



Doctoral Thesis

Medium-term technical and economic analysis of storage
impacts on power systems under different scenarios with a high
renewable share

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Declaration

I, Sébastien Huclin, the undersigned, hereby declare that the present Ph.D. thesis work has been prepared by myself and without any unauthorized help or assistance. Only the specified sources (references, tools, etc.) were used. To improve the clarity and flow of my work, I have utilized various AI tools, such as ChatGPT, Grammarly, and Writefull. I have reviewed the output generated by these tools to ensure it accurately conveys my intended message and is free of grammatical errors. Additionally, all parts taken from other sources, word by word or after rephrasing but with identical meaning, were unambiguously identified with explicit reference to the sources utilized.

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Abstract

At the heart of the global efforts to combat climate change, as delineated by the Paris Agreement, lies the urgent need to curtail greenhouse gas emissions, with the energy sector playing a pivotal role. This sector, traditionally a significant contributor to carbon emissions, stands at the threshold of a transformative journey. The Agreement, through its nationally determined contributions, aims to diminish greenhouse gas emissions across various economic sectors. Within the energy domain, this commitment heralds a paradigm shift towards more sustainable, low-emission energy systems, pivoting away from the reliance on fossil fuels. This transition is not without its challenges, as integrating variable renewable energy sources (VRESs) into the energy mix introduces a new dimension of inflexibility, marked by fluctuations in energy availability vis-à-vis electricity demand.

The quest for a sustainable energy future, characterized by a high penetration of VRES, brings to the fore the critical issue of power system flexibility. This new energy landscape, marked by the intermittent nature of VRES, necessitates a power system that can swiftly adapt its generation or consumption in response to supply or demand variability. Traditional power system regulatory frameworks, designed in an era dominated by fossil fuels, often fall short in accommodating the uncertainty and variability introduced by VRES and the emerging solutions aimed at enhancing system flexibility. The challenge lies in ensuring the power system's flexibility and adequacy in the face of significant VRES penetration, a challenge that calls for innovative solutions in energy storage, demand response programs, and regulatory reforms to incentivize the provision of flexibility, thereby ensuring the efficient and reliable operation of power systems.

The comprehensive review of existing studies and methodologies reveals several critical deficiencies in the current models for representing power systems with a substantial integration of VRES especially within a medium-

term time scope. There emerges a pronounced need for models that adeptly manage both energy and balancing services, distinguishing clearly between the operating reserve (i.e., power) and the actual activation of the operating reserve (i.e., energy). This delineation is crucial for assessing the roles of energy storage systems (ESSs) and their impacts on power system operations in scenarios dominated by renewable energy sources.

The thesis is based on a medium-term power system operation model. Such a model must maintain the chronological sequence and coherence of input data series, a cornerstone for ensuring the accuracy and reliability of power system operation models. This requirement addresses the critical gap in modeling the operation of power systems, ensuring that the temporal aspects of energy generation and consumption are accurately represented. Additionally, the accurate modeling of diverse ESSs is highlighted, considering their different storage durations and roundtrip conversion efficiencies. This aspect is paramount for evaluating their impact on the operation of power systems. The intricacies of ESS, from short-duration batteries to long-term Pumped Storage Hydro (PSH), play a pivotal role in balancing the intermittency of renewable energy sources, thus requiring meticulous modeling to capture their operational nuances. The need to develop an intricate hydrothermal operation planning model is also underscored. Such a model should accurately simulate market operations, especially for Hydro Storage, and model PSH as separate physical entities. This distinction is crucial for understanding the unique contributions of hydro storage technologies to the flexibility and adequacy of the power system. Moreover, there is a call for a novel approach that captures the behavior of different technologies in offering operational flexibility and adequacy. This approach should traverse various time scales and address multiple power system scarcities, which complicate the integration of VRES. Understanding how different technologies can meet these demands is crucial for optimizing the power system's operational strategy in a renewable-dominated landscape. Lastly, an urgent call for analysis of the competition between and within technologies in providing assorted wholesale system services is made. This analysis is vital for highlighting how technologies can optimize their roles and contributions in renewable-dominated power systems. The competition and complementarity between distinct dispatchable technologies shape the operation of power systems, influencing their ability to integrate renewable energy sources effectively. This comprehensive understanding is imperative for guiding policy, regulatory reforms, and technological advancements in the journey towards

a sustainable and reliable energy future.

The innovative methodology, designed specifically for this research, aims to meticulously assess flexibility requirements, evaluate the contributions of various technologies to system flexibility, and gauge their impact on the power system's overall adequacy. Its distinctive attribute lies in its scalability and replicability, enabling its application across diverse scarcity scenarios and suitability for any electricity system. This universal applicability is achieved through the methodology's reliance on hourly time series data, which includes load demand, outputs from VRES, and the technical characteristics of generation and storage systems, serving as the fundamental inputs.

The methodological approach begins with the ex-ante analysis, which determines the power system's flexibility requirements. This phase sets the stage for the application of a medium-term operation model, designed to represent the power system's operation across a one-year time scope with an hourly time step, incorporating considerations for wholesale flexibility services. The final stage, the ex-post analysis, involves a detailed examination of the model's outputs, focusing on calculating capacity values and contributions to flexibility. These pivotal calculations are rooted in the capacity factor approximation-based method and a novel methodology for assessing contributions to flexibility, which collectively underpin the analysis. Central to this methodology is the time series decomposition module, a sophisticated analytical tool that plays a crucial role in discerning the requirements for, and contributions to, flexibility across various time scales. This module employs a frequency analysis method, adept at identifying and quantifying the distribution of variations across different periodicities within the net load demand and technology outputs.

The development of this comprehensive methodological framework is a response to the European Commission's directives, emphasizing the critical importance of simultaneously considering flexibility aspects across multiple time scales as well as adequacy issues in the context of renewable energy integration. Moreover, it addresses the growing call from industry experts and regulatory bodies for incorporating flexibility considerations into power system adequacy assessments. By doing so, this methodology offers a robust and adaptable tool for navigating the complexities of managing modern electricity systems, particularly in scenarios characterized by high shares of VRES. This alignment with regulatory directives and the methodology's innovative design underscore its potential to significantly contribute to the field, providing a valuable asset for enhancing the adaptability and resilience of power

systems in the face of increasing renewable integration.

This thesis meticulously crafts a series of scenarios for the year 2030, drawing inspiration from the Spanish National Energy and Climate Plan (NECP)'s scenario with its ambitious target of generating 81% of its electricity from VRES by 2030. At the heart of these scenarios is the exploration of the pivotal role that ESSs are poised to play within the future landscape of 2030. The foundation for this investigation is the construction of a Base Case (BC), which utilizes average water inflow data from 2015 as a reference point. This approach not only grounds the study in a technologically neutral framework but also paves the way for an equitable comparison of ESS across both short- and long-term operational timelines.

Integral to the BC are scenarios that consider operating reserves to assess how a detailed modeling of these reserves might influence the analysis of ESS. Moreover, the thesis includes ramping services—a novel consideration in the Spanish power system—eager to uncover potential impacts and benefits these services may herald for the electricity system at large and the role of ESS within it. Additionally, a particularly compelling scenario, the *Dunkelflaute* (i.e., anticyclone), delves into the power system's resilience during critical periods marked by high demand but an absence of wind generation coinciding in winter when solar radiation is low. This scenario not only tests the system's operational robustness but also accentuates the crucial role of ESS in maintaining system reliability under such extreme conditions. Finally, given Spain's significant dependence on hydropower, the thesis embarks on a systematic exploration of the system's sensitivity to fluctuating water inflow conditions. This sensitivity analysis is instrumental in identifying potential scarcities within the power system, which is crucial for the holistic understanding of system vulnerabilities and resilience. Collectively, these scenario analyses, rooted in the objectives laid out by the NECP, embark on a forward-looking journey to dissect the medium-term impacts of ESS within a renewables-dominated Spanish power system. By doing so, the thesis not only aligns with the overarching goals of the NECP but also charts a course for the future, envisioning a power system that is both resilient and capable of embracing the variability and uncertainty inherent in the transition to renewable energy sources.

The study places a special emphasis on the energy storage capacity as a pivotal factor in determining the adequacy contributions of ESS technologies. It shows that Open-Loop Pumped Storage Hydro (OLPSH), with its capacity for water pumping, showcases a superior contribution to system adequacy

compared to Closed-Loop Pumped Storage Hydro (CLPSH) units, which are limited by their lower energy storage capacity. Within this context, batteries, despite their relatively smaller energy capacity, are highlighted as key players in the balancing market, underpinning the system's reliability. Indeed, according to BC's results, the income per capacity of batteries based on the services they provide is 14% higher than that of CLPSH. Thus, although batteries play a smaller role in matching demand, their active participation in the reserve market means that other controllable technologies are still available for critical times. This differentiation underscores the diverse roles that various storage technologies can occupy within a renewable-dominated power system, highlighting the need for a nuanced understanding of their operational and adequacy contributions. Another pivotal contribution is the detailed scrutiny of different ESS under a spectrum of critical scenarios, ranging from variations in water inflow conditions to examine the system's resilience under the Dunkelflaute scenario. This multifaceted analysis enriches the understanding of the complex roles that storage technologies assume under varying environmental and operational conditions, offering a deep dive into how these technologies can both complement and compete within the power system to boost reliability and efficiency.

An integral aspect of this research is the incorporation of ramping services into the operational model, marking a significant stride in understanding the complex roles of dispatchable technologies in providing an array of power system services. The novel integration of ramping services prompts a recalibration in the operation of batteries, enhancing their contributions to energy and ramping services. This adaptation, in turn, enables OLPSH to bolster its availability during critical periods, thereby supporting system adequacy and illustrating the intricate interplay within the power system. Moreover, the exploration of the economic and operational impacts of ramping services uncovers insights into the intricate relationships among dispatchable technologies within the power system and the potential for a redistribution of revenue among them. These insights accentuate the critical importance of including such services in medium-term operational planning, especially in scenarios characterized by a high penetration of renewable energy.

Resumen

En la lucha contra el cambio climático, tal como lo establece el Acuerdo de París, yace la necesidad urgente de limitar las emisiones de gases de efecto invernadero, desempeñando el sector energético un papel crucial. Este sector, tradicionalmente un significativo contribuyente a las emisiones de carbono, está al umbral de un viaje transformador. El Acuerdo, a través de sus contribuciones determinadas a nivel nacional, pretende disminuir las emisiones de gases de efecto invernadero en varios sectores económicos. Dentro del sector energético, este compromiso anuncia un cambio de paradigma hacia sistemas energéticos sostenibles y de bajas emisiones, alejándose de la dependencia de los combustibles fósiles. Esta transición no está exenta de desafíos, ya que la integración de las energías renovables variables (VRES, por sus siglas en inglés) en el mix energético introduce una nueva dimensión de inflexibilidad, marcada por la incertidumbre de la disponibilidad de las VRES frente a la demanda eléctrica.

La búsqueda de un futuro energético sostenible, caracterizado por una alta penetración de las VRES, pone de relieve la cuestión crítica de la flexibilidad del sistema eléctrico. Este nuevo paisaje energético, marcado por la naturaleza intermitente de las VRES, exige un sistema eléctrico que pueda adaptar rápidamente su generación o consumo en respuesta a la variabilidad de la oferta o la demanda. Los marcos regulatorios de sistemas eléctricos tradicionales, diseñados en una era dominada por combustibles fósiles, se quedan cortos al acomodar la incertidumbre y variabilidad introducidas por las VRES y las soluciones emergentes destinadas a mejorar la flexibilidad del sistema. El desafío radica en asegurar la flexibilidad y la firmeza del sistema eléctrico frente a una penetración significativa de VRES, un desafío que requiere soluciones innovadoras en almacenamiento de energía, programas de respuesta de demanda y reformas regulatorias para incentivar la provisión de flexibilidad, asegurando así la operación eficiente y confiable de los sistemas

eléctricos.

La revisión exhaustiva de estudios y metodologías existentes revela varias deficiencias críticas en los modelos actuales para representar sistemas eléctricos con una integración sustancial de VRES, especialmente dentro de un alcance temporal de medio plazo. Surge una necesidad pronunciada de modelos que gestionen hábilmente tanto la energía como los servicios de balance, distinguiendo claramente entre la potencia solicitada para la reservas de operación y la activación de las mismas (i.e., energía). Esta delimitación es crucial para evaluar el rol de los Sistemas de Almacenamiento de Energía (ESS, por sus siglas en inglés) y su impacto en la operación de los sistemas eléctricos en escenarios dominados por fuentes de energía renovable.

La tesis se basa en un modelo de operación del sistema eléctrico de medio plazo. Tal modelo debe mantener la secuencia cronológica y coherencia de las series de datos de entrada, un pilar para garantizar la precisión y fiabilidad de los modelos de operación de sistemas eléctricos. Este requisito aborda la brecha crítica en el modelado de la operación de sistemas eléctricos, asegurando que los aspectos temporales de la generación y consumo de energía estén representados con precisión. Además, se destaca que el modelado distingue entre diversos ESS, considerando sus diferentes duraciones de almacenamiento y eficiencias de conversión durante la carga y la descarga. Las complejidades de los ESS, desde baterías de corta duración hasta almacenamiento hidroeléctrico de bombeo a largo plazo, juegan un papel pivotal en equilibrar la intermitencia de las fuentes de energía renovable, por lo que requieren una representación meticulosa para capturar sus matices de operación. Tal modelo debe simular con precisión las operaciones de mercado, especialmente para el almacenamiento hidráulico en embalses, y modelar el bombeo como entidades físicas separadas. Esta distinción es crucial para comprender las contribuciones únicas de las tecnologías de almacenamiento hidroeléctrico a la flexibilidad y a la potencia firme del sistema eléctrico. Además, se propone un enfoque novedoso que capture el comportamiento de diferentes tecnologías al ofrecer flexibilidad y firmeza. Este enfoque debe abarcar diversas escalas de tiempo y abordar múltiples aspectos críticos del sistema eléctrico, los cuales aparecen en escenarios de alta penetración de VRES. Comprender cómo diferentes tecnologías pueden satisfacer estas demandas es crucial para optimizar la operación del sistema eléctrico en un escenario dominado por las renovables. Por último, se presenta un análisis de la competencia entre cada las tecnologías controlables para el mismo servicio y para cada una de ellas, al proporcionar diversos servicios al mercado

mayorista del sistema. Este análisis es vital para resaltar cómo las tecnologías pueden optimizar sus roles y contribuciones en sistemas eléctricos dominados por las renovables. La competencia y complementariedad entre distintas tecnologías despachables, configura la operación de los sistemas eléctricos, influenciando su capacidad para integrar fuentes de energía renovable de manera efectiva. Esta comprensión integral es imperativa para guiar la política, reformas regulatorias y avances tecnológicos en el camino hacia un futuro energético sostenible y confiable.

La metodología innovadora, diseñada específicamente para esta investigación, tiene como objetivo evaluar meticulosamente los requisitos de flexibilidad, valorar las contribuciones de varias tecnologías a la flexibilidad del sistema y medir su impacto en la firmeza general del sistema eléctrico. Su atributo distintivo radica en su escalabilidad y replicabilidad, lo que permite su aplicación en diversos escenarios de escasez y su idoneidad para cualquier sistema eléctrico. Esta aplicabilidad universal se logra a través de la dependencia de la metodología en datos de series temporales por hora, que incluyen la demanda de carga, los resultados de las VRES y las características técnicas de los sistemas de generación y almacenamiento, que son los datos de entrada fundamentales.

El enfoque metodológico comienza con el análisis ex-ante, que profundiza en la determinación de los requisitos de flexibilidad del sistema eléctrico. Esta fase prepara el escenario para la aplicación de un modelo de operación a medio plazo, diseñado para representar la operación del sistema eléctrico a lo largo de un año con granularidad horaria, incorporando consideraciones para servicios de flexibilidad del sistema mayorista. En la etapa final, el análisis ex-post, implica un examen detallado de las salidas del modelo, centrándose en el cálculo de valores de capacidad y contribuciones a la flexibilidad. Estos cálculos fundamentales se basan en el método aproximado del factor de capacidad y una metodología novedosa para evaluar las contribuciones a la flexibilidad, que colectivamente sustentan el análisis. Central a esta metodología es el módulo de descomposición de series temporales, una herramienta analítica sofisticada que juega un papel crucial en discernir los requisitos de, y contribuciones a, la flexibilidad a través de diversas escalas de tiempo. Este módulo emplea un método de análisis de frecuencia, necesario para identificar y cuantificar la distribución de variaciones a través de diferentes periodicidades dentro de la demanda neta de carga y las producciones de las tecnologías.

El desarrollo de este marco metodológico integral es una respuesta a las

directivas de la Comisión Europea, enfatizando la importancia crítica de considerar aspectos de flexibilidad a través de múltiples escalas de tiempo en el contexto de la integración de energía renovable. Esta alineación con directivas regulatorias y el diseño innovador de la metodología subrayan su potencial para contribuir significativamente al campo, proporcionando un activo valioso para mejorar la adaptabilidad y resiliencia de los sistemas eléctricos frente a la creciente integración de renovables.

Esta tesis elabora meticulosamente una serie de escenarios para el año 2030, inspirándose en el escenario del Plan Nacional Integrado de Energía y Clima (PNIEC) de España con su ambiciosa meta de generar el 81% de su electricidad a partir de VRES para 2030. En el corazón de estos escenarios se encuentra la exploración del papel pivotal que se prevé jugarán los ESS en el paisaje futuro de 2030. La base para esta investigación es la construcción de un Caso Base (BC), que utiliza datos promedio de aportaciones de agua de 2015 como punto de referencia. Este enfoque no solo fundamenta el estudio en un marco tecnológicamente neutral sino que también allana el camino para una comparación equitativa de los ESS a través de líneas de tiempo operativas tanto a corto como a largo plazo, desentrañando los impactos matizados que las diferentes dinámicas operativas pueden ejercer en el rendimiento de los ESS.

Integral al BC son escenarios que consideran las reservas de operación, para evaluar cómo un modelado detallado de estas reservas podría influir en el análisis de los ESS. Además, la tesis incluye de servicios de rampa, una consideración novedosa para el sistema eléctrico español, para evaluar impactos y beneficios potenciales que estos servicios puedan anunciar para el sistema eléctrico en general y el papel de los ESS dentro de él. Adicionalmente, un escenario particularmente convincente, la Dunkelflaute o anticiclón, profundiza en la resiliencia del sistema eléctrico durante períodos críticos marcados por una alta demanda pero ausencia de generación eólica que sucede además en invierno donde la radiación solar es baja. Este escenario no solo pone a prueba la solidez operativa del sistema sino que también subraya el papel crucial de los ESS en mantener la firmeza del sistema bajo tales condiciones extremas. Finalmente, dado la dependencia significativa de España en la hidroelectricidad, la tesis considera condiciones fluctuantes de la hidráulidad. Este análisis de sensibilidad es instrumental para identificar posibles criticidades dentro del sistema eléctrico. Colectivamente, estos análisis de escenarios, arraigados en los objetivos establecidos por el PNIEC, emprenden un viaje prospectivo para diseccionar los impactos a medio plazo de los

ESS dentro de un sistema eléctrico español dominado por renovables. Al hacerlo, la tesis no solo se alinea con los objetivos generales del PNIEC sino que también traza un curso para el futuro, imaginando un sistema eléctrico que es a la vez resiliente y capaz de manejar la variabilidad e incertidumbre inherente en la transición a fuentes de energía renovable.

El estudio pone un énfasis especial en la capacidad de almacenamiento de energía para determinar las contribuciones a la firmeza del sistema de las tecnologías de ESS. Se evidencia que el Bombeo Mixto, con sus aportaciones hidráulicas, muestra una contribución superior a la firmeza del sistema en comparación con las unidades de Bombeo Puro, que están limitadas por su menor capacidad de almacenamiento de energía. Dentro de este contexto, las baterías, a pesar de su capacidad energética relativamente menor, se destacan como actores clave en el mercado de reservas. Efectivamente, según los resultados del BC, los ingresos por capacidad de las baterías en función de los servicios prestan son un 14% superiores a los de Bombeo Puro. Así, aunque las baterías desempeñan un papel menor en la satisfacción de la demanda, su participación activa en el mercado de reserva permite a otras tecnologías controlables estar disponibles para los momentos críticos. Esta diferenciación pone de manifiesto los roles que diversas tecnologías de almacenamiento pueden ocupar dentro de un sistema eléctrico dominado por renovables, resaltando la necesidad de una comprensión matizada de sus contribuciones a la operación y a la firmeza del sistema. Otra contribución esencial es el escrutinio detallado de diferentes ESS bajo un espectro de escenarios críticos, que van desde variaciones en las condiciones de entrada de agua hasta examinar la resiliencia del sistema bajo el escenario Dunkelflaute. Este análisis multifacético enriquece la comprensión de los roles de las tecnologías de almacenamiento bajo diversas condiciones ambientales y operativas, ofreciendo una inmersión profunda en cómo estas tecnologías pueden complementarse y competir dentro del sistema eléctrico para mantener la firmeza y la flexibilidad del sistema eléctrico.

Un aspecto innovador de esta investigación es la incorporación de servicios de rampa en el modelo de operación y su importancia económica, permitiendo entender los roles complejos de las tecnologías despachables en la provisión de una gama de servicios del sistema eléctrico. La integración novedosa de servicios de rampa exige una recalibración en la dinámica operativa de las baterías, mejorando sus contribuciones a los servicios de energía y rampa. Esta adaptación, a su vez, permite al bombeo mixto reforzar su disponibilidad durante períodos críticos, apoyando así la potencia firme del sistema e

ilustrando la interacción compleja dentro del sistema eléctrico. Además, la exploración de los impactos económicos y sobre la operación, de los servicios de rampa descubre percepciones sobre las relaciones intrincadas entre tecnologías despachables dentro del sistema eléctrico y el potencial de redistribución de ingresos entre ellas. Estos conocimientos acentúan la importancia crítica de incluir tales servicios en la planificación de la operación a medio plazo, especialmente en escenarios caracterizados por una alta penetración de energía renovable.

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Acronyms

BC Base Case.

CCGT Combined Cycle Gas Turbines.

CLPSH Closed-Loop Pumped Storage Hydro.

DFT Discrete Fourier Transform.

EFC Equivalent Firm Capacity.

EFOR Expected Forced Outage Rate.

ELCC Effective Load Carrying Capability.

ESS Energy Storage System.

IRENA International Renewable Energy Agency.

MIP Mixed Integer Problem.

NECP National Energy and Climate Plan.

OLPSH Open-Loop Pumped Storage Hydro.

PCI Project of Common Interest.

PSH Pumped Storage Hydro.

REE Red Eléctrica de España (Spanish system operator).

RoR Run-of-River hydro power plant.

RS Ramping Services.

SEED Spanish Electricity and Economic Dispatch.

SO System Operator.

Solar PV Solar photovoltaic.

SoS Security of Supply.

TYNDP Ten-Year Network Development Plan.

VRES Variable Renewable Energy Source.

Chapter 1

Introduction

1.1 Background and Context

As the Paris Agreement states, the global imperative to combat climate change underscores the urgency of reducing greenhouse gas emissions [1]. Central to this effort is transforming the energy sector, historically a significant contributor to carbon emissions. The Paris Agreement, through its nationally determined contributions (NDCs), establishes a framework for global cooperation, aiming to achieve substantial reductions in greenhouse gas emissions in several economic sectors. In the context of the energy sector, this global commitment signifies a paradigm shift in energy production and consumption patterns, necessitating a move away from fossil fuel-based energy systems towards more sustainable, low-emission alternatives.

