frequently activated throughout the days regardless of the quarter of the year, except for periods 21 to 23 where activations were rarely recorded. Although 85% of the times the downward reserve activated represented up to 6% of the historical largest energy reserve calculated, only 3% represented more than 10% of that historical value (Figure C-2f), which occurred in the first and third quarters.

Concerning 2023, the upward reserve profile of activation per hour (Figure C-3a) shows that the more frequent ones occurred between periods 12 and 18 during the second and third quarters. While 87% of the times the upward reserve activated represented up to 6% of the historical largest energy reserve calculated, Figure C-3b shows that only 0.7% represented more than 10% of that historical value regardless of the quarter. Furthermore, Figure C-3e shows that the downward reserve was frequently activated throughout the days, except for period 22, where a reduced percentage of activations was recorded. 87.5% of the downward reserve activations represented up to 6% of the historical largest energy reserve calculated. Instead, only 0.3% represented more than 10% of that historical value (Figure C-3f), regardless of the quarter.

Figures C-1c, C-2c, and C-3c, and Figures C-1g, C-2g, and C-3g, show the upward and downward reserve profile of successive activation, respectively, which were determined as a percentage value of the times the pumping units were successively activated throughout the year. Figures C-1d, C-2d, and C-3d, and Figures C-1h, C-2h, and C-3h show the profile of the range of upward and downward energy successively activated, respectively, which were determined as a percentage value of the times a range of energy values was successively activated regarding the historical largest energy reserve calculated from the sum of the energy reserves activated during two or more successive periods between 2019 and 2023.

Specifically, the upward reserve profile of successive activations recorded for 2019 (Figure C-1c) shows that similar to the profile in Figure C-1a, the more frequent activations occurred between periods 2 and 7 during the third and fourth quarters. 86.5% of the time the upward reserve was successively activated representing up to 30% of the historical largest energy reserve calculated. But only 1.7% represented more than 70% of that historical value (Figure C-1d), which occurred in the fourth quarter. On the other hand, the downward reserve profile of successive activations (Figure C-1g) shows that this type of reserve was frequently activated between periods 4 and 8 during the first and fourth quarters, nonetheless, between periods 15 and 19 important percentages of successive activations were also recorded. Although 85% of the times the downward reserve successively activated represented up to 30% of the historical largest energy reserve calculated, only 5,3% represented more than 70% of that historical value (Figure C-1h), which occurred in the first and third quarters.

As for 2022, (Figure C-2c) shows the more frequent successive activations of the upward reserve occurred between periods 14 and 17, and between 4 and 6. While 95.8% of the times the upward reserve successively activated represented up to 30% of the historical largest energy reserve calculated, no activations were recorded for more than 70% of that historical value (Figure C-2d). Furthermore, the downward reserve profile of successive activations (Figure C-2g) shows that this type of reserve was frequently activated between periods 12 and 17 regardless of the quarter, nevertheless, between periods 3 and 7 important percentages of activations were also recorded. 80.2% of the time the downward reserve was successively activated representing up to 30% of the historical largest energy reserve calculated. Instead, only 0.5% of the successive activations represented more than 70% of that historical value (Figure C-2h), which occurred in the second quarter.

The upward reserve profile of successive activations recorded for 2023 (Figure C-3c) shows that similar to the profile in Figure C-3a, the more frequent ones occurred between periods 12 and 18 during the third and fourth quarters. 90.3% of the time the upward reserve was successively activated representing up to 30% of the historical largest energy reserve calculated. In contrast, no activations were recorded for more than 70% of that historical value (Figure C-3d). Figure C-3g shows that the downward reserve profile of successive activations was frequently activated throughout the days, except for period 22, where a reduced percentage of activations was recorded. Although 89.4% of the time the downward reserve successively activated represented up to 30% of the historical largest energy reserve calculated, only 0.6% of the activations represented more than 70% of that historical value (Figure C-3h), which occurred in the fourth quarter.

APPENDIX D

ANALYSES OF HISTORICAL DATA ON ELECTRICITY AND REGULATION PORTUGUESE MARKETS

This appendix summarizes analysis and findings from historical data of the Portuguese electricity and regulation market prices in 2019, 2022, and 2023.

Figure D-1 records the percentage value of the electricity and energy prices at each period of the year (every year represented by 8,760 periods) based on the maximum electricity price recorded for the year under analysis.