Integrating variable renewable energy sources (VRES) is essential for the energy transition. VRESs are non-dispatchable and, therefore, introduce additional inflexibility into power systems, creating energy surplus or deficit periods relative to electricity demand. This shift introduces significant challenges, primarily due to the instantaneous nature of electricity generation and the inherent variability and uncertainty associated with VRES, such as wind and solar power, making the task of continuously matching VRES generation and demand harder. The power system requires enhanced flexibility to counterbalance this complexity. Flexibility in this context refers to the ability of a power system to rapidly adjust generation or consumption in response to variability in supply or demand [2]. The flexibility aspect is critical in maintaining the electricity supply and ensuring a reliable power system in

the context of the high shares of VRES [3].

Addressing flexibility challenges requires a variety of solutions. In this regard, Energy Storage Systems (ESSs), such as batteries and Pumped Storage Hydro (PSH), have emerged as key technologies. By storing excess energy during periods of high VRES output and releasing it when demand exceeds supply, ESSs play a vital role in balancing VRES inflexibility. Additionally, improvements in power systems, such as demand response programs and increased interconnection capacities, improve the global flexibility of power systems [4]. Furthermore, the integration of VRES calls for adaptations in regulatory frameworks. Traditional regulatory structures designed for fossil fuel-based power systems often lack the provisions necessary to accommodate the unique characteristics and requirements of VRES and emerging flexibility solutions. Over the past 25 years, significant regulatory revisions have been made, particularly in countries like Spain, to better integrate VRES into the power system. However, ongoing reforms are still required to fully deploy flexibility solutions, further integrate VRES, and incentivize technology that provides the necessary flexibility for efficient and reliable power system operations [5].

The Spanish power system presents a compelling case study in this context. By 2030, the country aims to generate 81% of its electricity from VRESs, as it has committed to an ambitious renewable energy target [6]. To achieve this target, the Spanish power system will rely on a heterogeneous mix of ESS technologies, such as batteries and hydro storage, to cover flexibility requirements on several timescales. These goals align with the European Union's directives and the Paris Agreement's objectives. However, the high penetration of VRES into Spain's energy mix introduces significant challenges to the flexibility and reliability of the power system. The Spanish power system is a relevant case study for examining the technical and economic impacts of storage operation within a medium-term time scope in a scenario of high shares of VRES.

1.2 Motivations

In the context of increasing shares of VRES, the need for enhanced methods to assess flexibility and adequacy in power systems represents active research, as stated by several institutions. The authors in [7] underline the importance of considering operational flexibility when evaluating power systems'

adequacy. Traditional methods designed to assess the adequacy of power systems based on fossil fuel technologies often need to capture the flexibility contributions in the context of a high share of VRES. This deficiency becomes more pronounced when considering the various timescales of variability in the generation and demand of VRES, such as seasonal, monthly, weekly, daily, and hourly fluctuations. The authors in [2] demonstrate that demand and VRES generation present several cycles of variations recurring at different frequencies, ranging from a few hours a day to a season or even several years.

Comprehensively analyzing ESS roles requires studying how ESS behave according to the several variations cycles present in load demand and VRES patterns, from short- to long-term time scope. Therefore, focusing on medium-term impacts is relevant given that the medium-term time scope can encompass VRES integration challenges according to short- and long-term time scope [8]. Additionally, given the additional contributions that flexible technology can provide, the research on developing new approaches to analyze technology's flexible behavior is crucial. Addressing this gap is critical to ensure the economic sustainability of renewable energy transitions.

Although ESSs appear essential for managing the intermittency and variability of VRES, they present unique challenges in modeling. They must balance the need for immediate response to unforeseen variations and the storage of enough energy to maintain the adequacy of power systems during critical events with long-term energy storage requirements while considering economic viability and system efficiency. Addressing these challenges requires a deep understanding of the operational characteristics of various ESS technologies, their interactions, and their optimal integration within the power system, a crucial aspect in enhancing the flexibility and adequacy of power systems. Given the disparity in the time scales covered by different ESSs, a medium-term operation model would represent a technology-neutral tool and facilitate an equitable evaluation and comparison of the roles of batteries, which possess short-term storage characteristics, and other ESSs, such as PSH, capable of energy storage across multiple seasons.

Understanding how technologies compete and collaborate to address the multi-scaled variability of VRESs is crucial for optimizing system performance and efficiency. This gap in understanding competition and collaboration between technologies, particularly in medium-term operation models, is essential for developing strategies that effectively manage the intermittent nature of VRES.

1.3 Research Objectives and Questions

The research questions and objectives of this Ph.D. thesis are closely related to the critical research gaps identified in Section 1.2 regarding the roles of ESSs in integrating VRES into power systems. These gaps highlight vital areas that require more profound understanding and innovative approaches, which guide the focus of this research. The questions formulated aim to address these gaps and contribute significantly to the body of knowledge in this rapidly evolving domain.

- **What role will ESSs play in scenarios involving high shares of VRES?** This question arises from the need to explore the impact and optimization of ESS technologies in power systems characterized by high VRES penetration. Given the intermittency and variability inherent in VRESs, understanding the role of ESS is crucial to maintaining the stability and efficiency of the power system. This research will delve into the operation of various ESS technologies and analyze their roles in supporting power system adequacy and flexibility in high VRES scenarios.
- **What new methodologies can be developed to assess flexibility and adequacy contributions in scenarios with high VRES shares?** This question focuses on developing new approaches to assess the flexibility and capacity value of power systems increasingly dominated by VRES. The aim is to create advanced methodologies that accurately reflect all the contributions of technologies in terms of flexibility and adequacy, considering the various scales of variability inherent in VRESs.
- **what are the economic impacts of VRES integration on the operation of power systems?** This question seeks to fill the gap in understanding the economic effects of VRES integration on power system operations and new services to incentivize technologies to provide flexibility. It involves an in-depth analysis of how introducing new system services in the context of VRES integration transforms revenue streams and impacts the financial viability of different ESS technologies.

By addressing these research questions, the thesis endeavors to provide new insights and solutions on the roles of ESS technologies, mainly focusing

on the challenges and opportunities presented by high shares of VRES in power systems. The aim is to contribute valuable knowledge and strategies for the efficient and sustainable integration of VRES into existing power infrastructure.

1.4 Contributions

This thesis makes several critical contributions to integrating VRES into power systems, each addressing the critical gaps identified in Section 1.2. These contributions aim to answer the research questions listed in Section 1.3 and reflect the comprehensive nature of the study and its relevance to the study of ESS roles in power systems in the context of high penetration of VRES.

- (C1): Development of comprehensive operation models with a medium-term time scope.** A significant accomplishment of this research is the development and implementation of an operation model that is finely tuned to examine the functions of ESS in power systems with extensive VRES usage. This model accounts for system services in the medium-term operation model, more precisely depicting the adaptable behavior of dispatchable technologies. The emphasis of the analysis is on ESS, providing a comprehensive exploration of their contributions to power systems with high VRES penetration.
- (C2): Analysis of flexibility and adequacy in renewable energy systems.** In this study, a new method is presented to evaluate the effectiveness of dispatchable technologies in maintaining flexibility and adequacy in power systems. The goal is to understand better how these systems can manage the variability and uncertainty introduced by VRES generation. This research is crucial for advancing the need to update investment signals and regulatory frameworks related to ESS technologies in renewable-dominated systems.
- (C3): Case studies on the Spanish electricity system.** A significant contribution of this thesis is the application of the developed model and methodological approach to the Spanish electricity system. The research provides practical insight into managing a power system with

a significant VRES component through these case studies. This real-world application validates theoretical models and analyzes, offering a tangible context for understanding the implications of high-VRES integration.

- (C4): **Economic impact assessment and evaluation of technology competitiveness.** The research analyzes the economic impacts of considering additional system services. This analysis includes assessing revenue streams for different energy technologies according to the provided services and evaluating the intra- and inter-competition technologies according to the supply of one or several services. This contribution is essential for understanding the economic implications of the operation of ESS and for guiding policy and investment decisions.

The completion of this thesis journey and the presentation of its findings have yielded academic contributions. These contributions have been disseminated through several publications led by the author of this thesis. The articles include:

- **Huclin, S.**, et al. (2022). Exploring the roles of storage technologies in the Spanish electricity system with high share of renewable energy. *Energy Reports*, 8, 4041–4057. <https://doi.org/10.1016/j.egy.2022.03.032>
- **Huclin, S.**, et al. (2023). A methodological approach for assessing flexibility and capacity value in renewable-dominated power systems: A Spanish case study in 2030. *Energy*, 285, 129491. <https://doi.org/10.1016/j.energy.2023.129491>
- **Huclin, S.**, et al. (2024). Evaluating the economics and competition of providing wholesale system services in a renewable-dominated power system: the Spanish case study. *Applied Energy* (*In revision*)

Table 1.1 links the contribution of the PhD thesis with the scientific publications listed above in this section:

Table 1.1: Scientific publications and contributions of the PhD thesis

| | C 1 | C 2 | C 3 | C 4 |
|--------------------|-----|-----|-----|-----|
| Huclin et al. 2022 | X | | X | |
| Huclin et al. 2023 | | X | X | |
| Huclin et al. 2024 | X | | X | X |

1.5 Dissertation Structure

This dissertation is structured to provide a coherent and comprehensive exploration of the role of ESS technology in power systems in scenarios with a high share of VRES, addressing identified research gaps and contributing to the field through its distinct chapters.

Chapter 2 delves into the current body of knowledge and the existing research on power system operations with a high share of VRES. It covers detailed reviews of operation models, operating reserves, adequacy assessment methods, and flexibility. This chapter lays the foundational understanding necessary for research development, highlighting the existing gaps and setting the stage for the following techniques and analyses.

Chapter 3 outlines the methodological approach and the medium-term operation model developed and used in the investigation. It details the theoretical and computational approaches, tools, and techniques used to address the research questions, clearly understanding the research framework and its applications.

Chapter 4 focuses on applying the developed models and methodologies to a specific case study, the Spanish electricity system. This chapter offers a practical context for research, allowing for examining and validating the proposed models and methods in a real-world setting with a significant VRES component.

Chapter 5 thoroughly analyzes the data and findings of the case study. It includes an evaluation of the operational and economic aspects of the ESS technologies. This chapter is critical in translating the theoretical models and methods into actionable insights and understanding their implications in a practical case study.

Chapter 6 concludes the research findings. It synthesizes key insights, discusses the study's implications, and provides future research and practice recommendations. This chapter culminates the research journey, offering a comprehensive summary of the contributions.

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Chapter 2

State-of-the-art

This chapter critically overviews the evolution of power system models. It traces the historical progression of power systems from simple structures to complex, interconnected networks, emphasizing the significant shift towards incorporating VRES such as wind and solar PV. This chapter explores the adaptations and challenges in power system operation models in the energy transition context, highlighting the increased need for system flexibility. The discussion further extends to various stakeholders' diverse applications of these models in a deregulated energy market, illustrating the complexities and requirements imposed by the increasing reliance on VRES. Overall, this chapter aims to lay the groundwork for understanding the intricate roles of ESS and the necessity for updating power system models to align with the contemporary energy landscape.

2.1 Evolving Power System Models in a Renewable Era

2.1.1 Origins of Power System Operation Models

The development of power systems over time has shifted from basic structures to complex and interconnected networks. This transformation, driven by significant technological advances, size, and complexity, is essential for understanding the development and need for modern power system operation models.

Initially, power systems relied primarily on hydropower generators for

public lighting and industrial needs. Today, power systems consist of a heterogeneous mix of generation technologies ranging from traditional fossil fuel energy to VRESs such as wind and solar photovoltaic (Solar PV). In addition, contemporary power systems have expanded significantly in scale and reach. Initially designed to serve localized areas, they have evolved into vast networks that often span multiple regions or countries. These power systems meet the needs of millions of people, making them large-scale integrated networks. This expansion highlights the transition of power systems from smaller and localized units to larger and more interconnected ones.

The technological advancements in the energy sector have led to significant changes in regulatory and market structures. These changes have been particularly noticeable since the end of the 20th century when the deregulation of electricity system operations began. The traditional vertical integration model, where a single entity, the system operator, was responsible for controlling all aspects of power generation, transmission, and distribution, has been transformed. Since the deregulation process, different entities handle these aspects separately. Although the system operator's responsibility for maintaining the electricity supply has not changed, its decision-making process in a deregulated power system now faces trade-offs, including market mechanisms, generation companies' strategies, and the need to balance supply and demand efficiently.

Finally, the move towards environmental sustainability marks a paradigm shift in power system design and operation. Early systems rarely considered environmental impacts, whereas modern systems increasingly prioritize sustainability, integrating non-dispatchable VRESs in response to environmental concerns. The inherent variability and uncertainty of VRESs, coupled with the instantaneous character of electricity and the phase-out of thermal power plants, challenge the tasks of the system operator. As a result, the tools and technologies employed by system operators are undergoing a significant evolution to meet new needs. These advanced decision-making aids are being refined and enhanced to enable operators to meet the load demand at the least cost while accommodating the complexities of modern electricity systems. This evolution integrates sophisticated analytical models, real-time data processing capabilities, and predictive algorithms, all critical in navigating the intricacies of a deregulated and increasingly renewable-dominated energy landscape [1].

This narrative of the evolution of power systems elucidates the increasing complexities and changing requirements imposed on power system operation

models. It highlights the necessity for sophisticated power system operation models capable of managing the current electricity demands, technological advancements, and environmental considerations.

2.1.2 Modelling of Power Systems

A power system operation model is a sophisticated computational framework that uses a collection of mathematical equations, algorithms, and data sets to reproduce the behavior of a power system under different conditions.

Before deregulation, power system operation models were primarily used by system operators to meet load demand safely and efficiently. Given that the aim here is to provide the reader with an overview of the various possible uses of the operation models, the details of the operation models for power systems are not shown. For each focus adopted, the representation of the power system within the model is adapted accordingly. However, for more details on the different operation models, readers are invited to consult [2] and [3], who organized the operation model and electricity market modeling trends, respectively.

By highlighting the interconnected evolution of the users of power system operation models and their objectives, it becomes evident how the functions of power system operation models have adapted to the changing landscape of the electricity market. The successive changes in power systems, such as the deregulation and the integration of massive VRES in power systems, have diversified the usage of these models and enhanced their sophistication to meet the emerging challenges and opportunities in the electricity sector.

2.1.3 Timing and Rationale in Power System Operation Models

Power system operation models are designed to explore the complexities of modern electricity systems. The effectiveness and efficiency of these models lie in carefully calibrating various parameters, each of which ties closely to the specific objectives of the model's user, depicted in Section 2.1.2. Understanding these interdependencies is crucial, especially in integrating renewable energy sources, a challenge that introduces new dimensions of variability and uncertainty.

In the domain of power system operation modeling, the interplay of accuracy, reliability, and applicability stands as a cornerstone in determining the

effectiveness of these models. Accuracy ensures the model's output closely reflects real-world power system operations, capturing crucial elements like load, generation outputs, and power system interactions. Reliability is critical for the model's ability to consistently yield valid results over various scenarios and time frames, an attribute essential for reliable planning and operational decision-making. Applicability encompasses the model's flexibility and relevance in addressing diverse challenges, such as adapting to different operational scenarios, integrating emerging technologies, and fitting within varied regulatory frameworks.

However, striking a balance among these traits can be intricate. Improving accuracy through increased model complexity might reduce applicability due to greater computational demands or affect reliability with heightened sensitivity to input data variability. Thus, modelers engage in a nuanced optimization process, aligning these attributes to meet the specific objectives and constraints of the power system under study. This careful calibration is about accurately representing current system states and ensuring robustness and adaptability to the power systems, especially when analyzing the role of ESS in the era of VRES integration. This leads to the necessity of delving into a detailed list of crucial parameters of power system operation models, each playing a critical role in shaping the model's response to these evolving power systems.

- **Time Representation.** The selection of time representation is pivotal, directly linked to the model's objectives and the hierarchy of decisions it is designed to support [2]. While shorter time scopes in a model are tailored for immediate operation decisions, longer time scopes cater to strategic planning and policy-making. Particularly in scenarios with high shares of VRES, operation models address challenges across varied time scales. This complexity is accentuated by the technical disparity among different ESS technologies, each with distinct technical parameters. Although medium-term models have traditionally been utilized for analyzing the annual management of water reserves [4], in the VRES era, these models need to incorporate details from shorter time scales, such as operating reserves. This approach is essential for a neutral representation of various storage technologies, ensuring that no single technology is unduly favored or misrepresented. Therefore, an updated medium-term operation model becomes increasingly necessary. It must provide the granularity to capture the small imbalance corrections of

2.1. EVOLVING POWER SYSTEM MODELS IN A RENEWABLE ERA 17

ESS due to the VRES variability while offering a broad enough temporal scope for considering seasonal variations of water reservoirs and effective long-term storage planning. This balanced medium-term perspective is crucial for analyzing and comparing the roles of ESS in a renewable-dominant energy landscape, enabling a comprehensive understanding of both immediate and extended power system operations [5].

- **Electricity Market Operation Details.** The instantaneous nature of electricity, as an energy vector, necessitates organizing electricity market operations across several platforms to balance generation and demand continuously. Electricity markets cover short- to long-term operations, such as bilateral contracts. The day-ahead market focuses on planning for the upcoming day, the intraday markets adjust for unforeseen changes close to real-time, and the real-time market responds to immediate system needs. Critical decisions in providing services in these markets include unit commitment, determining which power plants will run to meet the required service, economic dispatch, and optimizing the output of committed plants for cost efficiency. Although representing these electricity market operations in power system operation models is a complex task, this complexity is further heightened considering the diverse technical parameters of ESS and the broad spectrum of services ESS can provide across different time scales. In this context, a medium-term time scope is a suitable compromise for power system operation models. It balances the need to represent the various market operations while maintaining a manageable computational scale. However, there is an inherent challenge in enhancing the representation of short-term electricity market operations within these medium-term models. This enhancement is crucial to capture the interplay between ESS technologies and market operations, ensuring models accurately reflect the evolving landscape of energy systems driven by the integration of renewables.
- **Electricity Market Representation.** In power system operation models, the representation of electricity markets significantly influences the decision-making process through price mechanisms. These models vary from perfect competition, characterized by numerous entities and efficient resource allocation, to complex oligopolistic markets with

strategic behaviors. Linear optimization models under perfect competition assumptions are often preferred for operational impact analysis. These models allow for the 'derivation of marginal prices,' which means calculating the cost of producing one additional unit of electricity. This calculation is closely linked to the concept of dual variables in optimization. In this context, dual variables of demand balance constraints represent the marginal cost, determining the marginal price in the market. This aligns with the theory of perfect competition, where the pursuit of profit maximization by individual entities leads to the minimization of total system operation costs by the System Operator [3]. However, the model's actual approach to market representation depends on its specific focus. While the assumption of perfect competition helps simplify the analysis, real-world market conditions and strategic behaviors of market participants may necessitate adjustments to this approach, ensuring a comprehensive and realistic understanding of how various market structures affect power system operations.

- **Transmission Network.** The transmission network represents an essential driver in the energy transition. Many lines of research focus on improving the expansion and utilization of the existing network to reduce operating costs and increase available flexibility. Consideration of the network opens the door to optimizing the location of specific technologies, thus highlighting the strategic value of ESS in alleviating network bottlenecks or supporting voltage regulation. This level of detail can reveal the potential for location-specific ESS deployment to enhance the stability and efficiency of the electricity system. However, this granular focus might detract from understanding the broader system-level impacts of ESS, such as their role in overall system balancing or integrating large-scale renewable projects. Conversely, the copper plate representation of the transmission network, which assumes the network operates as a single node with unlimited transmission capacity and no congestion, might overlook these critical local effects and interactions, potentially underestimating the value of ESS in specific transmission expansion scenarios. Balancing these aspects requires a model that can accurately represent the transmission network's complexities while still capturing the systemic role of ESS in a broader energy context.

- **Technology Representation.** Integrating non-dispatchable VRES into power systems brings forth the imperative of accurately representing these technologies in operation models. It is crucial to correctly capture each technology’s technical and economic parameters to ensure the model’s fidelity to real-world scenarios. As operation models are approximations of reality, their representation of technologies must be consistent and justifiable, aligning with the model’s objectives. For instance, thermal technologies might be detailed in a short-term operation optimization model with aspects such as downtime and several start-up processes. In contrast, in an investment planning model, the same technologies could be simplified to installed capacities and load factors, reflecting their contribution to the electrical system. Furthermore, the representation of different ESS technologies is vital for understanding their roles within scenarios of high VRES shares. Precise modeling of specific ESS characteristics, such as discharge duration, roundtrip efficiency, and energy capacity, is essential for an in-depth analysis of each technology’s optimal utilization [6]. This detailed modeling approach is instrumental in evaluating how these technologies can effectively support the integration of renewables, contributing to both immediate system stability and long-term strategic planning.

Thus, a balance must be struck between the physical size of the problem and its solvency, particularly when excessive details risk insolvency due to computational constraints. The optimal level of detail and scope in power system modeling is fundamentally linked to the user’s perspective. Whether focused on short-term operations or long-term strategic planning, each viewpoint contributes complementary insights to the overall analysis.

In contexts focused primarily on operational considerations, especially in analyzing the integration and role of ESS within scenarios with high shares of VRES, a medium-term time scope offers a viable compromise. This approach effectively balances the need for detailed time steps, essential for capturing the nuances of electricity system operations in the short term, with a broader time scope encompassing wider operational trends and strategic implications. The medium-term perspective successfully navigates between the granular details of ESS functionality and the overarching system behavior, providing a comprehensive and computationally feasible analysis. Such a balanced approach underscores the multifaceted nature of power system modeling, where different scales and levels of detail converge to enhance the

understanding of ESS roles in renewable-dominated power systems.

Moving forward, the following section delves into the necessity of updating medium-term operation models in high VRES scenarios for analyzing the roles of ESS.

2.1.4 Modelling Challenges in the Evaluation of ESS Roles

Integrating new non-dispatchable VRES transforms energy landscapes, presenting multifaceted challenges in power system generation, transmission, and distribution. References [7]–[9] recognize the growing necessity to consider new flexibility solutions, such as new ESS capacities, and mainly through battery and PSH technologies, to counterbalance the variable and uncertain output from these VRES. While battery technology is nearing maturity at the generation level, it still needs extensive operational experience. Consequently, exploring and comparing the roles of PSH and batteries in optimizing the energy mix becomes crucial.

The technical aspects of ESS, essential for assessing their impact on electricity system operations, are discussed in [10], [11]. These studies provide methodologies for modeling hydropower plants, focusing on aggregating hydraulic power plants and water reservoirs. They emphasize the critical distinction between Closed-Loop and Open-Loop Pumped Storage Hydro (CLPSH and OLPSH). Given the differing technical parameters like energy reservoir capacity and energy inflows, conflating these sub-technologies could lead to inaccuracies in assessing their respective contributions. Hence, in this context, 'ESS' refers exclusively to PSH (i.e., CLPSH and OLPSH) and batteries unless indicated otherwise.

The evaluation of the operating roles of various ESS across different time scales necessitates a methodology that balances the long-term variability of VRES with the time representation required for managing operating reserves. This approach is critical, as emphasized by [10], [11], for understanding how Hydro Storage, PSH, and batteries can mitigate the inflexibility introduced by non-dispatchable VRES. Essential to this process is maintaining temporal consistency in input data, including solar and wind patterns, water inflows, and load demands. The modeling must cover every hour of the year, rather than relying on representative periods, to accurately capture critical events varying from brief to extended durations, such as high-demand periods, low

renewable production, scarce hydro inflows, and thermal unit unavailability. This detailed temporal characterization is vital for assessing the role of storage systems during fluctuating supply and demand conditions.

Authors in [12] utilized a combination of expansion and operation optimization models, along with simulation modules, to examine the impacts of regulatory frameworks on ESS usage in Brazil and Mexico. Their findings indicate that the operational role of ESS varies with the power system's characteristics. With a more diversified energy mix in Mexico, batteries play a crucial operational role due to the power system's need for flexibility. In contrast, Brazil's heavy reliance on hydropower and the consequent energy flexibility requirements limit the utility of batteries due to their lower energy capacity. Despite the significant insights provided by their study, the methodology used in [12] deviates from the modeling guidelines outlined in [10], [11]. Furthermore, using representative days for modeling, their approach fails to maintain the chronological consistency and intricacies of different time series, which is crucial for a comprehensive analysis of ESS roles in diverse power systems.

2.2 Wholesale System Services in Renewable Integration

As part of the comprehensive analysis of the roles played by ESS in integrating VRES into power systems, this section delineates the operational framework of the electricity system as examined in this section. The first step in this analytical process involves establishing a clear taxonomy derived from an extensive literature review. This taxonomy categorizes and clarifies the various components and functions within the electricity system, providing a structured foundation for the subsequent analysis. Following the establishment of this taxonomy, the section delves into a detailed description of the different services central to this thesis's scope. These services include, but are not limited to, operating reserves, ramping services, and contributions to system adequacy. Each of these services plays a unique and crucial role in the functionality and stability of electricity markets, particularly in the context of increasing VRES integration.

2.2.1 Definition and Taxonomy

Operating procedures in power systems have been integrated with mechanisms to schedule operating reserves, effectively allowing the system to manage discrepancies between forecasted demand, the output from VRES, and extreme situations. This integration plays a crucial role in maintaining system reliability and stability. For instance, one of the critical balancing services includes frequency regulation, which helps to keep the system frequency within its designated range, compensating for unexpected changes in supply or demand. Another significant service is voltage control, ensuring that voltage levels remain within safe limits despite fluctuations in power flow. Additionally, contingency reserves are maintained to respond to unexpected outages or system failures, providing a safety net to prevent cascading failures in the power system. These services ensure that deviations in power generation or demand forecasts do not adversely affect the power system's performance [13].

The power system operations are undergoing significant changes in the evolving landscape of power systems, characterized by an increasing reliance on VRES and a corresponding phase-out of thermal generation units. The existing thermal units are necessitated to modify their dispatch patterns, aligning more responsively to fluctuations in load demand. This adjustment is critical for preserving the reliability of the power system at satisfactory levels [14]. Concurrently, integrating emerging technologies, such as batteries, into the electricity mix underscores the urgency to refine existing mechanisms. These enhancements aim to effectively incentivize the provision of flexibility by various technologies [15].

Additionally, the inherent characteristic of VRES, notably their negligible production costs, has precipitated a substantial decline in marginal electricity prices. This price decline manifests as reduced revenue streams for dispatchable technologies, diminishing their motivation to contribute to power generation. This emerging scenario risks the overall adequacy and security of the power supply system [16]. In response to these challenges, the introduction of additional wholesale services is advocated. Such services are designed to bolster the economic incentives for diverse technologies and reinforce the system's adequacy and security, ensuring a balanced and resilient power system [17].

In this thesis, the primary focus is placed on a detailed analysis of the role of ESS within the context of medium-term power system operation. A

unique taxonomy has been established to facilitate this analysis, wherein all balancing services are collectively referred to as wholesale system services. This categorization is strategically chosen to address the limitations of representing time in the modeling framework (i.e., minutes to hours).

Grouping these services under a single umbrella term enables a more holistic examination of the diverse range of services that ESS can provide. These include operating reserves, ramping services, and significant contributions to the overall system adequacy. The rationale behind this taxonomy is to enhance the clarity and depth of the analysis. By merging these services into one comprehensive category, the thesis endeavors to streamline the study, making it more efficient and focused.

The medium-term operation model must consider short-time scale services to capture the variability and uncertainty impacts of VRES integration accurately. However, since these models are typically based on hourly time steps, approximating sub-hourly services is necessary when evaluating the roles of ESS. This approximation allows for an effective representation of the various balancing services without needing to model each service separately on a sub-hourly basis.

Using this taxonomy, the model acknowledges the importance of short-time scale services and incorporates their impacts into the medium-term analysis. While this approach may limit the ability to differentiate between specific balancing services and their unique requirements in future power systems, it provides a practical solution for integrating these services into medium-term operation models. This method ensures that the variability and uncertainty introduced by VRES are appropriately accounted for, thereby offering a comprehensive understanding of the roles of ESSs.

Despite this simplification, the chosen taxonomy allows for a robust analysis of ESS's capabilities in providing essential services. It ensures that the study remains focused and efficient, highlighting the critical role of ESS in enhancing system adequacy and flexibility. This approach also facilitates a more straightforward comparison of ESS's contributions across different scenarios and operational conditions, ultimately providing valuable insights into their potential in future power systems.

This approach is particularly pertinent in examining the impacts of VRES on the power system's operations over a medium-term horizon. It allows for a nuanced understanding of how ESS can adapt and respond to the needs of a power system increasingly reliant on renewable sources. The taxonomy thus serves as a crucial tool in the thesis, setting the stage for a more effective

and insightful exploration of ESS's capabilities and roles in supporting and stabilizing power systems as they evolve with higher VRES integration.

2.2.2 Operating Reserves

A vital responsibility of the System Operator involves managing the security and adequacy of the electricity supply, a task supported by various mechanisms, notably balancing services. These services are crucial for maintaining frequency stability and managing the energy balance within the power system, as highlighted by The European Commission [18]. Frequency regulation services, a subset of balancing services (e.g., automatic Frequency Restoration Reserves (aFRR), manual Frequency Restoration Reserves (mFRR), Restoration Reserves (RR) [19]) are categorized into different operating reserves based on their response times. These reserves range from immediate response (a few seconds) to short-term response (up to two hours). They play a critical role in adjusting energy injections (upward) and withdrawals (downward), thereby addressing discrepancies in VRES generation and demand forecasts, as well as coping with unexpected events like contingencies and outages in generation or network assets [18]. Further dissecting these services reveals two distinct products: availability and activation. Availability pertains to the capacity offered by these services, measured in megawatts (MW), while activation refers to the actual energy delivered or absorbed, quantified in megawatt-hours (MWh) [19].

The escalation in the integration of non-dispatchable VRES brings an increased demand for operating reserves. This correlation, as authors in [20] articulate, is a direct consequence of the variable nature of these energy sources. The Spanish System Operator, in its report [21], further elucidates this concept by emphasizing the significant role of PSH in electricity generation. It highlights that hydropower technologies encompassing dams and PSHs are predominantly utilized for supplying operating reserves. This reliance on hydropower technologies is rooted in their capacity to offer quick and flexible responses to the power system's needs, a feature crucial for maintaining system stability amidst fluctuating renewable energy inputs.

Additionally, reference [22] underscores that integrating non-dispatchable VRESs, like wind and solar PV, magnifies the value of PSH technologies. This significance is particularly pronounced when PSH systems are heavily involved in providing operating reserves. This observation aligns closely with the central theme of the thesis, exploring the intricate balance between

renewable energy integration and the necessity for effective energy storage solutions, like PSH and batteries, to ensure the security and adequacy of power systems. Understanding these complexities is critical to assessing the technical and economic feasibility of storage impacts on power systems in scenarios dominated by renewable energy sources. Thus, analyzing the roles of ESS within scenarios of high VRES share imposes the detailed modeling of balancing services.

Authors in [23] conducted a study focusing on the benefits of PSH technology investments in enhancing greenhouse gas mitigation in scenarios heavily reliant on non-dispatchable VRES. Their analysis, grounded in the Distributed Generation scenario 2030 of the TYNDP [24], utilized a hydrothermal linear medium-term operation planning model with hourly details to represent the annual operation of the Spanish power system. This study highlighted the critical role of PSH in accommodating increasing shares of non-dispatchable VRES. However, it is crucial to note that their methodology did not incorporate operating reserves, and the scenarios did not reflect the projections of the Spanish National Energy and Climate Plan (NECP) [25], which anticipates a 50% increase in PSH installed capacity in Spain by 2030, according to 2019. Consequently, the modeled power system operation in [23] lacked the flexibility services envisaged in the NECP scenario. Despite providing valuable insights into the interplay between PSH investments and non-dispatchable VRES shares, [23] study, as supported by the works of [20], [21], and [22], did not fully explore the role of ESS in high-RES scenarios due to its non-technology-neutral approach.

Parallely, authors in [26] examined how various ESS, including batteries, PSH, Electric Vehicles, Compressed Air Energy Storage, and Concentrated Solar Power, could facilitate the integration of wind and solar energy into the Spanish electricity mix. Based on 2020 scenarios, their study utilized a hydrothermal medium-term operation planning model with detailed consideration of energy and operating reserves, as delineated in [27]. They maintained chronological consistency between input parameters, aligning hourly load and VRES generation profiles with storage options. Their findings underscored that ESSs can significantly smoothen peak load variations, thereby aiding the integration of renewables. However, the study's basis on 2020 forecasts, assuming 20% renewable capacity, limits its applicability to highly renewable scenarios.

Furthermore, while operating reserves were considered, the study should have extensively addressed the challenges the System Operator might en-

counter in maintaining system security and continuity in scenarios where VRES dominate the generation mix. This aspect becomes increasingly relevant, as highlighted by [8] and [10], where the frequency of critical events is expected to rise. A more detailed characterization of these events could provide a comprehensive analysis of the complementary and competitive roles of different ESSs, a perspective that needed to be fully explored in [26] and [27].

Authors in [28] developed a hydrothermal operation planning model that includes energy and reserve markets, focusing on operating reserves using a deterministic approach based on historical data. However, their model does not adequately address scenarios with high penetration of non-dispatchable VRES. It also overlooks the nuances of different ESS technologies, like batteries and PSH technologies. Reference [29] investigated the potential of batteries as peaker capacity in the U.S. under high non-dispatchable VRES scenarios by approximating the Effective Load Carrying Capability (ELCC), an adequacy metric for assessing the contribution of technologies to maintain the adequacy of power systems [30]. Battery technology could effectively serve as peaker capacity, especially with increasing solar PV shares. Despite these findings, both studies exhibit limitations in comprehensively comparing the roles of various ESS. Authors in [29] disregarded operating reserves by assuming perfect forecast accuracy, and neither study thoroughly the technical differences among ESS types. As highlighted in literature by [10], [11], [20]–[22], the methodologies in the presented studies lack a technology-neutral perspective, which is crucial for accurately assessing the role of ESS in high-VRES scenarios.

2.2.3 Ramping Services

In this thesis, special attention is given to ramping services within electricity systems, particularly concerning the integration of VREs. Notably, California Independent System Operator (CAISO) and Midcontinent Independent System Operator (MISO) have pioneered, in the 2010s, in implementing ramping services, known as the Flexible Ramping Product [31] and the Ramp Capability Product [32], respectively. These services are increasingly relevant in today’s power systems due to the rising capacity of VRES and the inherent variability and uncertainty they introduce. As outlined in studies [15], [33], research in this domain focuses on three primary areas: real-world implementation of ramping services, addressing challenges and solutions in their

deployment, and exploring their availability from different energy sources.

The methodologies used by power systems with integrated ramping services are diverse, yet they commonly account for the fluctuating nature of net demand [33]. As noted in [32], the calculation of ramping requirements is influenced by factors such as historical uncertainties and forecast deviations. This necessitates a robust verification and validation process to accept these influences. When it comes to implementing these services, questions arise regarding the most effective stage within operational procedures—be it day-ahead, unit commitment, economic dispatch, or real-time operations [34]. Despite these methodological differences, the consensus is that ramping services introduce new incentives for technology providers, promoting greater flexibility and reducing curtailments, especially in systems with high VRES penetration.

Studies focusing on the impacts of these operational changes, particularly those implemented in CAISO and MISO since 2016, have been extensive. For instance, [35] examined these services’ environmental, economic, and reliability impacts in MISO, concluding that appropriate ramping service parameterization can significantly reduce wind curtailment while maintaining system adequacy.

However, there remains a gap in understanding ramping services’ medium- and long-term impacts. Originally designed to address short-term deviations in VRES production, these services also play a vital role across broader time scales [36]. For instance, in systems with a significant solar PV share, the need for ramping services varies substantially across seasons [37]. [17] emphasizes the importance of these services in addressing the ‘missing money’ problem, a financial challenge arising from reduced market prices due to the large-scale introduction of low-cost VRES.

The long-term evolution of flexibility requirements and adequacy challenges was explored in the Greek power system by [38], utilizing a model [39] that integrates ramping service constraints. This approach facilitated assessing medium-term impacts and exploring income distribution across technologies based on the marginal price. However, as critiqued in [40], this methodology may only partially capture the nuanced ramping requirements due to its representation of time series. The study potentially underestimates the need for ramping services and needs to adequately address the competition among technologies in providing multiple services [38]. Additionally, [41] highlights the limited research on these services’ medium- and long-term effects, pointing to a critical area for future exploration.

In conclusion, accurately assessing and fulfilling ramping service requirements is essential for effectively integrating VRES and incentivizing flexibility among dispatchable technologies. While most studies have concentrated on the short-term impacts, this thesis aims to extend the analysis into the medium-term, assessing how the introduction of ramping services influences the revenue streams of different technologies in scenarios with high VRES presence. This expanded focus is crucial for addressing the immediate and future challenges of power system operation and planning in a renewable energy integration era.

2.3 Power System Adequacy in High-VRES Contexts

This section delves into the contributions of technologies in maintaining power system adequacy, a topic previously introduced in Section 2.2. It aims to clarify the concept of supply security and review existing methods for assessing power system adequacy. A particular focus is placed on how dispatchable technologies contribute to sustaining a reliable power system. The section emphasizes the urgent need to revise adequacy assessment methodologies. This revision is crucial for accurately evaluating the role of ESS in renewable-dominated power systems.

2.3.1 Definition and Taxonomy

As identified by authors in [42], the security of supply issues can be categorized based on the time frame they encompass. Each time scale addresses specific concerns and requires tailored approaches to ensure the stability and reliability of power systems.

- **Security in the Short Term:** In the short-term context, the security of supply primarily deals with the power system's ability to respond to immediate disruptions. This includes managing sudden imbalances between supply and demand, handling unexpected outages of power plants, or coping with rapid fluctuations in VRES output. The focus here is on real-time balancing and quick response mechanisms to maintain system stability.

- **Adequacy in the Medium Term:** Adequacy concerns emerge in a medium-term time frame. It ensures the power system has sufficient resources to meet the expected demand under standard operating conditions. Adequacy assessments consider the predictability of demand and supply patterns, including seasonal variations and foreseeable changes in the generation mix. This time frame is critical for assessing the operational roles of ESS as it relates to their capability to bridge gaps between demand and renewable energy supply, especially during periods of low VRES output.
- **Strategic Energy Policy in the Long Term:** Strategic energy policy decisions come into play over the long term. These decisions are centered around ensuring that the power system can meet future demand sustainably and reliably. This involves planning for capacity expansion, integrating new technologies, and considering the long-term impacts of policy decisions on energy security. The long-term perspective is crucial for guiding investments in infrastructure and technology, including ESS, to support the transition to a renewable-dominated power system.

The relevance of adequacy assessments becomes particularly pronounced when there is no immediate option for new capacity installations to resolve short-term security of supply issues. In such scenarios, the operational roles of ESS are brought to the forefront, as they offer flexible solutions to bridge the intermittency of VRESs. Therefore, understanding and assessing adequacy within these varied time scopes is critical for comprehensively evaluating the operational roles of ESS in high VRES contexts. This understanding forms the backbone of developing robust and resilient power systems that seamlessly integrate increasing shares of VRES.

2.3.2 Existing Adequacy Assessment Methods

The capacity value, also known as capacity credit [43], firm capacity [44], or firm supply [45], serves as an indicator of a technology’s contribution towards upholding the reliability standards of a power system. This metric essentially quantifies the ability of generation units to support system reliability, especially during periods of peak load demand, by assigning a coefficient reflecting their availability [46].

Methods for calculating the capacity value can generally be classified into two categories: reliability-based and approximation-based approaches

[46]. Standard reliability-based techniques include the Equivalent Firm Capacity (EFC) and Effective Load Carrying Capability (ELCC) [30], which are extensively utilized to evaluate technology contributions to power system reliability. On the other hand, approximation methods, such as those employing capacity factors, estimate a technology's capacity by averaging its capacity factor across numerous critical hours of load or net demand. These critical periods are chosen based on the prevalence of VRES in the power system.

Research conducted by [47] indicates that the capacity factor approximation-based method closely aligns with results from reliability-based methods. Despite its sensitivity to the selected critical hours and the specific electricity system under study [47], the capacity factor approximation-based method has gained traction in both industrial applications [48] and academic research [29]. For example, [29] employs this method to assess how ESSs could potentially replace thermal units for peak capacity by averaging their capacity factor over crucial net demand hours. Similarly, in Mexico, the System Operator (SO) calculates capacity based on the historical performance of technologies during the most critical 100 hours annually [48].

Nonetheless, reliance solely on capacity value for assessing power system adequacy overlooks the flexible behavior of the technologies [49]. The integration of VRESs, as noted by [50], increases the net load ramps and operating reserves requirements and introduces enhanced variability and uncertainty. Hence, flexible technologies, in addition to supporting system adequacy, play a pivotal role in managing these challenges. Consequently, any assessment of individual contributions to system adequacy must encompass considerations of variability and uncertainty, particularly in the context of the ongoing energy transition [51].

2.3.3 Adequacy assessment's Update Needed

The escalating capacity of VRESs necessitates a power system that can effectively handle increased uncertainty and variability to safeguard the Security of Supply (SoS) [52]. SoS studies also recognized as adequacy analysis, are crucial in determining if power systems possess adequate capacity to meet load demands while adhering to reliability standards (e.g., Loss of Load Expectation, Expected Unserved Energy). Traditionally, these standards have relied on the historical performance of thermal and hydroelectric generation units [6]. However, the shift towards renewable-centric power systems, ac-

accompanied by the emergence of new technologies like batteries, mandates a fresh perspective on adequacy assessment. Specifically, [49] emphasizes the necessity of incorporating operational flexibility in the adequacy evaluation of power systems.

Although various tools exist for analyzing power system flexibility [53], there still needs to be more clarity regarding how to simultaneously assess the contributions of different technologies to both adequacy and flexibility [54]. A straightforward, technology-neutral assessment approach would pave the way for novel market mechanisms, appropriately acknowledging technologies for their diverse contributions to system services, such as balancing, energy, ramps, and capacity. While services like energy and balancing are well-established, newer concepts like the Flexible Ramp Product in California’s electricity market [15] are emerging. It is essential to recognize that while dispatchable technologies are theoretically capable of providing multiple services, their inherent characteristics may limit their effectiveness in specific roles. Therefore, the methodology for evaluating flexibility and adequacy contributions must address this technology dilemma, identifying which services can be most efficiently delivered by specific technologies.

Recent research endeavors are focused on how adequacy assessment methodologies could integrate flexibility considerations. Studies have critiqued existing adequacy metrics for their inadequacies, with [55] suggesting an adequacy metric that accounts for ramp shortages, thereby incorporating flexibility into adequacy assessments. Although this proposal exposes the limitations of traditional capacity value metrics in a renewable-heavy system, it must address the multifaceted flexibility challenges across different timescales. In addition, [56] conducted an extensive review of flexibility metrics, underscoring the imperative for a more cohesive approach.

Despite these advancements, a significant knowledge gap persists. Current methodologies and analytical tools for exploring flexibility and reliability have been developed separately, such as works like [36] and [30], needing a comprehensive framework for their integration. The energy sector still awaits a holistic methodology that synergizes these aspects, particularly in renewable-centric power systems. This integrated approach is fundamental for a more accurate and practical analysis of power system adequacy in the era of renewable energy dominance.

2.4 Concluding Remarks

The comprehensive review of existing studies and methodologies underscores various critical deficiencies in the current models for representing power systems with substantial renewable energy source integration, particularly within a medium-term framework:

- The need for models that effectively handle both energy and balancing services, distinctly capturing the capacity available for balancing and the actual utilization of balancing energy.
- The requirement for a medium-term operational optimization model with an hourly time step that rigorously preserves the chronological sequence and coherence of input data series, ensuring accuracy and reliability in power system operation models.
- The importance of accurately modeling diverse ESS, considering their varying storage durations, and evaluating their impact on the operation of power systems.
- The development of an intricate hydrothermal operation planning model that accurately simulates market operations, particularly for Hydro Storage, and distinctly models PSH as separate physical entities.
- The necessity to evaluate flexibility demands across multiple time scales, examining the effects of modeling energy, ramping services, operating reserves, and the surrogate of firm capacity on the integration of VRES.
- The emergence of a novel approach that captures the behavior of different technologies in offering operational flexibility and adequacy. This approach should consider various time scales and address multiple power system scarcities that complicate the integration of VRES.
- An urgent call for analysis of the competition between and within technologies in providing assorted wholesale system services, highlighting how technologies can optimize their roles and contributions in a renewable-rich power landscape.

These identified gaps highlight the evolving challenges and complexities in modeling power systems with high renewable energy penetration and emphasize the need for advanced methodologies to address these multifaceted issues effectively.