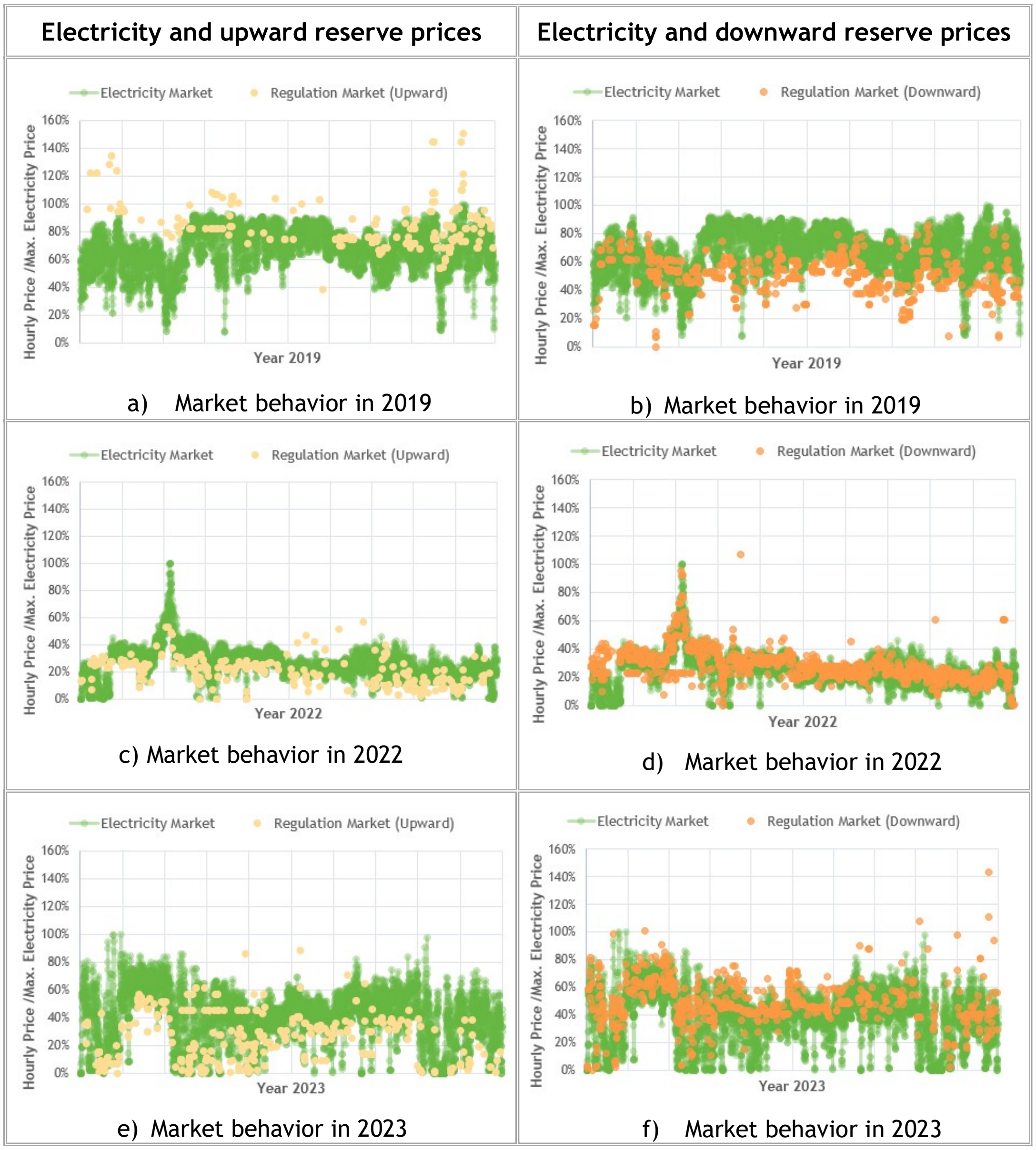
As can be seen in Figure D-1, the price behavior in the regulation market compared to the electricity market over the years has changed their patterns and the amounts at which the energy transactions were executed, which was expected given the changes the electricity and regulation markets have been facing in recent years, as mentioned in Section 4.2.

Specifically, in 2019, electricity market prices never took values equal to zero, and even, in the lowest periods, the price was rarely near zero. Regarding the reserve, the upward and downward activations recorded led to many transactions being executed based on more attractive prices than those reported in the electricity market. From the perspective of a BESS that can trade in both markets, it could be seen as the regulation market represents an opportunity to buy energy/charge the batteries at a lower price or to sell it/discharge the batteries at a higher price.

In 2022 and 2023, electricity market prices frequently took values equal to zero. Even market prices equal to and very close to zero became frequent behavior in 2023. This behavior was caused by supplying the energy demand from generation sources like RES whose marginal cost was equal to zero [120].

Regarding the upward and downward reserve activation, the transactions were made at prices more concentrated within the profile described by the electricity market prices. From the perspective of a BESS that can trade in both markets, it could be seen that the regulation market has been losing its attractiveness, which would lead to carefully analyzing the feasibility of simultaneously participating in both markets.

On the other hand, during these years there has been a notable increase in the need for tertiary reserve provision which could be challenging for a BESS since it must be available to provide the tertiary reserve requirements.



a) Market behavior in 2019
b) Market behavior in 2019
c) Market behavior in 2022
d) Market behavior in 2022
e) Market behavior in 2023
f) Market behavior in 2023

Figure D - 1. Historical electricity and regulation market prices behaviors over the year 2019,2022, and 2023.

APPENDIX E

TEST SYSTEMS FOR CASE STUDIES

This appendix summarizes information about the test system used as case studies to assess the planning methodology proposed in Chapter 5.