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Nomenclature

Indices

| | |
|------|--|
| n | Load level |
| g | All kind of generating unit (thermal, hydro, VRES, and ESS unit) |
| t | Thermal unit |
| h | Hydro unit |
| or | Unit available to provide operating reserve |
| s | Energy Storage System (ESS) |
| r | Energy reservoir associated with an ESS |

Parameters

| | |
|------------------------------|--|
| D_n | Hourly load demand [MW] |
| DUR_n | Duration of each load level [h] |
| $CENS$ | Cost of Energy Non-Served [€/MWh] |
| EF_s | Roundtrip efficiency for ESS unit (i.e., percentage of electricity put into storage that is latter retrieved) [p.u.] |
| $EI_{n,s}$ | Weekly energy inflow for ESS unit [MWh] |
| $\bar{P}_g, \underline{P}_g$ | Maximum and minimum output of generating unit [MW] |
| \bar{C}_s | Maximum pumping of ESS unit [MW] |

- CV_g Total variable cost of generating unit (includes fuel, variable O&M and emission costs) [€/MWh]
- CV_s Variable cost of ESS unit [€/MWh]
- I_s Energy capacity of ESS unit [MWh]
- τ_s Duration of ESS discharge cycle (e.g., 24, 168, 672 for daily, weekly, monthly) [h]
- CD, CU Percentage of activated energy concerning the balancing capacity for generating unit providing downward/upward operating reserve [%]
- DR_n, UR_n Hourly downward and upward operating reserve [MW]
- RD_g, RU_g Ramp down and ramp up limits of thermal unit [MW/h]
- TD_g, TU_g Minimum downtime and uptime of thermal unit [h]
- CSD_g, CSU_g Shutdown and start-up costs of committed unit [M€]
- RSU_n, RSD_n Upward and downward ramping requirements for each load level [MW/h]

Variables

- ens_n Energy non-served [MWh]
- $gp_{n,g}, gc_{n,g}$ Generator output and consumption (discharge if ESS) [MW]
- $p_{n,g}$ Production of unit above minimum output [MW]
- $c_{n,s}$ Consumption of ESS unit above minimum output [MW]
- $uc_{n,g}$ Commitment of a generating unit per load level 0,1
- $sd_{n,g}, su_{n,g}$ Shutdown, and start-up event of generating unit 0,1
- $\phi_{n,or}$ Commitment in activating balancing energy from balancing capacity provided 0,1
- $SoC_{n,s}$ State of Charge (SoC) of the energy reservoir for ESS unit MWh
- $s_{n,s}$ Spilled energy of the energy reservoir for ESS unit [MWh]

- $dr_{n,or}, ur_{n,or}$ Provision of upward and downward operating reserves for generating unit [MW]
- $dr'_{n,s}, ur'_{n,s}$ Provision of upward and downward operating reserves for ESS unit [MW]
- $ad_{n,or}, au_{n,or}$ Activated energy associated with the provision of upward and downward operating reserves for generating unit [MWh]
- $ad'_{n,s}, au'_{n,s}$ Activated energy associated with the provision of upward and downward operating reserves for ESS unit [MWh]
- $rsu_{n,g}, rsd_{n,g}$ Upward and downward ramping services provided by generating unit for each load level [MW/h]
- $ru_{n,g}, rd_{n,g}$ Ramp-up and -down of generating unit for each load level [MW/h]
- $nrsu_n, nrsd_n$ Non-served Upward and downward ramping services for each load level [MW/h]
- π_{1n} Dual variables of demand balance constraint [€/MWh]
- π_{2n}, π_{3n} Dual variables of upward and downward operating reserves' constraints [€/MWh]
- π_{4n}, π_{5n} Dual variables of upward and downward ramping services' constraints [€/MWh]

Chapter 3

Methodology

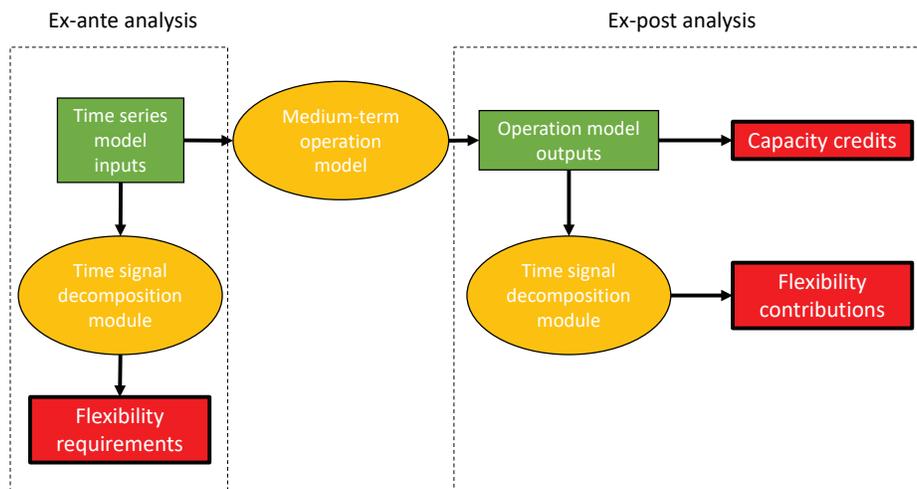


Figure 3.1: Overview of the methodology for assessing flexibility and capacity value simultaneously

This chapter introduces the operation optimization model specifically developed to analyze the roles of ESS technologies in high VRES penetration

scenarios. Initially, this chapter provides a comprehensive overview of the model, focusing on its fundamental equations. Subsequently, the chapter delves into the model updates according to wholesale system and flexibility services modeling. The final section outlines the methodology built to evaluate the contributions of dispatchable technologies in terms of flexibility and adequacy within the power system. This model, previously presented in Huclin et al. 2022 [1] and applied in Huclin et al. 2023 [2], serves as a critical tool in understanding the roles of ESSs in renewable-dominated power systems.

The comprehensive methodology developed in the context of this thesis aligns with the European Commission’s directive [3], emphasizing the necessity to consider flexibility aspects across multiple time scales. Furthermore, it responds to the growing need, as underscored by [4] and [5], to incorporate flexibility considerations in power system adequacy assessments, thus ensuring a more robust and adaptable approach to managing modern electricity systems in scenarios with high shares of VRES.

This Chapter thoroughly explains the methodological approach developed within the context of this thesis, which is provided and summarized in Figure 3.1.

The methodology unfolds through three principal stages, each elaborated in subsequent sections. The initial stage, termed the *ex-ante* analysis, depicted in the dotted box of Figure 3.1, delves into determining the flexibility requirements, as presented in Section 3.3.2. This is followed by executing a medium-term operation model, presented in Section 3.1, which reproduces the power system’s operation over one year, considering wholesale flexibility services. The concluding stage described in Section 3.3.3, the *ex-post* analysis of the model’s outputs, also highlighted in the dotted box of Figure 3.1, involves the computation of capacity values and contributions to flexibility.

All flexibility and adequacy analysis calculations were performed using a MATLAB script specifically developed for this thesis. The details of this script, along with the code and the SEED model written in GAMS are available in [6]

3.1 SEED Model

3.1.1 Global presentation

The study of how various ESSs compete operationally in a diverse electricity mix necessitates a detailed hourly analysis at the operational level, maintaining a chronological sequence of events related to demand and non-dispatchable VRES production. This approach is essential for medium-term analysis. In modeling the intricacies of electricity system operations, linear optimization models are typically employed due to their high efficiency in algorithms, which helps in reliably identifying optimal solutions [7].

The SEED (Spanish Electricity Economic Dispatch) model, introduced in this research, serves as a medium-term operation planning tool for various case studies and sensitivity analyses. This tool is instrumental in projecting the operation of power systems for future scenarios, such as the year 2030. SEED meticulously reproduces the centralized operation of an electricity system, adopting the viewpoint of the System Operator, providing hourly data over a year-long period, amounting to 8760 hours. The model's formulation shares some constraint formulations with the open-access openTEPES model [8] and incorporates key constraints thoroughly detailed in this section.

SEED's approach includes consideration of hourly demand and the necessary balancing services, such as balancing capacity and balancing energy, in line with [9]. While operating reserves are typically associated with shorter time frames, their representation in medium-term models through an hourly approximation is considered sufficient. The model maintains a clear distinction between the power availability of a unit and the energy it delivers further. Various methodologies exist for linking availability and activated energy, ranging from stochastic to deterministic approaches. A commonly used deterministic method associates balancing capacity and energy through an activation coefficient derived from historical data [10]. SEED not only manages different ESSs but also quantifies the contribution of each technology in providing hourly operating reserves and energy generation, preserving the chronological integrity of the input data.

SEED's capacity as a hydrothermal medium-term operation planning model categorizes hydroelectric power plants per guidelines from [4] and [11]. The model encapsulates various forms of hydroelectric generation, including Hydro Storage, CLPSH, OLPSH, and Run-of-River technologies. Given that run-of-river hydro has no storage capabilities, it is often treated as a non-

dispatchable hydropower technology. SEED further differentiates ESSs based on their energy reservoirs' efficiency, installed capacity, and maximum and minimum energy capacities. The model internally assesses these parameters, along with the ratio of installed power to maximum reservoir capacity, to determine the optimal operation of each ESS, including generation, storage, pumping, or water spilling.

Echoing the methodologies of [12], [13], and [14], SEED also incorporates the provision of upward and downward operating reserves on an hourly basis. As the provision of operating reserves is critical for the continuity of the electricity system, participation in providing operation reserves is limited to dispatchable technologies such as thermal, ESS facilities, and Hydro Storage (e.g., dams) [15]. Although wind technology can provide downward operating reserves [16], to be more conservative, this aspect is not considered in this thesis.

An additional parameter in SEED is set to regulate the operation of CLPSHs and batteries, distinguishing between daily operating storage (Daily ESS) and weekly operating storage (Weekly ESS). While Weekly ESS is designed to charge during weekends and discharge during weekday peak hours, Daily ESSs are configured to charge in off-peak hours and discharge during peak hours. ESSs with a maximum discharge time of up to 6 hours are categorized as daily storage. The model considers hydro market units and OLPSHs as seasonal storage, meaning these technologies must achieve the target reservoir level by the year's end. It is important to note that the specified regulation for ESSs serves as a guideline for their potential operation, not as a strict constraint. Ultimately, the SEED model autonomously determines the optimal operation of ESSs within the framework of these guidelines, ensuring that the physical and technical limits of the ESSs are respected.

3.1.2 Basic Model Equations

The SEED model formulation is detailed below. All parameters and variables are presented in capital and lower-case letters, respectively. The SEED model, developed from an academic model named STARNET and developed at the Institute for Research in Technology (IIT) [17], incorporates several enhancements to address modern power system requirements. These enhancements include mechanisms to consider operating reserves (i.e., balancing capacity and energy activation) and the integration of ramping ser-

vices. Additionally, the model now accounts for discharging time, allowing for differentiation between various ESSs.

The SEED model shares similarities with the openTEPES model [8], as they share certain constraint formulations. Although the capability to explore stochasticity is not utilized in the study presented in this thesis, the SEED model shows high versatility and, therefore, potential for broader applicability in future research endeavors.

Equation (3.1) delineates the objective function, which is strategically designed to minimize the aggregate cost of operating the entire system over an entire year. This comprehensive system operation cost encapsulates various components, such as the production costs of generation CV_g , which include fuel costs, variable operation and maintenance (O&M) expenses, and costs associated with emissions. Additionally, the cost associated with charging ESSs, denoted as CV_s , and the cost attributed to energy not served ($CENS$) are integral parts of the total system operation cost.

In this equation, the parameter DUR_n signifies the duration for each considered load level n . In the context of this model, the duration for each load level is uniformly set to $DUR_n = 1$. This standardization facilitates a streamlined calculation process across all load levels. The model considers the set g , which encompasses all installed generating units within the system, offering a comprehensive view of the generation landscape. Concurrently, the set ess is specifically tailored to include only those generating units that can consume energy through charging or pumping activities. This distinction ensures that the model accurately reflects the roles of ESSs in the system operation, accounting for their unique role in balancing energy supply and demand. The ens_n is used as a slack variable representing the volume of energy non-served for each load level n in case the installed capacity can not meet the load demand.

$$\min \sum_{n,g} DUR_n (CV_g p_{n,g} + CV_s g c_{n,s} + CENS ens_n) \quad (3.1)$$

Equation (3.2) shows the balance between generation and demand. The equation applies simultaneously for all the considered load levels over the time scope. π_n represents the dual variables of the generation-demand balance constraint of the SEED model. In the context of the power system optimization model assuming perfect competition, the value of π_{1_n} can be interpreted as the incremental cost change in the system's total operation

for satisfying an additional unit of demand. This interpretation is crucial for making informed decisions in managing and optimizing power systems. It allows system operators and planners to gauge the cost-effectiveness of generating additional power, thereby ensuring efficient and economical operation of the power system.

$$\sum_g \{gp_{n,g} - gc_{n,g}\} + ens_n = D_n \quad : \pi_{1_n} \quad \forall n \quad (3.2)$$

The generation output variable of generation units $gp_{n,g}$ is defined in Equation (3.3). In this equation, \underline{P}_g represents the minimum output level of the generating unit once committed. The term $uc_{n,g}$ is a binary variable that indicates whether a generating unit is committed (active) or not at a specific time. When this variable is set to one, it implies that the unit is in operation, and its output at least equals the minimum generation level, \underline{P}_g . The second term, $p_{n,g}$, refers to the generation output above this minimum level. Therefore, the total output of a generating unit, $gp_{n,g}$, is the sum of its committed minimum output and any additional generation above this threshold. Equation (3.3) effectively models the operational characteristics of power generation units, reflecting the physical reality that a power unit, once committed, will at least generate its minimum output level. Any additional generation capacity is then considered based on the system's demand and the unit's maximum capacity.

$$gp_{n,g} = \underline{P}_g uc_{n,g} + p_{n,g} \quad \forall n, g \quad (3.3)$$

The logical interplay between the commitment, start-up, and shutdown statuses of a committed generation unit is eloquently captured in Equation (3.4), as explained in [18]. $uc_{n,g}$ represents the commitment status of a generating unit, indicating whether the unit is operational at a particular load level. The term $uc_{n-1,g}$ refers to the commitment status of the same unit at the immediately preceding load level. This differential, $uc_{n,g} - uc_{n-1,g}$, effectively tracks the change in the commitment status of the unit from one load level to the next. The right-hand side of the equation, $su_{n,g} - sd_{n,g}$, represents the start-up and shutdown activities of the unit, respectively. The start-up variable, $su_{n,g}$, is activated (i.e., takes the value of one) when a unit transitions from an uncommitted to a committed state, signifying that the unit is starting up. Conversely, the shutdown variable, $sd_{n,g}$, is activated when a unit transitions from committed to uncommitted, indicating that the

unit is shutting down. For the first load level of the first period, Equation (3.4) integrates an initial commitment status for all units. This initial status is determined according to the merit order principle, where the system operator commits to generating units from the lowest to the highest variable costs. This ordering ensures the system prioritizes deploying units with lower operational costs before resorting to more expensive options.

$$uc_{n,g} - uc_{n-1,g} = su_{n,g} - sd_{n,g} \quad \forall n, g \quad (3.4)$$

The modeling of maximum ramp-up and ramp-down capabilities is mathematically represented in equations (3.5) and (3.6), as detailed in the research by [19]. These equations are instrumental in capturing the behavior of power generation units, specifically in their ability to adjust power output over time. Equation (3.5) describes the maximum ramp-up capacity, which is the ability of a generating unit to increase its power output from one hour to the next. Conversely, Equation (3.6) delineates the maximum ramp-down capacity, which refers to the capability of a unit to decrease its power output. In both equations, $p_{n,g}$ represents the power output at the current hour, while $p_{n-1,g}$ signifies the output in the preceding hour. The terms RU_g and RD_g in the denominators denote the ramp-up and ramp-down rates and are specific to each technology and generating units. The duration of each load level, denoted by DUR_n , is also factored into these calculations.

$$\frac{p_{n,g} - p_{n-1,g}}{RU_g DUR_n} \leq uc_{n,g} - su_{n,g} \quad \forall n, g \quad (3.5)$$

$$\frac{p_{n,g} - p_{n-1,g}}{RD_g DUR_n} \leq -uc_{n,g} + sd_{n,g} \quad \forall n, g \quad (3.6)$$

Equation (3.7) illustrates the State of Charge (SoC) for energy reservoirs of all ESS units. This equation is fundamental in managing ESS units' charge and discharge cycles. The model takes into account the roundtrip efficiency, EF_g , for the consumption ($gc_{n,s}$) of an ESS unit. This efficiency factor is crucial as it determines the effectiveness with which energy is stored and later retrieved from the ESS units.

$$SoC_{n-\tau_s,s} - SoC_{n,s} - s_{n,s} + \sum_{n'=n+1-\tau_s}^n (EI_{n,s} - gp_{n,s} + EF_g gc_{n,s}) = 0 \quad \forall n, s \quad (3.7)$$

While hydropower production output is typically dependent on the energy level in the reservoirs, the model assumes a simplification for ESS units like Hydro Storage and PSH. Specifically, it posits that water head dependency does not influence the production output ($gp_{n,s}$). This means that both generating and pumping actions impact the state of charge of the energy reservoirs, but the available power capacity remains constant, regardless of the reservoir's energy level. As a result, the power output of the ESS units does not vary with changes in their state of charge.

Energy inflows, represented by $EI_{n,s}$, are determined weekly, adding another layer of detail to the model's representation of ESS operations. The state of charge of ESS units is formulated with the duration of their discharge parameter, τ_s . This parameter effectively limits the usage of ESSs based on their maximum discharge time, imposing realistic operational constraints. For instance, if an ESS has $\tau_s = 24$ or $\tau_s = 168$, Equation (3.7) will set the state of charge variable once per day or week, respectively. This results in 360 or 52 updates within a year, aligning with the daily or weekly operational cycles of the ESS.

The model, thus, accommodates various levels of flexibility offered by ESSs with different discharge timeframes. By accounting for different timeframes and operational characteristics of ESSs, the model provides a nuanced understanding of how ESSs contribute to overall power system adequacy and flexibility.

Equations (3.8) and (3.9) specifically define the operational boundaries for the second block of output (i.e., output above the minimum load of a generating unit) from committed thermal and ESS units. Equation (3.8) delineates the maximum output level of the second block of a committed unit. In this equation, the ratio of the unit's power output $p_{n,g}$ to the difference between its maximum \overline{P}_g and minimum \underline{P}_g output capacities establishes an upper limit. This limit is further constrained by the unit's commitment status, indicated by $uc_{n,g}$. This equation ensures that the power output does not exceed the operational capacity designated for the unit's second block.

$$\frac{p_{n,g}}{\overline{P}_g - \underline{P}_g} \leq uc_{n,g} \quad \forall n, g \quad (3.8)$$

Conversely, Equation (3.9) specifies the minimum output level, affirming that the ratio of the unit's power output to its operational range should be non-negative. This formulation guarantees that the power output remains

within a feasible and realistic range, adhering to the physical constraints of the unit.

$$\frac{p_{n,g}}{\overline{P}_g - \underline{P}_g} \geq 0 \quad \forall n, g \quad (3.9)$$

Additionally, Equation (3.10) is a critical constraint that prevents ESS units from simultaneously charging and discharging using their full installed capacities. This constraint is crucial for ensuring ESS units' practical and efficient operation.

$$\frac{p_{n,s}}{\overline{P}_s - \underline{P}_s} + \frac{c_{n,s}}{\overline{C}_s} \leq 1 \quad \forall n, s \quad (3.10)$$

In this equation, the sum of the ratios of discharging power output and charging capacity to their respective maximum limits must not exceed one. This equation limits the Energy ESS units to operate within their physical capacities. It effectively prevents the scenario where an ESS unit simultaneously charges and discharges at total capacity, which is practically infeasible and could lead to operational inconsistencies. Instead, this equation ensures that the combined activities of generating (discharging) and pumping (charging) do not exceed the total installed capacity of the ESS unit. This formulation allows ESS units to provide multiple services simultaneously.

Equations (3.11 - 3.17) show variable bounds.

$$0 \leq gp_{n,g} \leq \overline{P}_g \quad \forall n, g \quad (3.11)$$

$$0 \leq gc_{n,s} \leq \overline{C}_s \quad \forall n, s \quad (3.12)$$

$$0 \leq p_{n,g} \leq \overline{P}_g - \underline{P}_g \quad \forall n, g \quad (3.13)$$

$$0 \leq c_{n,s} \leq \overline{C}_s \quad \forall n, s \quad (3.14)$$

$$0 \leq s_{n,s} \quad \forall n, s \quad (3.15)$$

$$0 \leq SoC_{n,s} \leq I_s \quad \forall n, s \quad (3.16)$$

$$0 \leq ens_n \leq D_n \quad \forall n \quad (3.17)$$

3.2 Wholesale Flexibility Services Modelling

This section is dedicated to elucidating how wholesale flexibility services (i.e., operating reserves and ramping services) have been integrated within the framework of a medium-term operation model. Including these services is a critical advancement, reflecting modern power systems' evolving needs and complexities.

To maintain clarity and focus, this section will highlight the modifications and additions to the model's equations. Readers need to note that these changes build upon the foundational model as detailed in Section 3.1.2. Therefore, the equations presented in the forthcoming sections should be viewed as enhancements or updates to the existing model structure rather than as standalone components.

3.2.1 Operating Reserves Modelling

The generation output variable for generation units, defined initially as $gp_{n,g}$ in Equation (3.3), has been redefined and updated in Equation (3.18). This updated equation expands its scope to encompass the unit's energy generation and usage, particularly energy activation for providing upward and downward operating reserves. The modeling of energy activation for these reserves is approached deterministically, aligning with methodologies presented in [12], [20], [21].

Energy activation, in this context, involves the application of deterministic activation coefficients (CD, CU) to the quantity of operating reserve provided ($dr_{n,or}, ur_{n,or}$). This approach ensures a precise and predictable way of incorporating the energy activation of these reserves into the model, as demonstrated in Equations (3.33) and (3.36). It is crucial to note that Equation (3.18) excludes non-dispatchable technologies, focusing solely on dispatchable units.

$$gp_{n,g} = \underline{P}_g uc_{n,g} + p_{n,g} + au_{n,or} - ad_{n,or} \quad \forall n, g \quad (3.18)$$

In parallel, the consumption output variable for installed ESS units, denoted as $gc_{n,s}$, is defined in Equation (3.19). This equation integrates the unit's power consumption with its energy activation related to providing upward and downward operating reserves. Unique variables are employed to account for the participation of ESS units in operating reserves when they are

consuming (charging), distinguishing them from the variables used in Equation (3.18), which relate to production (discharging). Unlike thermal units, this differentiation is critical since ESS units can generate and pump. Consequently, the model differentiates ESS and non-ESS technologies regarding their contributions to operating reserves.

$$gc_{n,s} = c_{n,s} + au'_{n,s} - ad'_{n,s} \quad \forall n, s \quad (3.19)$$

Equations (3.20) and (3.21) are extensions of the original ramping equations (3.5) and (3.6), incorporating additional dimensions to reflect better the capabilities of generating units. These equations consider not only the units' generation capacity $p_{n,g}$ but also include the aspects of balancing capacity $ur_{n,g}$. Equation (3.20) calculates the ratio of the difference in generation and upward balancing capacity between the current and previous hours to the ramp-up rate and duration. This calculation is pivotal in determining the ramp-up capability of the units while considering their contribution to upward balancing reserves. Similarly, Equation (3.21) addresses the ramp-down process, factoring in the difference in generation and downward balancing capacity between consecutive hours, providing a comprehensive view of the unit's ability to decrease its output.

$$\frac{p_{n,g} + ur_{n,g} - (p_{n-1,g} + dr_{n-1,g})}{RU_g DUR_n} \leq uc_{n,g} - su_{n,g} \quad \forall n, g \quad (3.20)$$

$$\frac{p_{n,g} - dr_{n,g} - (p_{n-1,g} + ur_{n-1,g})}{RD_g DUR_n} \leq -uc_{n,g} + sd_{n,g} \quad \forall n, g \quad (3.21)$$

Equations (3.22) and (3.23) detail the provision of upward and downward operating reserves by dispatchable units such as thermal and ESS units. In the context of ESS units, the model differentiates between the supply of operating reserves when the units are in the production phase ($dr_{n,s}$, $ur_{n,s}$) versus when they are in the charging phase ($ur'_{n,s}$, $dr'_{scd,p,n,s}$). This differentiation is vital because ESS units have the unique capability to generate and charge, and thus, their role in providing operating reserves changes depending on their operational state. The constraints (3.22) and (3.23) ensure

that the amount of operating reserves provided at each load level meets or exceeds the set requirements (DR_n, UR_n) , thus incorporating a safety margin to protect against critical events, as emphasized in the literature [12]–[14], [22]. The dual variables π_{2_n} and π_{3_n} correspond to these operating reserve equations, respectively.

$$\sum_{or} ur_{n,or} + \sum_s ur'_{scd,p,n,s} \geq UR_n \quad : \pi_{2_n} \forall n \quad (3.22)$$

$$\sum_{or} dr_{n,or} + \sum_s dr'_{scd,p,n,s} \geq DR_n \quad : \pi_{3_n} \forall n \quad (3.23)$$

Equations (3.24) and (3.25) represent the refined versions of Equations (3.8) and (3.9), specifically formulated to define the maximum and minimum outputs of the second block of a committed generation unit. Equation (3.24) addresses the maximum output by incorporating the provision of upward operating reserves $(ur_{n,g})$, whereas Equation (3.25) is concerned with the minimum output, considering the downward operating reserves $(dr_{n,g})$.

$$\frac{p_{n,or} + ur_{n,or}}{P_{or} - \underline{P}_{or}} \leq uc_{n,or} \quad \forall n, or \quad (3.24)$$

$$\frac{p_{n,or} - dr_{n,or}}{P_{or} - \underline{P}_{or}} \geq 0 \quad \forall n, or \quad (3.25)$$

Equations (3.26) and (3.27) focus on the consumption aspect of ESS units, particularly when they are involved in charging operations. They consider the ESS units' contribution to upward and downward operating reserves during the charging phase. These equations ensure that ESS units' consumption for charging is appropriately modulated, considering their involvement in providing operating reserves.

$$\frac{c_{n,s} + dr'_{n,s}}{\bar{c}_s} \leq 1 \quad \forall n, s \quad (3.26)$$

$$\frac{c_s - ur'_{n,s}}{\bar{c}_s} \geq 0 \quad \forall n, s \quad (3.27)$$

Lastly, Equation (3.28) is an updated version of Equation (3.10), and it serves as a crucial constraint to prevent ESS units from simultaneously charging and discharging at their full installed capacities. This equation maintains

consistency with Equations (3.24) and (3.26), ensuring that the operational constraints of ESS units are realistically represented. The adaptations of these equations, drawn from sources such as [18], [23]–[25], further enhance the model’s robustness and relevance in the context of the analysis of ESS roles in scenarios with high VRES shares.

$$\frac{p_{n,s} + ur_{n,s}}{\underline{P}_s - \underline{P}_s} + \frac{c_{n,s} + dr'_{n,s}}{C_s} \leq 1 \quad \forall n, s \quad (3.28)$$

Equations (3.29) and (3.30) are designed to ensure the operational feasibility of ESS units, particularly when they are engaged in providing operating reserves, both upward and downward, respectively. These equations are critical as they safeguard against the scenario where ESS units might be called upon to provide operating reserves when their energy reservoirs are depleted. Equation (3.29) links the provision of upward operating reserves to the state of charge (SOC) of the ESS unit, ensuring that an ESS unit cannot commit to providing upward reserves if its energy reservoir is empty. Similarly, Equation (3.30) connects the provision of downward operating reserves to the remaining capacity in the ESS unit’s reservoir, preventing the ESS unit from committing to downward reserves if its reservoir lacks sufficient energy.

$$ur_{n,s} \leq \frac{SoC_{n,s}}{DUR_n} \quad \forall n, s \quad (3.29)$$

$$dr_{n,s} \leq \frac{I_s - SoC_{n,s}}{DUR_n} \quad \forall n, s \quad (3.30)$$

Furthermore, Equations (3.31) to (3.33) manage the relationship between balancing capacity and balancing energy for generating units that are eligible to participate in operating reserves (i.e., dispatchable technologies). These equations are particularly relevant for thermal and ESS units and include a binary variable $\phi_{n,or}$ to account for activating the balancing capacity. Equations (3.33) and (3.36) specifically prevent units from simultaneously supplying upward and downward balancing energy, ensuring realistic and feasible operational scenarios. Additionally, Equations (3.34) to (3.36) address similar relationships for ESS units in pumping mode, differentiating between their roles in providing operating reserves when they are charging versus when they are producing. These equations, drawing from the insights of [9], [26], play a relevant role in accurately capturing the capabilities and limits

of dispatchable technologies, especially in their ability to provide operating reserves within power system operations.

$$au_{n,or} \leq (\overline{P_{or}} - \underline{P_{or}}) \phi_{n,or} \quad \forall n, or \quad (3.31)$$

$$ad_{n,or} \leq (\overline{P_{or}} - \underline{P_{or}}) (1 - \phi_{n,or}) \quad \forall n, or \quad (3.32)$$

$$au_{n,or} - ad_{n,or} = CUur_{n,or} - CDdr_{n,or} \quad \forall n, or \quad (3.33)$$

$$au'_{n,s} \leq (\overline{C_s} - \underline{C_s}) \phi_{n,s} \quad \forall n, s \quad (3.34)$$

$$ad'_{n,s} \leq (\overline{C_s} - \underline{C_s}) (1 - \phi_{n,s}) \quad \forall n, s \quad (3.35)$$

$$au'_{n,s} - ad'_{n,s} = CUdr'_{n,s} - CDur'_{n,s} \quad \forall n, s \quad (3.36)$$

Lastly, Equations (3.37) and (3.38) mirror the logic of Equations (3.29) and (3.30), but they apply to ESS units while charging. These equations ensure that ESS units do not commit to providing operating reserves if their energy reservoirs are inadequate for such operations while in the charging state.

$$ur'_{n,s} \leq \frac{I_s - SoC_{n,s}}{DUR_n} \quad \forall n, s \quad (3.37)$$

$$dr'_{n,s} \leq \frac{I_s - SoC_{n,s}}{DUR_n} \quad \forall n, s \quad (3.38)$$

Equations (3.39) - (3.46) list variable bounds.

$$0 \leq ur_{n,g} \leq \overline{P_g} - \underline{P_g} \quad \forall n, g \quad (3.39)$$

$$0 \leq ur'_{n,s} \leq \overline{C_s} \quad \forall n, s \quad (3.40)$$

$$0 \leq dr_{n,g} \leq \overline{P_g} - \underline{P_g} \quad \forall n, g \quad (3.41)$$

$$0 \leq dr'_{n,s} \leq \overline{C_s} \quad \forall n, s \quad (3.42)$$

$$0 \leq au_{n,g} \leq \overline{P_g} - \underline{P_g} \quad \forall n, g \quad (3.43)$$

$$0 \leq au'_{n,s} \leq \overline{C_s} \quad \forall n, s \quad (3.44)$$

$$0 \leq ad_{n,g} \leq \overline{P_g} - \underline{P_g} \quad \forall n, g \quad (3.45)$$

$$0 \leq ad'_{n,s} \leq \overline{C_s} \quad \forall n, s \quad (3.46)$$

3.2.2 Ramping Services Modelling

As delineated by [27], the introduction of ramping service requirements in power systems considers several factors, such as deviations from forecasts, historical uncertainties, and prevailing policies that manage variability aspects, such as reserves margin. Consequently, it is essential to tailor these wholesale flexibility service requirements specifically to the characteristics of each power system. Initially, the constraints that define both upward and downward ramping services, as per [27], were conceived for short-term operational models with time steps typically spanning minutes. However, to align these ramping service constraints with the needs of a medium-term operation model, adaptations have been made to suit hourly time steps.

According to variable costs related to supplying operating reserves and ramping services, these might diverge from the costs associated with demand and supply, as discussed in [28]. However, to maintain simplicity in the model and avoid arbitrary decision-making, a uniform cost is applied irrespective of the specific services rendered by the various technologies.

Equations (3.47) and (3.48) describe how dispatchable technologies provide upward and downward ramping services (i.e., $rsu_{n,g}$, $rsd_{n,g}$). These equations require that the ramping services offered at each load level should at least match the predefined ramping requirements (i.e., RSU_n , RSD_n). This approach ensures that ramping services are incorporated as a crucial component of wholesale flexibility services, effectively integrating a safety ramp margin to mitigate the effects of critical events. The dual variables π_{4n} and π_{5n} correspond to these ramping service equations, respectively. $nsrsu_n$ and $nsrsd_n$ represent the non-served upward and downward ramping services.

$$\sum_g rsu_{n,g} + nsrsu_n \geq RSU_n \quad : \pi_{4n} \quad \forall n \quad (3.47)$$

$$\sum_g rsd_{n,g} + nsrsd_n \geq RSD_n \quad : \pi_{5n} \quad \forall n \quad (3.48)$$

Furthermore, the total output of generation units, previously defined in Equation (3.3, is redefined in Equation (3.49). This equation incorporates the minimum output level (\underline{P}_g) of a committed generating unit, the commitment status ($uc_{n,g}$), and additional parameters reflecting both the generation of energy and its utilization. These include the provision of activated energy

of the upward and downward operating reserves ($au_{n,g}$, $ad_{n,g}$), as well as the adjustments made for ramping service requirements.

$$gp_{n,g} = \underline{P}_g uc_{n,g} + p_{n,g} + au_{n,g} - ad_{n,g} + rsu_{n,g} + rsd_{n,g} \quad \forall n, g \quad (3.49)$$

The total ramp-up and ramp-down abilities of a generation unit, outlined in Equations (3.50) and (3.51), are critical for ensuring that units can respond effectively to fluctuations in demand. These abilities must exceed the sum of the unit's ramp-up and ramp-down contributions and any additional ramping service provided, thus enabling the unit to adapt to changing demand curves and fulfill additional ramping service requirements.

$$RU_{n,g} \geq ru_{n,g} + rsu_{n,g} \quad \forall n, g \quad (3.50)$$

$$RD_{n,g} \geq rd_{n,g} + rsd_{n,g} \quad \forall n, g \quad (3.51)$$

The added variable bounds are shown in Equations (3.52) - (3.55):

$$rsu_{n,g} \leq RU_{n,g} \quad \forall n, g \quad (3.52)$$

$$rsd_{n,g} \leq RD_{n,g} \quad \forall n, g \quad (3.53)$$

$$0 < ru_{n,g} \leq RU_{n,g} \quad \forall n, g \quad (3.54)$$

$$0 > rd_{n,g} \geq -RD_{n,g} \quad \forall n, g \quad (3.55)$$

3.2.3 Wholesale System Services's Income

The SEED model is designed to simulate the centralized operation of the Spanish power system under ideal market conditions. These conditions presuppose market efficiencies, perfect information, and transparent pricing mechanisms, all contributing to optimal system operations. In this idealized scenario, the system operator's pursuit of minimizing total operational costs is in harmony with the generation companies' objective to maximize their profits, thereby leading to an optimized operational outcome [29].

This section elucidates the role of dual variables concerning constraints associated with wholesale system services. Dual variables signify the incremental cost of producing an additional unit of electricity required for enhanced service provision, commonly referred to as the Short Run Marginal Cost (SRMC), denominated in €/MWh. These dual variables fulfill a dual

purpose: firstly, they represent the cost change in the objective function resulting from the increase of the limit constraints to meet an extra unit of load demand. Secondly, they measure the revenue a production unit generates for rendering a specific service.

Given that this thesis aims to thoroughly analyze the revenue streams of technologies across various provided services, the dual variables linked to the service constraints are multiplied by the volume of service rendered by the technology. The aggregate income of technology is computed using Equations (3.56)-(3.58), where I_g^{Total} symbolizes the total income, I_g^{Energy} represents the income from energy, I_g^{RS} reflects the income from ramping services, and I_g^{OR} corresponds to the income from operating reserves.

$$I_g^{Total} = I_g^{Energy} + I_g^{FR} + I_g^{OR} \quad \forall g \quad (3.56)$$

$$I_g^{Energy} = \sum_n gp_{n,g} \cdot \pi_{1n} \quad \forall g \quad (3.57)$$

$$I_g^{OR} = \sum_n ru_{n,g} \cdot \pi_{2n} + \sum_n rd_{n,g} \cdot \pi_{3n} \quad \forall g \quad (3.58)$$

$$I_g^{RS} = \sum_n rsu_{n,g} \cdot \pi_{4n} + \sum_n rsd_{n,g} \cdot \pi_{5n} \quad \forall g \quad (3.59)$$

3.3 Operational Flexibility Assessment

The next phase of this research presents a comprehensive framework designed to analyze the electricity system's needs in terms of wholesale energy flexibility. This section introduces a developed methodology for assessing the flexibility of power systems across various time scales. Recognizing that flexibility signifies the system's ability to handle variability and uncertainty [30], it becomes clear that both load demand and VRES productions show variability across different time scales. This methodology is required for quantifying and analyzing how effectively a power system can adapt to these fluctuations. It enables a detailed evaluation of strategies and technologies that can significantly enhance the power system's flexibility. By doing so, the methodology addresses the need to optimize power system operations, ensuring flexibility in the context of high shares of VRES.

3.3.1 Time signal decomposition

Despite their inherent variability and uncertainty, both load demand and VRES generation exhibit discernible periodic patterns, such as those driven by seasonal changes (hot and cold seasons), daily cycles (day and night), and weekly rhythms (workdays and weekends). The predictability within these patterns lends itself to applying frequency analysis methods, notably the Discrete Fourier Transform (DFT), as highlighted in the work of [30].

The DFT is a powerful mathematical tool for converting a signal from its original time-discrete form into a frequency-discrete representation. This transformation is crucial for analyzing the frequency components of a signal, especially in the context of power systems, where understanding these components can provide insights into demand and generation patterns. The DFT's formulation, as shown in Equation 3.60, allows for the extraction of discrete frequency-domain components ($X[k]$) from discrete time-domain samples ($x[n]$). Here, N denotes the total number of samples in the time series, while n and k represent indices in the time and frequency domains, respectively. Through the DFT, it is possible to identify and quantify the frequencies that dominate a signal, as indicated by their higher amplitudes in the transformed output. This capability is particularly valuable in the analysis of power systems. By understanding the frequency components of load demand and VRES output, planners and operators can better anticipate and manage the cyclical variations in energy supply and demand.

$$X[k] = \sum_{n=0}^{n=N-1} x[n] \cdot e^{-j\frac{2\pi nk}{N}} \quad (3.60)$$

Figure 3.2 illustrates the application of the DFT to the annual load demand time series, spanning 8760 hours, for various power systems, as documented by [31]. This figure provides a visual representation of the frequency components inherent in the load demand patterns of these power systems. On the horizontal axis, frequencies are measured in $\frac{1}{\text{year}}$, denoting the pseudo-periodicity of events in the power system. The vertical axis, normalized to the most prominent frequency component, indicates the relative intensity or strength of each frequency in the spectrum.

In Figure 3.2, all plots exhibit significant periodic components at frequencies of 52, 365, and 730 $\frac{1}{\text{year}}$. These frequencies correspond to the weekly (with 52 oscillations per year), daily (365 oscillations per year), and 12-hours

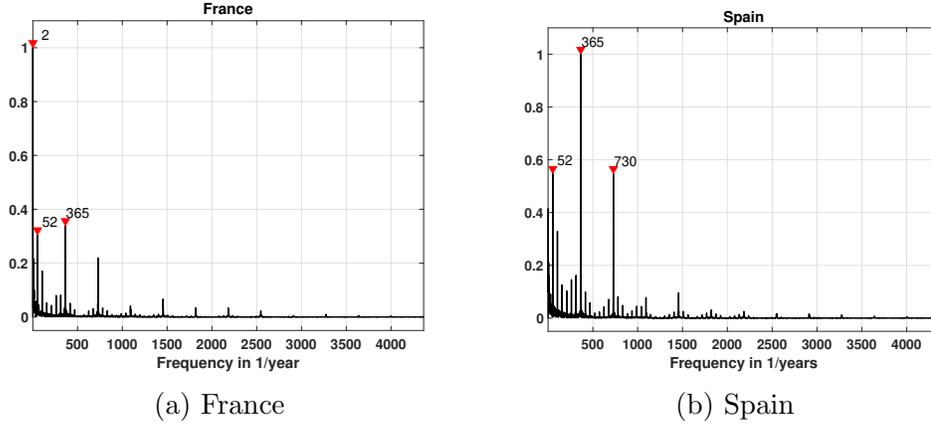


Figure 3.2: Hourly load demand in the frequency domain for different power systems in 2019 [31]. Red triangles signal the highest frequencies and their corresponding cycle number.

(730 oscillations per year) cycles. However, the intensity of these cycles varies depending on the specific power system under analysis. For instance, the power system in France displays a dominant frequency at $2 \frac{1}{\text{year}}$, indicating two primary cycles annually. This is predominantly attributed to the pronounced summer-winter seasonal cycle, heavily influenced by the widespread use of electrical heating. In contrast, Spain's power system showcases a less pronounced seasonal pattern than France's. Instead, the daily cycle, occurring 365 times a year, is more prominent in relative terms. This difference in cycle intensities underscores the diversity in power system behaviors across different regions and climates.

Further analysis uses three bandpass filters on the frequency signal to isolate and examine the relevant components, as demonstrated in [30], [32]. Figure 3.3a uses distinct colors to represent each filtered spectrum component, corresponding to the weekly, daily, and 12-hours signals (depicted as blue, red, and green boxes, respectively, in Figure 3.3a). The pseudo-periodicity observed in the load demand signals justifies the application of periodic bandpass filters. For example, the spectrum of the daily component is typically concentrated around multiples of the $365 \frac{1}{\text{year}}$ frequency. This pattern arises because periodic functions can be represented mathematically by a discrete spectrum or Fourier Series (as explained in [33]), with energy distributed at multiples of the fundamental frequency, which inversely correlates with the

signal's period.

Similarly, the 12-hours component's spectrum aligns with multiples of the $730 \frac{1}{\text{year}}$ frequency, following the same mathematical principle. Thus, using DFT and bandpass filters to analyze these power systems' load demand time series provides invaluable insights. This framework helps design flexible power systems and gives planners and investors insights according to dispatchable technologies' abilities to provide flexibility. Determining the appropriate width for the bandpass filter used in frequency analysis remains challenging due to its sensitivity. This sensitivity arises from the fact that aggregating the filtered signals inevitably leads to a minimal error, making it difficult to establish an optimal frequency cut-off point definitively. The existing literature acknowledges this challenge, including works by [30], [34], [35]. These authors have adopted varying methodologies for their analyses, justifying their chosen bandwidths based on the adequacy of the results they obtained. In this thesis, the focus is specifically on the Spanish power system, and the bandwidth for the bandpass filter is set at $120 \frac{1}{\text{year}}$. This decision is influenced by the nature and characteristics of the Spanish power system, taking into account its specific cyclic patterns and variability. The chosen bandwidth aims to effectively isolate the significant frequency components relevant to this particular system, ensuring that the analysis is tailored to its unique operational context.

Once the relevant spectrum bands for each component are identified, the next step involves reconverting these frequency-domain signals back into the time domain. This conversion is achieved using the Inverse Discrete Fourier Transform (IDFT). The IDFT performs the reverse operation of the DFT, effectively translating the frequency-domain information back into a time-based sequence. This process is crucial for interpreting the results in a temporal context, allowing for a more intuitive understanding of the patterns and trends within the data. Figure 3.3b displays the outcome of this process, showcasing three time-domain signals corresponding to the distinct components under analysis. Each signal represents a specific component – weekly, daily, or 12-hours cycles – as identified through the bandpass filtering process. Visualizing these signals in the time domain provides a clear and comprehensive depiction of how these components manifest over time, offering valuable insights into the operations of the power system. This approach underscores the importance of precise and context-specific frequency analysis in understanding and managing the complexities of modern power systems,

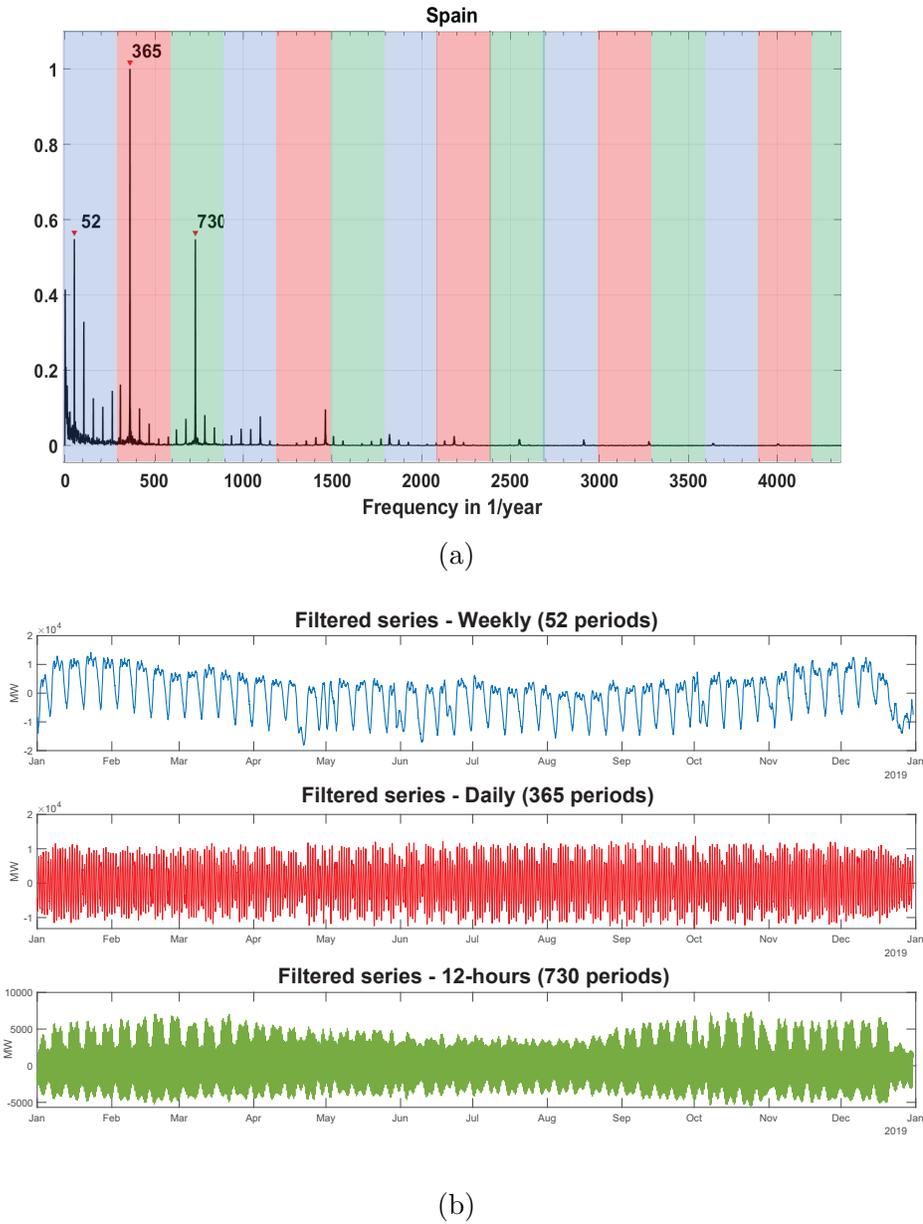


Figure 3.3: (a) Three bandpass filters for separating weekly (blue blocks), daily (red blocks), and 12-hours signals (green blocks); (b) Filtered time series obtained using IDFT on relevant frequencies

especially in the face of increasing renewable energy integration.

3.3.2 Assessing Operational Flexibility Requirements

Once hourly load demand is expressed according to different time scales, flexibility requirements are based on the distribution of the maximum variations during each signal cycle (i.e., 52 values for the weekly signal, 365 values for the daily signal, and 730 values for the 12-hours signal) as in [30], [35]. The measure of flexibility requirement considers the hourly time series of load demand over one year. Note that this measure applies to several scarcities in electricity systems, such as ramps, the energy required for a period, and operating reserves.

As an example, Figure 3.4 presents the operational flexibility requirements according to hourly load demand (blue), hourly load demand minus hourly solar PV output (yellow), hourly load demand minus hourly wind output (purple), and net hourly demand (i.e., load demand minus wind and solar PV) (red). Boxplots show the distribution of the different filtered time series according to the maximum variation observed in each period of signals. (e.g., the weekly boxplot includes 52 values corresponding to the maximum variation in hourly values observed each week of the year, and so on for other signals).