Figure E-1 shows the network configuration for both, a) the CIGRE MV Distribution Network Benchmark modified and b) IEEE 33-bus system.

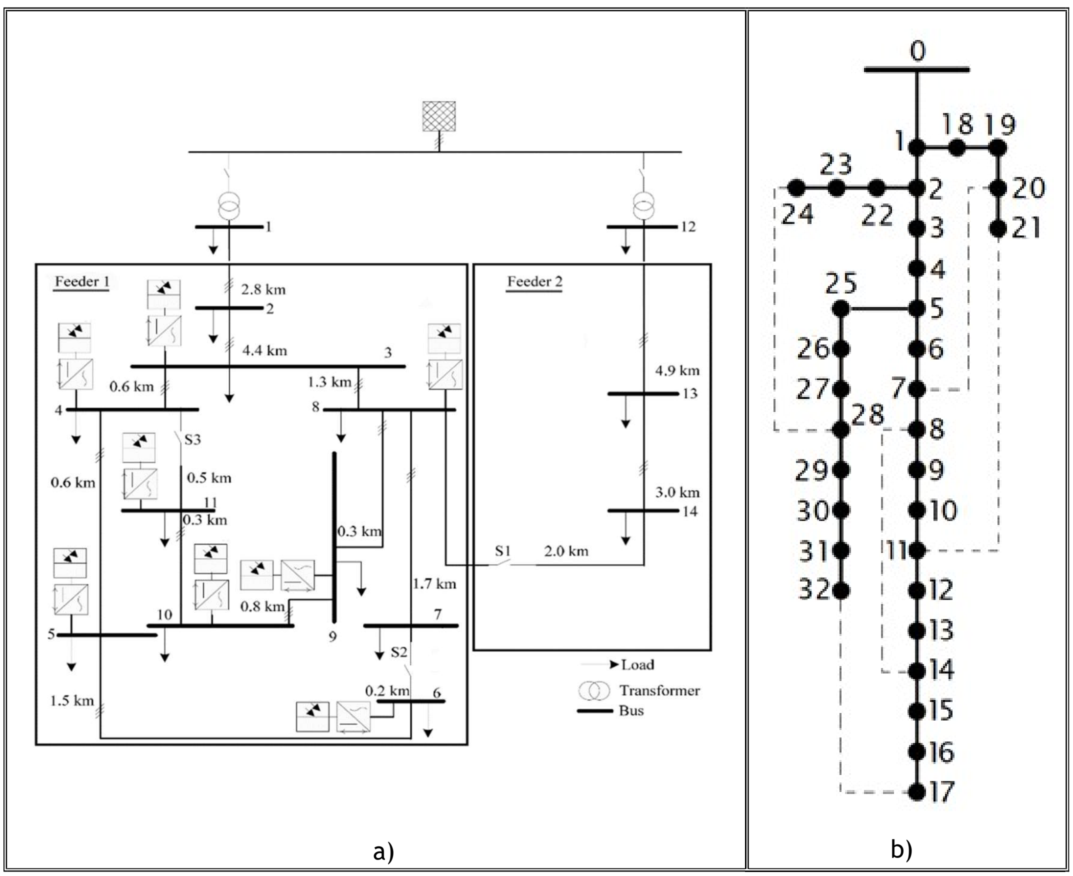


Figure E - 1. Test systems (a) CIGRE MV Distribution Network Benchmark modified and (b) IEEE 33-bus system

(i) **CIGRE MV Distribution Network Benchmark:** this test system is used in the European configuration [81]. It is operated with 20 kV of nominal voltage and is composed of

2 feeders and 15 buses. An external grid at 110kV is located at the bus registered as 0 (see Figure E-1a). Feeder 1 (F1) and Feeder 2 (F2) are fed via separate transformers connected to the same 110kV substation.

This network has total power consumption of 11.88 MVA for commercial loads and 34.29 MVA for residential loads. In normal operating conditions this test system operates on the radial topology, nevertheless, switches S1, S2, and S3 can introduce a variety of configurations used by the DN operator to reduce the energy not supplied under contingencies scenario (to transfer load between faulted areas to healthy areas).

Some modifications were proposed to adapt this network to the test subject, namely the L1-2 and L2-3 in F1 were modified to be similar to L12-13 in F2 (thus, equaling the feeders' nominal capacity)

(ii) **IEEE 33-bus system:** This test system is composed of 1 feeder, 3 branches, and 33 buses. Under normal conditions, this test system operates on radial topology, but the tie lines can introduce a variety of configurations used by the DN operator to reduce the energy not supplied under contingencies scenarios.

Some modifications were proposed to adapt this network to the test subject: (i) the configuration used is the one specified in [136] (nevertheless, the radial topology is ensured); (ii) all consumers (commercial and residential loads identified by their consumption) connected to the feeder and branches comprises a REC; (iii) REC already owns dispersed PV generation optimally located according reported in [100]; and (iv) both commercial and residential loads are considered as balanced.