According to Figure 3.4, solar PV output shows more variability than wind on the 12-hours time scale, while the reverse is valid for the daily and weekly signals. Solar PV causes the 12-hours variability, while wind is the leading cause of the daily and weekly variability. Moreover, the maximum variation of solar PV is similar for the 12-hours and daily signals, while wind shows a more significant difference. In the case of the Spanish power system in 2019, the larger the time scale considered, the more wind variability impacts the operational flexibility requirements. This can be explained by the fact that in 2019, the share of wind energy in the Spanish electricity system was higher than that of solar PV. Thus, this thesis analyses net load demand and its components to study how technologies maintain adequacy and provide flexibility to power systems in a scenario with high VRES shares. These results are relevant for analyzing alternative future scenarios where the ratio between wind and solar changes, and so do the expected flexibility requirements in different time frames.

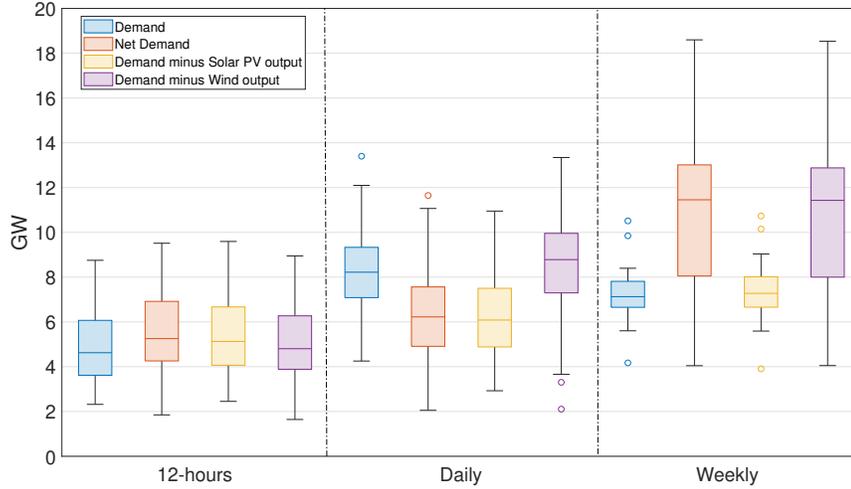


Figure 3.4: Operational flexibility requirements in power for the Spanish electricity system in 2019 [36]

3.3.3 Assessing contributions to operational flexibility

After obtaining the hourly outputs from the economic dispatch of generation and storage technologies through the operational model, a critical subsequent step involves filtering these outputs using a time series decomposition module. This process, aligned with methodologies in [34], [35], is pivotal for extracting the flexibility contributions of various technologies. The essence of this approach lies in analyzing how the dispatch outputs of these technologies fluctuate from their peak to average values over each considered signal period. This fluctuation effectively captures the contributions of different technologies to the operational flexibility of the power system.

In this context, the technology's contribution to the power system's operational flexibility is quantified by examining the ratio of changes in a technology's output relative to the net demand variations. This ratio clearly indicates how a technology deviates from its typical behavior across different timescales and in response to various power system scarcities. Essentially, this measurement offers a quantitative assessment of a technology's ability to adapt to the load demand and inherent variations in the electricity system. However, due to the frequent minor fluctuations in net demand and the one-hour time resolution data, primarily caused by the output variability

of VRES, a threshold of 20% is applied to filter out these less significant changes, as suggested in [34].

Based on [34], the following formulation is used in this thesis to quantify the flexibility contributions of dispatchable technologies, where $M_{n,g}^{cycle}$ defines the output variation¹ (i.e., in MW) of dispatchable units g for each load level n of the corresponding variability cycles (i.e., 12-hours, daily, weekly), and $CF_{n,g}^{cycle}$, stands for the flexibility contribution of a dispatchable unit for each load level, expressed in %. This formula is applied to the production output of technologies previously separated into different variability cycles. Consequently, each cycle period (i.e., 52, 365, and 730 periods for weekly, daily, and 12-hour cycles) determines how each dispatchable technology adjusts its production in response to variations in net demand.

$$\forall t = [1, 8760] : \left| \sum_g M_{n,g}^{cycle} \right| \geq 0.2 * \max \left(\left| \sum_g M_{n,g}^{cycle} \right| \right) \quad (3.61)$$

$$CF_{n,g}^{cycle} = \frac{M_{n,g}^{cycle}}{\sum_g M_{n,g}^{cycle}} * 100\%$$

Figure 3.5 is an illustrative example, showcasing the flexibility contributions of dispatchable technologies within the Spanish power system in 2019, as per data from [31]. This figure presents a detailed distribution of each technology's contribution to flexibility across various cycles. Here, data for OLPSH and Hydro Storage are only available in aggregate.

The boxplots in Figure 3.5 demonstrate how different technologies adjust their power output in response to significant changes in net demand, explicitly focusing on variations exceeding 20% of the maximum net demand value. Interestingly, some boxplots indicate contributions exceeding 100%, signifying instances where a technology's power output adjustment surpasses the net demand variations. In the case of the Spanish power system, among all technologies, Combined Cycle Gas Turbines (CCGT) emerge as the most significant contributors to flexibility across all timescales. In contrast, coal technology, as shown, is less flexible than CCGT and ESS due to its higher variable costs and slower ramp rates. Although limited, coal technology's contribution to flexibility tends to increase with longer timescales.

¹Difference between two consecutive hours.

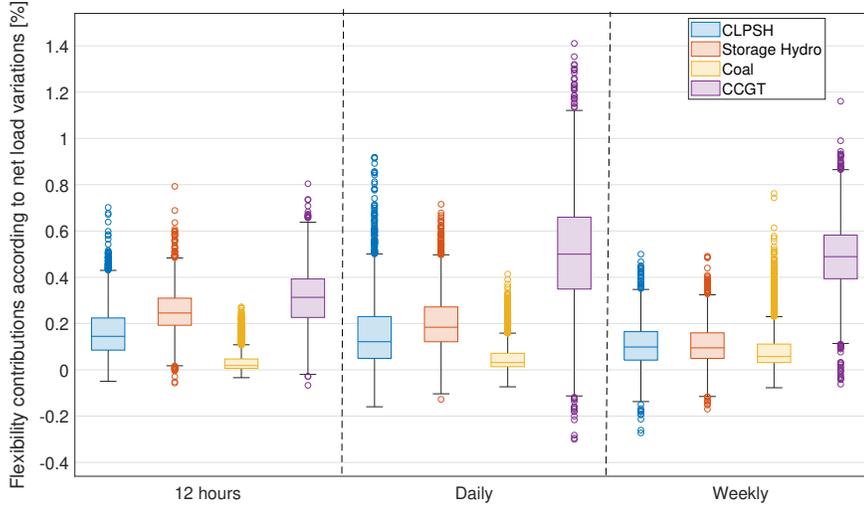


Figure 3.5: Operational flexibility contributions of dispatchable technologies according to net load variations in power for the Spanish electricity system in 2019[36]

Furthermore, Hydro Storage technology is observed to contribute more substantially to flexibility than CLPSH. This is attributed to Hydro Storage units having more excellent energy storage and installed capacities, enabling them to adjust their output more effectively in response to net demand variations. Such insights are invaluable for informing decisions on optimizing the mix of dispatchable technologies, specifically storage technology, to enhance overall operational flexibility and maintain the adequacy of power systems. This framework highlights the importance of considering different technologies' capacities and operational characteristics in shaping a responsive and resilient power system.

3.4 Concluding Remarks

The methodology conceptualized within the scope of the thesis, is primarily designed to assess flexibility requirements, gauge the contributions of various technologies to system flexibility, and evaluate their impact on the overall adequacy of the power system. Notably, the approach stands out for its scal-

ability and replicability across different scarcity scenarios and applicability to any electricity system. This universality is facilitated by the methodology's reliance on hourly time series data, encompassing load demand, VRES outputs, and the technical characteristics of generation and storage systems as its fundamental inputs.

The time series decomposition module is central to this methodology, explained in Section 3.3.1, which discerns the requirements for, and contributions to, flexibility. This module leverages a frequency analysis method, initially presented in [32] and subsequently adapted for hourly time steps in [30]. The decomposition process encompasses two steps: firstly, identifying the various relevant time scales present in the load demand and technology outputs, and secondly, quantifying the distribution of variations across these distinct periodicities.

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Chapter 4

Case Study & Scenarios

This chapter introduces the Spanish case study, methodically detailing the principal historical developments of the Spanish electricity system. It explores the challenges the Spanish power system is anticipated to encounter given their committed objectives of reducing electricity sector emissions to mitigate climate change [1]. Additionally, the chapter delves into the complexities involved in accurately modeling the Spanish electricity system, a task that becomes increasingly pertinent in the face of increasing non-dispatchable VRES capacity. Furthermore, it comprehensively discusses the various scenarios analyzed within this thesis. These scenarios are instrumental in offering analytical insights and potential solutions to the imminent challenges confronted by the Spanish power system, particularly in the context of an escalating reliance on renewable energy sources and the pursuit of sustainable energy policies.

4.1 Overview of the Spanish Power System

This section unfolds in two distinct segments. Initially, it embarks on a journey through the pivotal historical milestones shaping the evolution of Spain's electricity system. Following this retrospective, the focus shifts to a comprehensive evaluation of the current operational landscape of the Spanish power system. The overarching goal of this exploration is to equip readers with a thorough historical context essential for comprehending the multifaceted political, economic, and social intricacies and challenges integral to Spain's ongoing energy transition.

4.1.1 Beginnings to today

In the late 19th and early 20th centuries, coal-fired power plants predominantly shaped Spain's electricity landscape. The prevalent global energy practices and the technological constraints of that era dictated this choice. Coal was abundant and widely regarded as the cornerstone of early electricity generation [2].

The post-World War II period, stretching from the 1940s to the 1960s, marked a significant transition to hydroelectric power in Spain. This shift was part of the broader post-war reconstruction efforts, with hydroelectricity emerging as a reliable and economically viable power source, capitalizing on Spain's substantial hydrological resources.

The Nuclear Energy Era in Spain unfolded during a time of profound political and social change, marked by the transition from dictatorship to democracy, the threat of terrorism, the rise of left-wing political parties, growing environmental awareness, and economic challenges. This dynamic and occasionally turbulent backdrop significantly influenced the country's development and perception of nuclear energy. Emblematic examples, Lemoz Valdecaballeros, Trillo II, Regodola I, and Sayago I stand as testaments to Spain's aspirations in nuclear energy, although they remained unproductive, reflecting the challenges that characterized the sector during this era. Furthermore, the Chernobyl disaster played a pivotal role in shaping public sentiment, serving as a stark reminder of the inherent risks associated with nuclear power and contributing to a shift away from enthusiastic support for this energy source within Spanish society[3].

In the international context of electricity market liberalization, Spain took proactive measures. Simultaneously, the cost competitiveness of gas in comparison to coal became evident. Moreover, it was noted that the investment costs and construction durations for gas plants were significantly lower than those required for nuclear and hydroelectric facilities. These influencing factors played a substantial role in shaping Spain's investment decisions about gas infrastructure. Consequently, Spain successfully constructed multiple gas facilities within a relatively short period [4].

Furthermore, during a period of economic growth around the 2000s, the focus of electrical systems shifted towards environmental considerations. The Iberian Peninsula, blessed with highly advantageous topographical features for harnessing solar energy, experienced a surge of speculative investments in this technology. However, it is worth noting that this speculative boom

eventually subsided in the wake of the economic crisis of the 2010s.

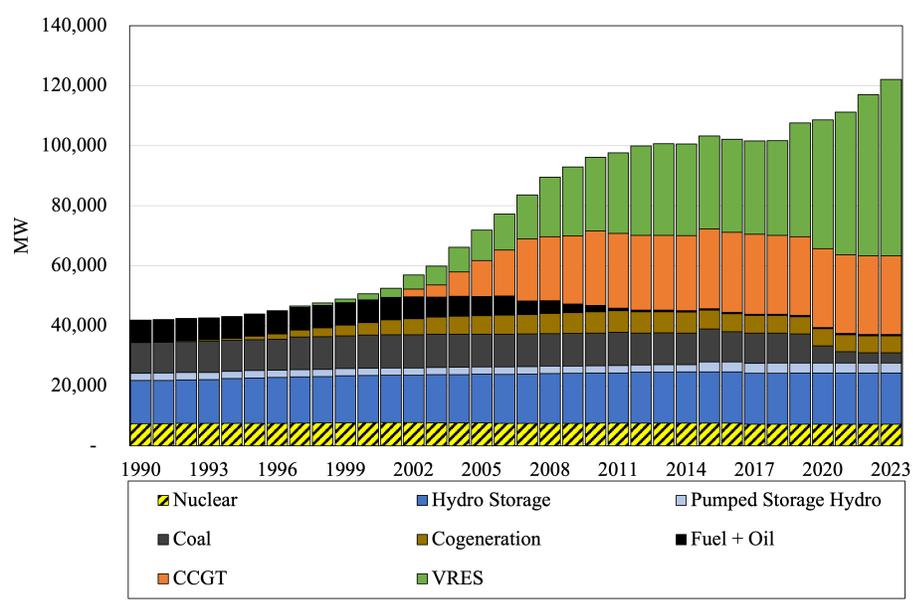


Figure 4.1: Evolution of the installed capacity in the Spanish power system from 1990 to 2023 [5]

Figure 4.1 summarizes the evolution of Spain’s installed electricity generation capacity. From 1990 to 2000, the electricity mix shows stability, with Coal, nuclear, and hydro storage.

Transitioning into the 21st century, a discernible shift begins to take shape. Alongside the nascent rise of VRES, there is an increase in the capacity installed of CCGT technology. This surge hints at a strategic move towards natural gas — driven by its lower carbon footprint, flexibility, and lower investment costs than coal. During this phase, the burgeoning commitment to sustainable energy likely stems from adherence to international climate agreements such as the Kyoto Protocol. It is catalyzed by European Union directives alongside national incentives that encourage the development of wind and solar technologies.

From 2011 to 2020, the Spanish energy system entered an era marked by an accelerated transition. The proliferation of VRES and a decline in coal capacity signal a restructuring of the energy mix, aligned with the EU’s carbon reduction targets and the economic allure of renewables. The financial downturn 2008 and the subsequent European debt crisis may have spurred

the shift towards economically and environmentally viable energy sources. Technological advancements, alongside a significant decrease in the cost of solar and wind installations, further propel this trend.

The contemporary snapshot from 2021 to 2023 illustrates a phase of consolidation and modernization within Spain's power system. The unwavering expansion of VRES against the backdrop of coal's decline reflects a solid commitment to renewable energy, likely reinforced by the European Green Deal and Spain's climate objectives. Economic drivers, such as the declining cost of renewable technologies, increased carbon pricing, and heightened ecological awareness, have collectively shaped the decision-making process, solidifying Spain's pathway to a more sustainable energy ecosystem.

Throughout these decades, the narrative of the electricity mix unfolds distinctively. The presence of coal diminishes, influenced by converging policy directives, economic considerations, and societal demands. Nuclear capacity holds steady, securing baseload stability within the energy system. VRES rise, supported by policy incentives, cost-effectiveness, and technological advancements. The CCGT expands, showcasing its adaptability as a back-up to VRES and signaling a strategic shift towards a more agile and cleaner energy infrastructure. Hydro storage maintains its pivotal role, highlighting its adaptability and indispensable contribution to energy storage.

4.1.2 Current Power System Operation

Changes in power system regulations and operating procedures have accompanied the evolution of Spain's power generation fleet. Notably, Spain's integration with the Portuguese market, forming an energy peninsula, has led to a more cohesive energy strategy between the two nations, with electricity prices now closely aligned.

Accompanying this surge in renewable energy, there has been a significant change in the volume of electricity demand, primarily due to the rise in self-consumption. Advances in technology and economic incentives have encouraged improving household efficiency and installing solar panels, leading to a decrease in reliance on the national electricity system. This trend towards self-consumption is not just a reflection of Spain's commitment to sustainable practices but also a testament to the evolving role of consumers in the energy landscape [6]. Figure 4.2 shows the installed evolution according to UNEF's (Spanish Solar Photovoltaic Association) data [7]. Figure 4.2 illustrates the progression of solar installations for self-consumption from

2014 to 2023. Despite a slight deceleration in growth by 2023, reaching the National Energy and Climate Plan's (NECP) goal of 19 GW by 2030 remains feasible.

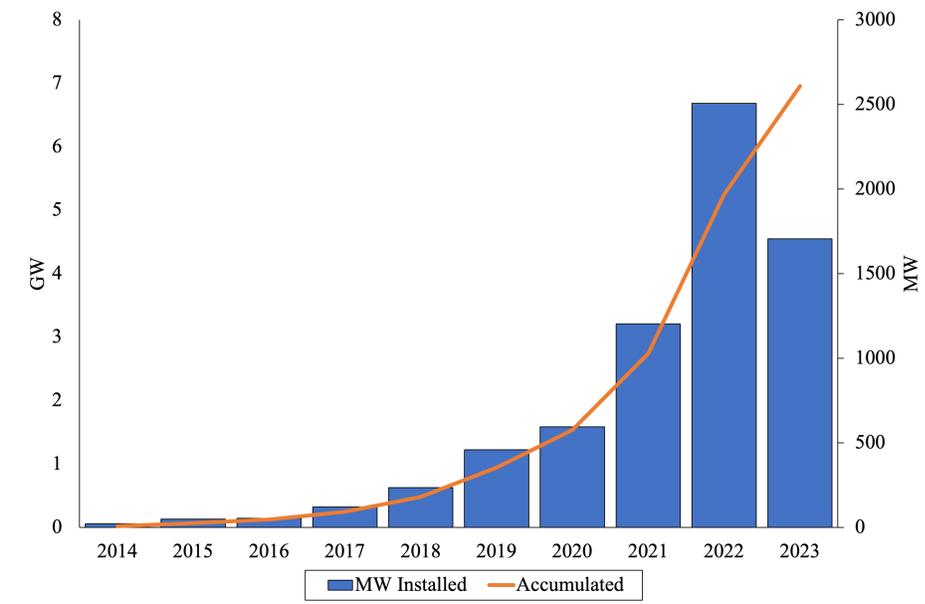


Figure 4.2: Evolution of the increase in the number of Spanish photovoltaic self-consumption installations[7]

Based on open data provided by the Spanish system operator, Figure 4.3 summarizes the evolution of the electricity mix in the Spanish power system from 1990 to 2023 [5]. According to Figure 4.3, coal, initially a prominent contributor, exhibits a declining trend while VRES and CCGT follow an increasing trend. This phase-out of coal and rise in gas usage may be interpreted not only as a move towards a cleaner fossil fuel but also as a strategic transition to a more flexible back-up system for VRES-dominated power systems. Due to their quicker ramp-up times and lower minimum load levels compared to coal, gas-fired power plants provide a responsive back-up option to accommodate the variability of VRES.

In the context of the evolving Spanish power system from 1990, the role of Hydro Storage in balancing the deployment of thermal dispatchable technologies, such as coal and CCGT, has remained constant. According to Figure 4.3, Hydro Storage yearly production shows a variability from year to year, due to inter-annual variability of natural water inflows, and therefore

conditioning the use of hydropower technologies for limiting emissions from thermal technologies, such as coal and gas.

Nuclear energy's contribution to the electricity mix remains relatively stable throughout these changes. The steadiness of nuclear power underscores its role in providing a consistent baseload capacity, irrespective of hydrological variability.

In sum, the graph captures Spain's evolving energy strategy, where coal's role as a back-up to hydropower gives way to gas, reflecting a broader trend towards energy sources that offer reduced carbon footprints and enhanced operational flexibility. This shift is emblematic of a power system adapting to the intrinsic unpredictability of renewable resources, seeking a balance between reliability and sustainability.

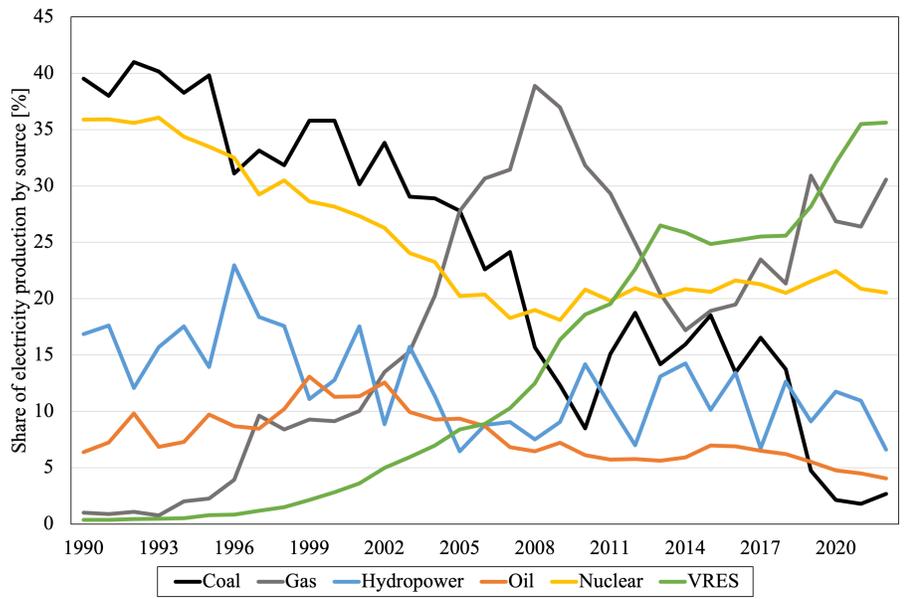


Figure 4.3: Share of electricity production per technology from 1990 to 2023 [5]

Although hydropower installed capacities produce on average 12% of the total electricity annually from 2008 to 2022, its dependence on variable water inflows exhibiting inter-annual presents a unique set of challenges for Spain's energy strategy. During years of ample rainfall, hydroelectric plants significantly contribute to the electricity supply as in the year 2014 (i.e., 16% of the total electricity produced), while in drier years, the system leans more

on fossil fuel power plants to meet the demand, as observed in the year 2017 in the Figure 4.3 (i.e., 8% of the total energy produced). This cyclical nature of hydroelectric power generation underscores the need for adaptability in Spain's energy policy. However, the growing penetration of VRES, such as wind and solar power, introduces even more complexity. While these renewable sources are crucial for a sustainable energy future, their intermittent nature adds another layer of uncertainty in power system planning and operation. For instance, the variability in solar and wind energy availability necessitates a more sophisticated approach to balancing energy supply and demand.

In 2023, although two coal power plants remain connected and producing (i.e., Soto de Ribera and Aboño [5]), the Spanish power system plans to phase out the coal technology by 2030 completely. In 2023, the Spanish power system is characterized by a diverse electricity technology mix, accounting for hydroelectric power, natural gas, nuclear power, cogeneration, and, increasingly, solar PV and wind. Figure 4.4 shows electricity generation shares per technology for the Spanish power system in 2023, the first year in the Iberian peninsula that VRES generation is the primary electricity source with 53%.

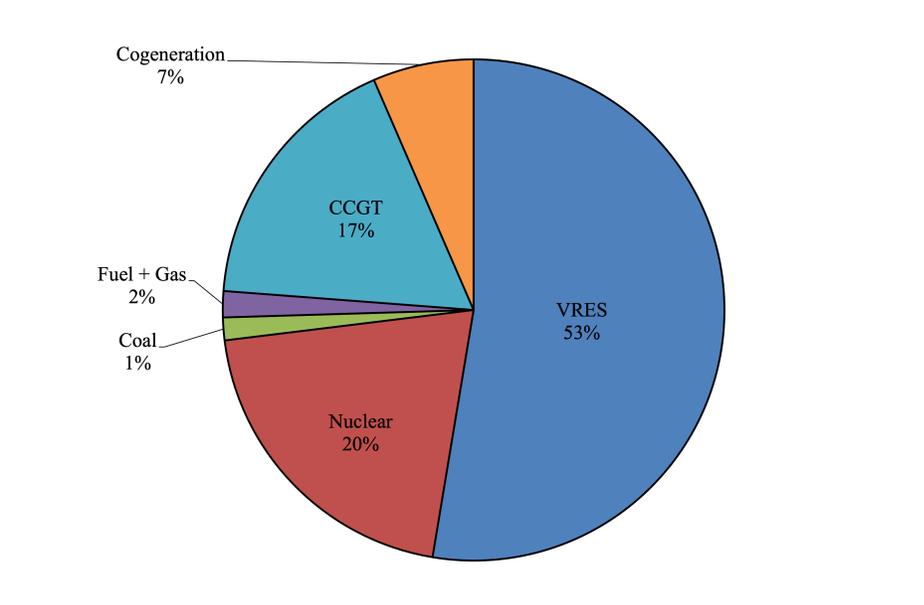


Figure 4.4: Share of electricity production per technology in 2023 [5]

According to Figure 4.4, 75% of the total electricity produced is decarbonized. The first reason is that 20% of Nuclear generation represents a free-CO₂ emission baseload. The second reason is the increasing new VRES generation (i.e., Solar PV, Wind, Other VRES, Hydro Storage, PSH) from 38% in 2019 to 53% in 2023. The third reason is that water inflows in 2023 correspond to the average water inflows between 2019 and 2022, making this a historically average hydrological year.

As Spain continues to increase its reliance on renewable energy, efficiently managing the power system becomes more complex. This requires advanced forecasting techniques, power system management technologies, and strategic planning to ensure that the power system remains resilient and capable of meeting changing energy needs. The integration of these diverse energy sources, each with its specificities, reflects Spain's commitment to a sustainable and forward-thinking energy policy, even as it navigates the complexities of an evolving energy landscape.

4.2 Spanish National Energy and Climate Plan (NECP)

After the Paris Agreement, where each signatory pledged to cut emissions, the European Union's member countries developed National Energy and Climate Plans (NECPs). These NECPs serve as blueprints for decarbonizing the energy sector. Within the context of the electricity system, the NECPs outline two distinct scenarios for power system expansion and operation in 2030: the trend and the target scenarios. The trend scenario poses less stringent emission reduction goals than the target scenario. This thesis focuses on the target scenario, which presents a more conservative approach with stricter constraints and, consequently, more significant challenges.

This section first outlines the anticipated changes in the power system according to the NECP 2030 goals. Subsequently, it discusses how the future power system is comprehensively modeled to reflect these impending challenges.

4.2.1 NECP 2030: Target Scenario

The Spanish NECP has set an ambitious target, aiming for at least 74% of its electricity generation to come from renewable sources by 2030, as detailed in

[1]. In nine years, from 2021 to 2030, the NECP anticipates a substantial increase in installed capacities across various energy technologies. Specifically, solar PV installations are projected to grow by 70%, while wind turbine is expected to see a 40% expansion. Additionally, there is a forecasted 64% increase in ESS, including PSH and batteries. The composition of ESS in Spain's future energy landscape will be a combination of newly installed and existing PSH facilities, along with batteries, as referenced in [8]. Meanwhile, the capacity of CCGT is anticipated to remain stable. Notably, the NECP includes a significant environmental milestone: the complete phasing out of coal-powered technology by 2030.

Per the NECP's projections, a notable shift in the country's nuclear energy strategy is on the horizon. By 2030, only three of the currently operational seven nuclear reactors are expected to remain in service. This strategic move signifies a marked reduction in nuclear energy's contribution to Spain's electricity mix, plummeting from the current level of approximately 20% to a projected 6%. While controversial in the Spanish context, this decision reflects the varying priorities and policies adopted by different political parties at the time of decision-making.

In their analysis of the medium-term expansion planning for Spain's power system, as outlined in [1], the authors of [9] recognize the significance of nuclear energy in the Spanish energy landscape. They highlight that as a decarbonized technology, nuclear power not only offers a consistent baseload but is also crucial in supporting the integration of VRES. Therefore, maintaining the operation of existing nuclear plants is an essential aspect of Spain's strategic plan to achieve its energy transition objectives.

According to NECP, in 2030, the Spanish electricity system will dispose of 12 GW of ESS composed of 9.5 GW of PSH and 2.5 GW of batteries. In 2020, Spain counted 5.6 GW of existing PSH installed capacity. Therefore, almost 3.9 GW of CLPSH should be installed up to 2030 [1], [10]. The emergence of innovative storage technologies, coupled with the increasing significance placed on ESS, necessitates revising current operating procedures. This is essential to acknowledge the distinct characteristics of ESS.

Moreover, there is a need to establish new regulations that are impartial to various technologies. Such regulatory adaptations ensure that the unique contributions of different ESS technologies to power system requirements are effectively accommodated, allowing for more efficient and equitable integration into the existing energy infrastructure. This approach is critical for maximizing the potential benefits of ESS in the evolving landscape of energy

production and distribution.

In this context, the Climate Change and Energy Transition Project Law foresees that the operation of all available ESS will contribute to the security and continuity of the electricity system at all times [11]. Indeed, battery participation in energy and ancillary services was included in December 2020 in the Spanish System Operator (SO) operating procedures [12]. All ESSs in Spain are permitted to participate in secondary regulation, tertiary regulation, and balancing services from replacement reserves, according to the proposed new operation procedure (i.e., PO 3.8 in [12]). However, further regulatory adjustments are still required to integrate these systems into the market fully [13].

Table 4.1 shows the installed capacity in the Spanish power system according to the target scenario in the NECP 2030 [1].

Table 4.1: Installed power capacity in the Spanish power system according to NECP [1]

| | 2030 [MW] | % |
|---------------------------------|------------------|------------|
| Hydro Storage | 17.097 | 11 |
| Pumped Storage Hydro | 7.043 | 5 |
| Nuclear | 3.050 | 2 |
| Coal | - | 0 |
| CCGT | 24.560 | 16 |
| VRES | 95.984 | 62 |
| Cogeneration | 3.980 | 3 |
| Batteries | 2.500 | 2 |
| Total Installed Capacity | 154.214 | 100 |

4.2.2 Modeling the Spanish Power System in 2030

This thesis employs a detailed modeling framework to reproduce the Spanish power system for the year 2030. This section delineates the foundational assumptions of the model, encompassing technological progress, economic variables, projections of energy demand, and environmental factors. Selecting appropriate simulation tools and software is pivotal, as they must aptly represent the intricacies of a power system heavily reliant on renewable energy sources.

In modeling the system's operation, especially for scenarios with high proportions of non-dispatchable VRES, it is advisable to incorporate a diverse mix of ESS as proposed in [14]. This approach enables the model to assess each ESS's contribution to system flexibility and their effects on operations under scenarios with significant non-dispatchable energy inputs, as detailed in [15].

Currently, the capacity of existing Closed Loop Pumped Storage Hydro (CLPSH) units in Spain ranges from 100 MW to nearly 1400 MW. These units' maximum energy storage capacity varies significantly, from about 1 GWh to 31 GWh [5]. Consequently, when fully charged, the maximum duration of energy discharge from these reservoirs can span from five hours to over a week. Thus, in examining the complementary roles and the operation of various ESSs for Spain by 2030, key parameters such as the energy capacity of reservoirs and round-trip efficiency of projected ESSs (i.e., PSH and batteries) are crucial.

Different ESSs, including batteries and PSH, are characterized by their installed power, the maximum discharge duration at full capacity, and round-trip efficiency, as defined in [16]. The Spanish NECP [1] and [17] state that installed batteries will have a minimum discharge duration of two hours and an installed power of 2.5 GW. Since the round-trip efficiency of batteries is not specified in [1] or [17], this thesis adopts the efficiency values from [18]. For the projected new CLPSH installations, only their total installed power is specified in these sources. Based on the technical characteristics of batteries and new CLPSH units, the model incorporates the following assumptions:

- The round-trip efficiency of batteries is derived from [18]. While [1] and [17] indicate a minimum discharge time of two hours for batteries, this model adopts a four-hour discharge time as an average value, aligning with common specifications for Lithium-Ion battery technology.
- The technical and economic parameters for new CLPSH units are extrapolated from current Project of Common Interest (PCI) initiatives, expected to be operational by 2030 [19]. Table 4.2 lists three CLPSH projects, PCI I, PCI II, and PCI III, along with their technical specifications incorporated into the analysis.

Furthermore, Spain's current energy generation mix includes an equal installed capacity of CCGT and Hydro Storage, each accounting for about 16%

of the total. Historical data spanning ten years [5] shows annual hydroelectric production ranging from 13 TWh in 2005 to 40 TWh in 2013, indicating significant yearly variability. This variability extends to seasonal fluctuations in water inflows. For instance, Fig. 4.5 illustrates the daily hydroelectric output for February and August in 2015 and 2019, based on hourly data from Spain [5].

Fig. 4.5 reveals notable variations in the trends for the same month across different years (e.g., March 2015 vs. 2019) and in the daily output magnitude for the same month in different years. Therefore, accurately representing hydropower in the Spanish electricity system requires considering annual and seasonal variations in water inflows. The model's representation of hydrothermal system operations hourly over a year, supported by a substantial historical database, allows for examining extreme scenarios. This approach is validated by references including [1], [20]–[22].

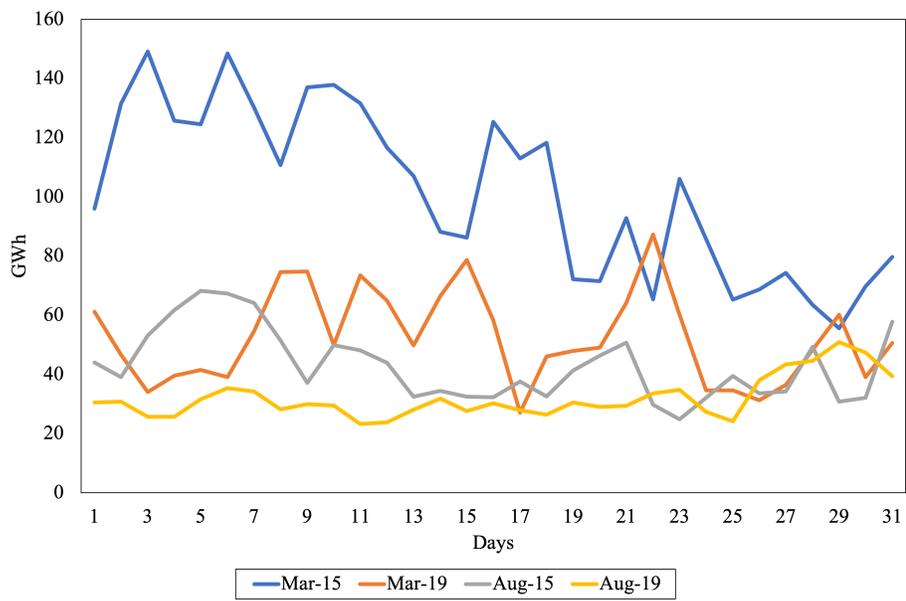


Figure 4.5: Daily hydropower electricity production over March and August in 2015 and 2019 in GWh

The model's load demand and hourly generation profiles are based on data from 2015 [5]. As presented in Chapter 3, the SEED model uses these profiles for solar PV and wind generation for each programming unit. Hydro programming units and their respective water reservoirs (i.e., energy reservoirs)

are grouped by hydro basins, acknowledging the variability of theoretical energy production across different hydro basins. Indeed, the Ebro basin in the Spanish peninsula experiences late winter snowfall, unlike the Duero basin, which changes hydro reservoir scheduling from one basin to another.

Thermal power plants in the model are defined by several parameters: installed capacity, Equivalent Forced Outage Rate (EFOR) based on historical data, emission rates, and variable costs. Renewable non-dispatchable technologies such as wind and solar PV, which do not incur variable costs, follow specific hourly generation profiles¹. Hydropower plants are described by installed capacity (MW), EFOR² (%), reservoir capacity (MWh), maximum discharge cycle time (hours), and round-trip efficiency (%).

The model's hourly operating reserve requirements are based on three parameters: demand and forecast errors in wind generation (3% and 10% respectively, as suggested in [23]), and the failure of the largest generation unit. The energy supplied by the committed power reserve capacity is derived from historical data [5]. In Spain, balancing energy constitutes 25% and 30% of the downward and upward operating reserves, respectively, as per [24].

Figure 4.6 shows the net load ramps in the Spanish power system, sorted in ascending order based on historical data for 2019 and projections for 2030 from the SEED model, aligned with the National Energy and Climate Plan (NECP). According to Figure 4.6, besides an increase of 70% of the upward and downward ramps, the current operational procedures of the Spanish power system do not consider ramping services. Consequently, in the context of this analysis, a series of tests were performed, producing relevant results, with ramping requirements derived from a 10% error in the hourly net demand ramp. According to the authors in [25], the requirements for ramping services may change depending on the power system scarcities.

Table 4.2 resumes the main input parameters for representing the Spanish electricity system regarding the NECP objective [1] based on scenarios presented in [17]. Table 4.2 shows variable costs (i.e., fuel costs), O&M variable cost, and emission rate according to [26] considered, and technical parame-

¹Other sources like biomass and cogeneration, also non-dispatchable, are included with their generation profiles. Future research should focus on modeling these resources considering their associated constraints.

²For hydropower, EFOR accounts for capacity limits due to insufficient water at the reservoir, based on a historical series of hourly production over ten years. It helps to factor in the capacity reduction due to the water-head effect. This, however, does not apply to CLPSH, as historical data indicate they operate at maximum installed capacity.



Figure 4.6: Net Load Ramps in the Spanish Power System: 2019 Data [5] and 2030 Projections according to SEED model results [1]

ters of generating units present in the system studied. Table 4.2 also presents the required parameters for defining ESS according to [1] and [22], such as installed power capacity, energy reservoirs associated with ESS technologies, and round-trip efficiency.

Table 4.2: Spanish electricity system, according to [1]

| Technologies | Installed power capacity (MW) | Installed pump capacity (MW) | Energy storage capacity (GWh) | Cycle Discharge (Seasonal/Weekly/Daily) | round-trip efficiency (%) | Variable Cost (€/MWh) | Emission rate (€/MWh) | OM Variable cost (€/MWh) |
|---------------------------------|-------------------------------|------------------------------|-------------------------------|---|---------------------------|-----------------------|-----------------------|--------------------------|
| Nuclear | 3050 | | | | | 23 | 0 | 0 |
| CCGT | 24560 | | | | | 40 | 0.33 | 2 |
| Cogeneration | 3980 | | | | | 0 | 0.575 | 0 |
| Solar PV | 38404 | | | | | 0 | 0 | 0 |
| Solar Thermal | 7300 | | | | | 0 | 0 | 0.46 |
| Wind Onshore | 48550 | | | | | 0 | 0 | 0 |
| Hydro Storage | 7500 | | 9780 | Seasonal | | 0 | 0 | 0 |
| No Hydro Storage (Run-of-River) | 1303 | | | | | 0 | 0 | 0 |
| OLPSH | 7750 | 2114 | 6208 | Seasonal | 0.75 | 0 | 0 | 0 |
| Existing CLPSH | 3648 | 3552 | 120 | Weekly/Daily | 0.75 | 0 | 0 | 0 |
| PCI I | 235 | 235 | 1.5 | Daily | 0.79 | 0 | 0 | 0 |
| PCI II | 3400 | 3400 | 27.2 | Weekly | 0.79 | 0 | 0 | 0 |
| PCI III | 552 | 548 | 3.67 | Daily | 0.78 | 0 | 0 | 0 |
| Batteries | 2500 | 2500 | 10 | Daily | 0.9 | 0 | 0 | 0 |
| Other VRES | 1730 | | | | | 0 | 0 | 0 |

Table 4.2 shows that the ESS mix can be heterogeneous regarding maximum energy reservoir capacity, storage duration cycle, and installed capacity. Table 4.2 details how SEED disaggregates hydropower technologies

into four technologies (i.e., programming unit -Hydro Storage-, Run of the river³ OLPSH, and CLPSH). Energy reserves capacity (GWh) associated with UGHs and OLPSH are considered similarly as [5]. As mentioned in [27], the total energy reservoir capacity of 18.538 GWh available in Spain does not include the energy reservoir capacity of CLPSH⁴.

Different methods exist to calculate the maximum energy reservoir capacity of CLPSH according to the net waterfall [28]. In this thesis, the energy reservoir capacity of each existing CLPSH is based on the maximum consecutive working hours multiplied by the capacity installed⁵ pumping efficiency considered for OLSPH and existing CLPSH is set according to [27], [29], and for new CLPSH according to [19]. The collection of data in line with hourly generation profiles and the aggregation considered for hydropower programming units have both followed the recommendations of [12], [14], [20] according to temporal consistency between input data and programming units.

This thesis considers a 'copper plate' assumption regarding the electricity network, a critical aspect given that the primary focus is not on the transmission. The 'copper plate' assumption simplifies the model by treating the entire network as a perfectly conductive entity with no transmission losses or capacity constraints. This theoretical framework allows for a more straightforward examination of the power system's generation and demand, especially relevant for the Spanish power system in the context of high shares of VRESs.

When considering Spain as an electric island under this assumption, the analysis focuses on how the system manages its energy needs solely based on internal generation and storage capabilities. This scenario tests the system's adequacy and self-sufficiency, particularly in handling the variability and intermittency of VRES.

While this modeling approach does not address the specifics of transmission network constraints, it provides valuable insights into the operational characteristics of the Spanish power system. The results from this analysis are instrumental in informing policy decisions and strategic investments, particularly in the context of Spain's evolving energy landscape and its com-

³Non-Hydro Storage includes non-dispatchable hydropower technology, also known as Run-of-River

⁴This value represents the maximum physical value. However, historically, the maximum reservoir level reached in Spain was around 14 TWh in 2016 [5]

⁵The energy reservoir capacities are obtained from a 10-year database providing hourly data for each existing CLPSH.

mitment to renewable energy integration.

4.3 Scenarios

Developing various scenarios for 2030 is pivotal for this thesis, reflecting the NECP’s projections and targets. This section discusses the rationale behind selecting these scenarios, emphasizing their relevance to the NECP’s objectives.

All scenarios were executed using GUROBI 11 under GAMS 47.0 with 32 GB of RAM.

Exploring the role of ESS in a 2030 scenario according to [1] requires firstly building the *Base Case (BC)*, which will be used as a reference case as represented in Table 4.2. A scenario of average water inflows – i.e., 25.1 TWh according to the year 2015 [20] – is used as a reference case.

In pursuit of a technologically neutral methodology that facilitates an adequate comparison of ESSs, this thesis develops a model encompassing a broad time scope and detailed power system operation. The model’s design aims to capture the intricacies and impacts of different operational aspects on ESS performance from short- to long-term. Various scenarios are meticulously crafted to achieve this, including operating reserves, energy reserve activation, and ramping services.

- The consideration of operating reserves is an inherent part of the *BC* since it reflects the existing operating procedures at the time of this thesis [12]. Specific scenarios are constructed to gauge the influence of detailed modeling of operating reserves on the analysis of ESS roles. Although modeling balancing services is approximated by hourly upward and downward operating reserves, the distinction between unit power reserve and energy activation is maintained. Therefore, balancing energy is not considered in the first scenario based on *BC (BC no balancing energy)*. To complete exploring the consequences of including balancing services in a medium-term model, this study analyzes another scenario based on *BC* without considering the provision of balancing capacity (*BC no balancing capacity*). This step-by-step approach allows for a systematic assessment of how each aspect of operating reserve modeling affects the perceived roles and effectiveness of ESS within the electrical system. Table 4.4 summarizes the scenarios described above.

- Ramping services, not yet a standard practice in the Spanish power system, represent an emerging aspect of system operation that this thesis aims to explore. As such, they are not included in the *Base Case*. By designing scenarios incorporating ramping services (i.e., *RS* scenario), the thesis aims to shed light on the potential impacts and benefits of their integration into the system. These scenarios provide a forward-looking perspective, enabling an evaluation of how ramping services might influence the operation of the electricity system and the roles of ESS therein. Table 4.3 summarises the main parameters of the scenarios analyzed according to the impacts of ramping services.
- The installed capacity proposed by the Spanish NECP and studied in the *Base Case* appears to be sufficient to meet the load demand, but what would happen if solar and/or wind VRES generation were to be unavailable for a time for meteorological and or technical reasons? This sensitivity is studied in the Ten-Year Network Development Plan (TYNDP) 2022 [30] and is called *DunkelFlaute* (“dark period” in German). Under the TYNDP method, the *DunkelFlaute* scenario considers two weeks of a year coinciding with high load demand and a total absence of wind generation. Although this scenario is not based on historical data (i.e., two weeks of high load demand have never actually coincided with two weeks of low wind generation), it highlights the impact of anticyclonic gloom⁶ on the operation of electrical systems. Thus, this thesis proposes a *DunkelFlaute*-sensitivity scenario built up following the author’s proposed method in [15]. The two weeks of low wind start in the fifth week of the year according to the time series used. Therefore, in the two weeks when the load demand is the highest, the wind power output is reduced to its historical lowest capacity factor (6% according to the 5th percentile). Table 4.5 summarises the main parameters of the scenarios analyzed according to power system scarcities.
- The Spanish electricity system strongly relies on hydropower output [5]. Thus, this thesis explores sensitivity scenarios according to different water inflow scenarios. Sensitivity scenarios are built up on the

⁶The *DunkelFlaute* scenario defines a meteorological phenomenon in Europe’s North Sea, but can represent a complex situation for maintaining reliability standards in the Iberian peninsula.

Base Case. *BC Wet* and *BC Dry* are based on the annual weekly profile of 2016 and 2017, respectively, with 34.5 TWh and 15.9 TWh of hydropower inflows, while the *Base Case* is based on the annual weekly profile of 2015, which is considered an average water inflow scenario with 25.1 TWh. Sensitivity according to water inflows is explored systematically and therefore appears in Tables 4.3, 4.4, 4.5.

Table 4.3: *Base Case, Ramping Services* and sensitivity scenarios based on the Spanish NECP [1] for analysing impacts of considering additional wholesale system services

| | BC | RS | BC Wet | BC Dry | RS Wet | RS Dry |
|---------------------|------|------|--------|--------|--------|--------|
| Water inflows (TWh) | 25.1 | 25.1 | 34.5 | 15.9 | 34.5 | 15.9 |
| Ramping services | No | Yes | No | No | Yes | Yes |

Table 4.4: Overview of base case and sensitivity scenarios based on the Spanish NECP [1] for analyzing impacts of considering operating reserves and energy reserve activation

| | BC | BC Dry | BC Wet | BC No Balancing Energy | BC No Balancing Capacity |
|----------------------------|------|--------|--------|---------------------------|-----------------------------|
| Water Inflows (TWh) | 25.1 | 34.5 | 15.9 | 25.1 | 25.1 |
| Energy Reserves Activation | Yes | Yes | Yes | No | No |
| Operating reserves | Yes | Yes | Yes | Yes | No |

Table 4.5: Overview of the *Base Case* and sensitivity scenarios based on the Spanish NECP [1]

| | BC | BC Wet | BC Dry | Dunkelflaute |
|-----------------------------|---------|---------|---------|--------------|
| Water inflows(TWh) | 25.1 | 34.5 | 15.9 | 25.1 |
| Wind annual generation(TWh) | 118.090 | 118.090 | 118.090 | 112.153 |

4.4 Concluding Remarks

This thesis designs various scenarios for 2030, reflecting the projections and targets of the NECP. The rationale behind these scenarios emphasizes their alignment with NECP objectives, focusing on the role of Energy Storage

Systems (ESS) in a 2030 scenario. It involves constructing a *Base Case (BC)* for reference, incorporating average water inflows based on 2015 data as the standard case. The thesis adopts a technologically neutral methodology to allow for an adequate comparison of ESSs across a broad timeframe and detailed power system operations, aiming to understand the intricate effects of various operational factors on ESS performance from short- to long-term perspectives.

Several specific scenarios are crafted to explore these dimensions further:

- **Operating Reserves (*BC No Balancing Capacity and BC No Balancing Energy*):** Integral to the *BC*, reflecting current operational procedures with scenarios designed to assess the impact of detailed operating reserves modeling on ESS analysis.
- **Ramping Services(*RS*):** As a novel aspect in the Spanish power system, scenarios include ramping services to investigate potential impacts and benefits on the electricity system and ESS roles.
- ***Dunkelflaute Scenario*:** Examines the system’s resilience during periods with high demand but no wind generation, highlighting the impact on electrical system operations.
- **Water Inflows Sensitivity:** Given Spain’s reliance on hydropower, scenarios explore the system’s sensitivity to varying water inflow conditions to analyze power system scarcities systematically.

To summarize these scenarios and their objectives, and to reflect the importance of water inflows, medium-term scope relevance, and flexibility aspects in the context of VRES integration, consider the following points:

1. **Hydropower dependency and water inflows:** Spain’s heavy reliance on hydropower production necessitates a detailed sensitivity analysis regarding water inflows. This critical parameter can reveal power system scarcities in fulfilling various services, making it essential for this thesis to analyze water inflow sensitivities for the Spanish power system systematically. The *Base Case* is structured to represent an average scenario for water inflows, providing a foundational reference for assessing system vulnerabilities and resilience.

2. **Medium-term time scope for VRES variability:** The variability and uncertainty associated with VRES, spanning from short to long-term, underscore the importance of modeling operating reserves within a medium-term operational model. This approach facilitates a neutral analysis of different ESSs, accommodating the broad spectrum of storage durations and technical abilities. It comprehensively evaluates how operating reserves modeling impacts ESS performance and their perceived roles within the power system.
3. **Flexibility and new power system services:** As VRES integration progresses, flexibility becomes increasingly critical. The thesis introduces new power system services, specifically focusing on ramping capabilities, to address this need. By evaluating scenarios that incorporate ramping services, the study aims to provide insights into how these services could enhance system operation and support the integration of ESSs, thereby contributing to a more flexible and reliable power system.

These summaries highlight the rationale and objectives behind developing various scenarios for 2030, aligned with NECP targets, to explore the integration and medium-term impacts of different ESSs within a renewable-dominated Spanish power system.

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Chapter 5

Analysis

This chapter exposes the results obtained from applying the methodology described in Chapter 3 on the Spanish case study and scenarios described in Chapter 4.

The results shown in this chapter are intended firstly to highlight the challenges accompanying the operation of the electricity system over the medium term in scenarios with a high penetration of renewables, precisely according to the operation of ESS. Secondly, this section proposes improvements in analysis and regulation so that operational problems do not hamper decarbonization objectives.

5.1 Medium-Term Power System Operation Modeling Results

5.1.1 The Effects of Operating reserves

The three scenarios outlined in Table 4.4 emphasize the importance of incorporating balancing services in medium-term operation planning models, especially when evaluating the future role of ESS amidst high renewable energy penetration. Traditionally, medium-term operation models have not fully captured the optimal utilization of ESS, primarily focusing on their economic aspects. However, with the anticipated high renewable energy shares by 2030, these models must integrate more detailed operational factors, such as balancing services. This integration is crucial for facilitating informed decision-making regarding the future functioning of the electricity system, as

Table 5.1: Annual full-time equivalent operation hours for technologies according to different scenarios based on the modeling of operating reserves (i.e., *BC*, *BC no balancing capacity*, and *BC no balancing energy*)

| | BC [h] | BC No Balancing Energy [h] | BC No Balancing Capacity [h] | BC No Balancing Energy / BC [%] | BC No Balancing Energy / BC [%] |
|------------------|-----------|--|--|--|--|
| Battery | 1093 | 1033 | 1028 | -5.8 | -6.3 |
| CCGT | 1267 | 1266 | 1266 | 0 | 0 |
| CLPSH | 1219 | 1203 | 1205 | -1.3 | -1.1 |
| New CLPSH | 1395 | 1392 | 1392 | -0.2 | -0.2 |
| OLPSH | 2476 | 2536 | 2555 | 2.4 | 3.1 |
| Hydro Storage | 2381 | 2381 | 2379 | 0 | 0 |

noted in [1].

The data presented in Table 5.1 and Table 5.2 provide insights into the scenarios of *BC*, *BC no balancing energy*, and *BC no balancing capacity*. These scenarios are analyzed through annual full-time equivalent operation hours and various electricity system indicators, including total operation costs, emissions, and VRES curtailment.

As indicated in Table 5.1, omitting energy activation against non-balancing services (i.e., neither balancing capacity nor balancing energy) may seem marginally impactful. Still, it significantly underrepresents the role of batteries in providing services by about 6% (i.e., encompassing both energy and balancing services). Furthermore, Table 5.2 illustrates that neglecting balancing services in the analysis leads to underestimating the annual total operating costs and the extent of VRES curtailment.

Moreover, Table 5.1 highlights that battery technology experiences the most significant effect when accounting for balancing services. Including balancing services in the model increases the full-time equivalent operation

Table 5.2: Indicators of electricity system operation for three scenarios (*BC*, *BC no balancing capacity*, *BC no balancing energy*).

| | | BC | BC No Balancing Energy | BC No Balancing Capacity | BC No Balancing Energy / BC [%] | BC No Balancing Capacity / BC [%] |
|----------------------|-------|-------|---------------------------|-----------------------------|------------------------------------|--------------------------------------|
| Total operation cost | M€ | 3.536 | 3.533,2 | 3.533,3 | -0,07 | -0,07 |
| Emission | MtCO2 | 20,9 | 20,8 | 20,8 | -0,04 | -0,04 |
| 5,8RES curtailment | % | 19,2 | 19 | 18,9 | -0,9 | -1,1 |
| RES | % | 76,7 | 76,8 | 76,8 | 0,1 | 0,1 |
| SRMC | €/MWh | 44 | 44 | 44 | - | - |
| ENS | MWh | - | - | - | - | - |

hours for both batteries and CLPSH, demonstrating their heightened role in maintaining system balance under these conditions.

5.1.2 The Effects of Ramping Services

Table 5.3 and Figure 5.1 provide detailed results for the *BC* and the *RS* scenarios, examining several critical indicators such as total emissions, and SRMC. Additionally, these resources offer insights into the annual energy production by different technologies. For enhanced clarity, Figure 5.1 focuses exclusively on the total energy output of dispatchable technologies, including battery, CCGT, CLPSH, New CLPSH, OLPSH, and Hydro Storage.

Table 5.3: Indicators of power system operations for the *BC* and the *RS* scenarios

| | | <i>BC</i> | <i>RS</i> | % |
|----------------|-------|-----------|-----------|------|
| Total Emission | MtCO2 | 21,5 | 21,5 | -0,1 |
| Average SRMC | €/MWh | 43,5 | 43,7 | 0,4 |
| Max SRMC | €/MWh | 89,5 | 82,7 | -8,3 |
| Std SRMC | €/MWh | 30,0 | 29,8 | -0,5 |
| ENS | GWh | 0 | 0 | 0 |

The data in Table 5.3 reveals that incorporating ramping services leads to a slight increase of 0.4% in the average SRMC due to the additional service requirements. However, this inclusion also results in a marginal decrease of 0.1% in total emissions, primarily due to a reduction in CCGT generation. While seemingly counterintuitive, the observed decrease in total operation cost requires nuanced interpretation. Conventionally, adding a constraint to the model would be expected to escalate operational costs. Despite this, the overall increase in total operation cost remains minimal.

Moreover, the SRMC's maximum value and volatility are reduced when ramping services are included in the model. Adding a service based on forecast errors in net demand ramping enhances the system's flexibility. This conclusion aligns with the findings in [2], which indicated that introducing a ramping service ensures adequate ramp availability during scarcity periods and influences how dispatchable technologies contribute to various services.

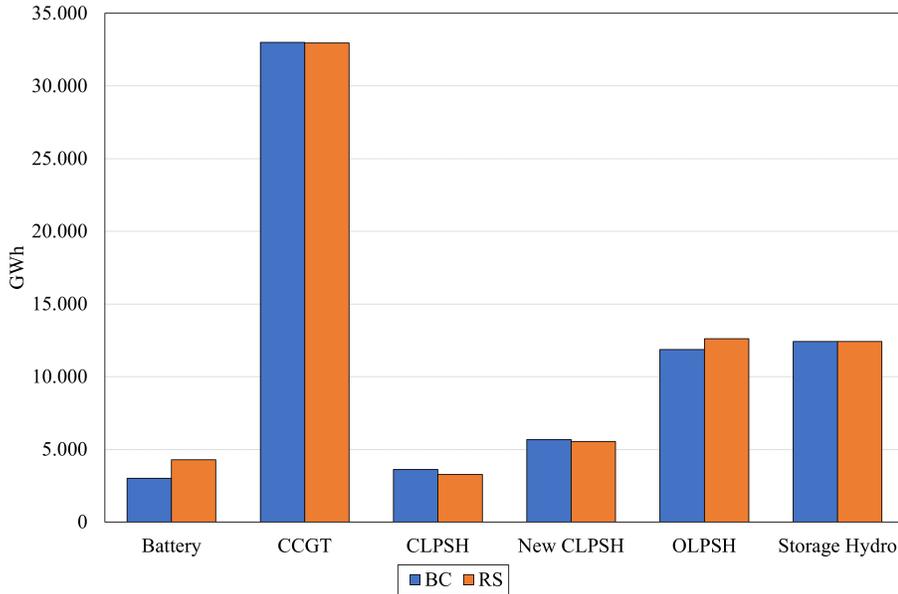


Figure 5.1: Total energy produced by dispatchable technologies according to results of the *BC* and *RS* scenarios

Figure 5.1 offers additional insights into the impact of ramping services within the medium-term operation model. It shows a slight decrease in CCGT production while favoring batteries and OLPSH, which see their total energy output increase by 42% and 6%, respectively. However, the effect of different ESS technologies varies. Specifically, both existing and new CLPSHs experience a decrease in annual production when ramping services are considered. These findings resonate with the conclusions in [3], where the suitability of batteries, with their smaller energy capacity and higher round-trip efficiency, for providing ramping services were highlighted.

In the *BC* scenario, daily and weekly flexibility requirements were primarily met by new and existing CLPSH and OLPSH technologies. However, the introduction of ramping services in the *RS* scenario shifts these roles,

favoring batteries for daily flexibility and OLPSH units for weekly flexibility needs.

While the changes in overall medium-term power system operations seem modest, the introduction of ramping services operates a redistribution of the roles among ESS technologies. This reconfiguration reveals a competition where each ESS aims to optimize its service provision based on its unique characteristics.

The subsequent section presents results that further elucidate how the roles of ESS technologies evolve about their contributions to the power system's flexibility.

5.2 Operational Flexibility

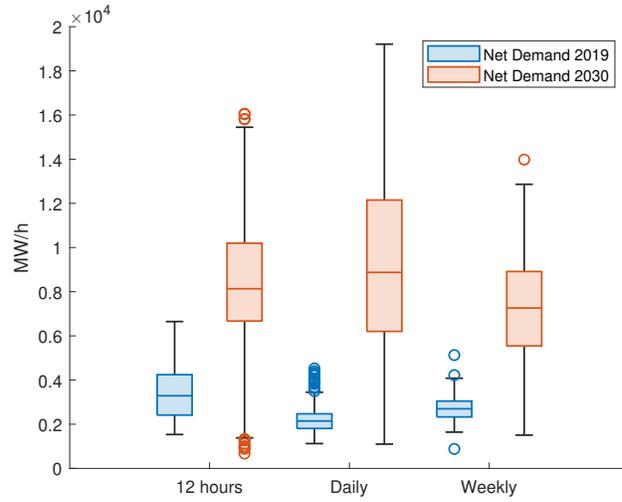
5.2.1 Requirements

The evaluation of operational flexibility is conducted across three distinct time scales, considering various limitations within power systems under scenarios featuring significant VRES. Figure 5.2 illustrates these flexibility requirements across different time frames for the *Base Case* (i.e., *BC*) and the Spanish electricity system as it stood in 2019.

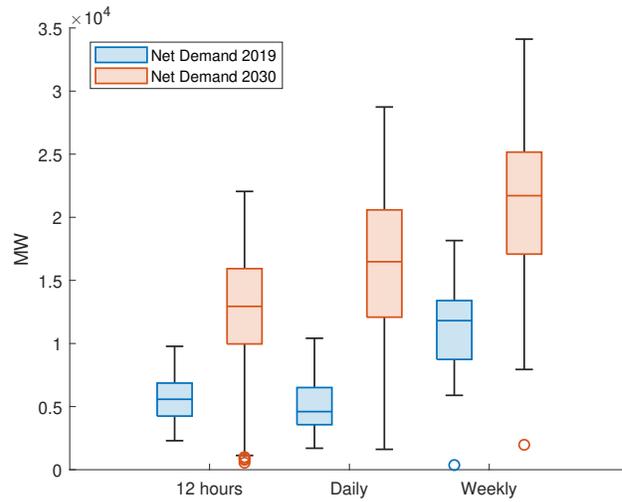
As delineated in Figure 5.2, there is an anticipated augmentation in the operational flexibility requirements, both in terms of ramps (i.e., Figure 5.2a) and power (i.e., Figure 5.2b), within the Spanish electricity framework by the year 2030. The distributions of flexibility requirements over various time scales show an elevation in the *BC* scenario compared to the year 2019. The most pronounced increase is observed in the daily signal distribution, attributed primarily to the substantial growth of solar PV within the Spanish electricity system between 2019 and 2030.

Furthermore, Figure 5.2b highlights a shift in the hierarchy of weekly, daily, and 12-hour flexibility requirements from 2019 to 2030. In the *BC* scenario, the median of daily flexibility requirements in 2019 was closely aligned with those of 12-hour. However, by 2030, the median daily requirement is projected to be 30% higher than the 12-hour requirement.

Contrastingly, for ramps shown in Figure 5.2a, the weekly signal represents the most significant variation in power flexibility requirements. However, it exhibits the slightest variation in ramp flexibility requirements. This indicates a relative consistency in weekly ramp fluctuations throughout the



(a)



(b)

Figure 5.2: Operational flexibility requirements in ramps (a) and power (b), according to net load demand in 2019 and 2030 for the Spanish electricity system

year.

The escalation in flexibility requirements is primarily due to the intensification of critical net demand parameters driven by the widespread incorporation of VRES. According to *BC* findings, the disparity between minimum and maximum hourly net demand values within a year is projected to be 39% greater in 2030 compared to 2019. Moreover, the magnitude of each time signal markedly expands with the increased proportion of VRES.

While sensitivity scenarios investigate the effects of fluctuating water inflows on electricity system operations, the flexibility requirements in scenarios *BC Wet* and *BC Dry* mirror those of the *BC*. This implies that changes in water inflows influence the system's flexibility abilities to meet flexibility requirements but do not significantly alter the inherent flexibility requirements (such as demand, VRES profile, and operating reserves) in these scenarios.

During *Dunkelflaute* conditions, the absence of wind during periods of peak demand notably influences flexibility requirements (with net demand exceeding that in the *BC* scenario), and its most significant effect is observed in terms of capacity requirements.

5.2.2 Technologies' Contribution to Power System Flexibility

The preliminary methodology to evaluate which dispatchable technologies compensate for reduced wind energy during the *Dunkelflaute* scenario or diminished water inflows in the *BC Dry* scenario involves an annual output comparison across different scenarios. Additionally, the extent of curtailments, the proportion of VRES in the energy mix, and the aggregate operational costs provide a comprehensive view of the power system's operational flexibility. Table 5.4 displays these indicators of medium-term power system operation for the *Base Case* (denoted as *BC*) along with the sensitivity scenarios (*Dunkelflaute*, *BC Wet*, and *BC Dry*).

The *BC Wet* scenario exhibits the most significant divergence from the *BC*, particularly in terms of total operating costs. This is attributed to the increased natural water inflows, resulting in heightened outputs from Hydro Storage and OLPSH and a corresponding reduction in CCGT utilization, thereby decreasing the overall operating costs.

Moreover, in both *BC Wet* and *BC Dry* scenarios, the outputs of battery and CLPSH technologies are elevated compared to the *BC*. In the *BC Dry*

Table 5.4: Indicators of power system operations for the *BC* and the sensitivity scenarios

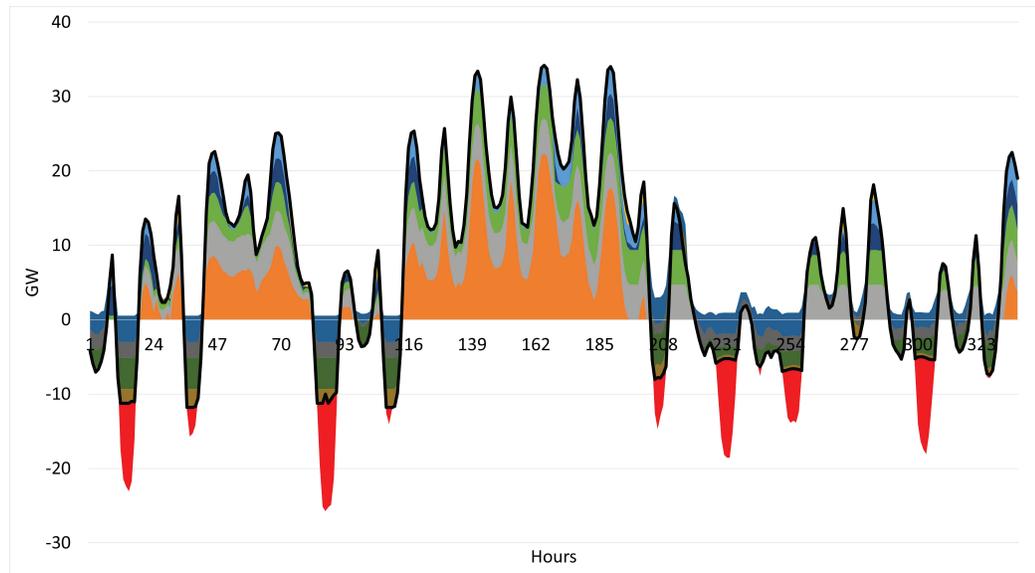
| | | <i>BC</i> | <i>Dunkelflaute</i> | <i>Dunkelflaute/BC</i> [%] | <i>BC Wet</i> | <i>Wet/BC</i> [%] | <i>BC Dry</i> | <i>Dry/BC</i> [%] |
|----------------------|-----|-----------|---------------------|-------------------------------|---------------|----------------------|---------------|----------------------|
| Total operation cost | M€ | 3,559 | 3,922 | 9% | 3,130 | -14% | 3,960 | 10% |
| Curtailement | % | 10% | 10% | 1% | 11% | 14% | 8% | -20% |
| VRES Shares | % | 78% | 76% | -2% | 80% | 3% | 76% | -2% |
| CCGT | GWh | 31,154 | 36,546 | 15% | 24,747 | -26% | 37,090 | 16% |
| Hydro Storage | GWh | 12,452 | 12,452 | 0% | 16,685 | 25% | 8,582 | -45% |
| OLPSH | GWh | 13,153 | 13,009 | -1% | 17,561 | 25% | 10,228 | -29% |
| Existing CLPSH | GWh | 4,560 | 4,319 | -6% | 4,818 | 5% | 4,664 | 2% |
| New CLPSH | GWh | 5,793 | 5,624 | -3% | 5,993 | 3% | 6,026 | 4% |
| Battery | GWh | 2,838 | 2,771 | -2% | 2,901 | 2% | 2,959 | 4% |

scenario, this increase in battery and CLPSH output compensates for the decreased output from Hydro Storage and OLPSH. Conversely, in the *BC Wet* scenario, the augmented output from batteries and CLPSHs aims to curtail the reliance on CCGT, further reducing the total operational costs.

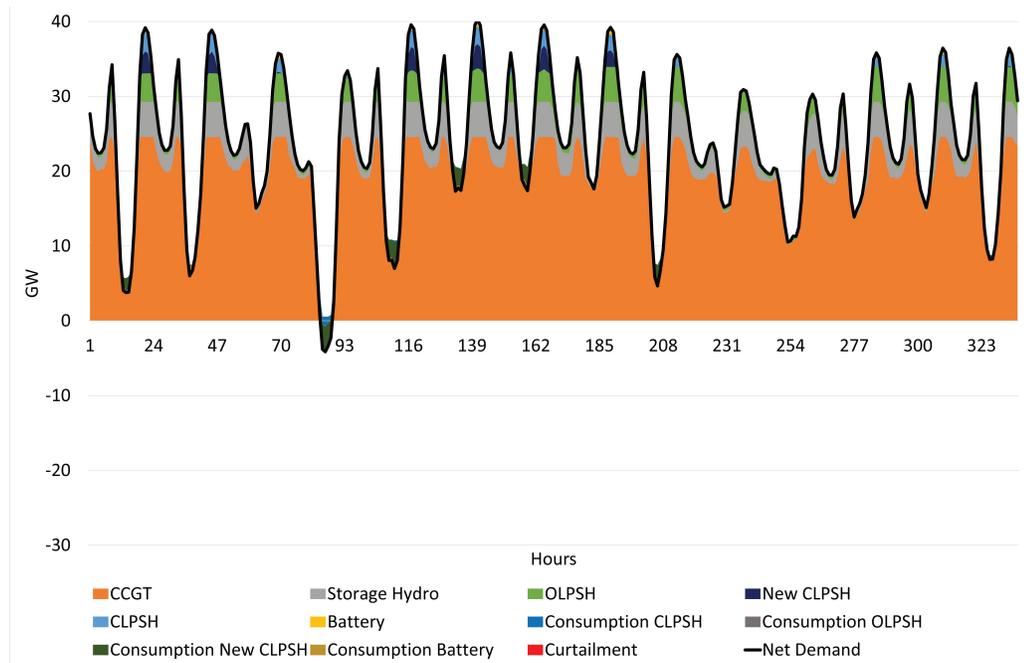
As indicated in Table 5.4, when contrasted with the *BC*, the operational consequences in terms of total operational costs and alterations in electricity output from various technologies are analogous for both the *BC Dry* and *Dunkelflaute* scenarios. Nonetheless, these impacts stem from disparate factors. Figures 5.3a and 5.3b elucidate this point by depicting the operation of the electricity system during the two-week absence of wind, as occurs in the *Dunkelflaute* scenario, for the *BC* and *Dunkelflaute* respectively. In the *BC Dry* scenario, the variance in output is observed throughout the year, with CCGT technology compensating for the reduced water inflows. In contrast, during the *Dunkelflaute* scenario, changes in technology outputs are pronounced explicitly during the two weeks without wind.

Table 5.5 presents the contribution of different technologies in providing upward and downward operating reserves. Despite having the least installed capacity among dispatchable technologies in the *BC*, battery technology contributes comparably to Hydro Storage in providing operating reserves. Operating reserves involve power capacities and energy volumes considerably smaller than the overall demand. Consequently, the substantial participation of batteries in operational reserves enables other ESSs to reserve their energy capacity entirely for more critical events.

In addition to medium-term system operation indicators, this study examines how various technologies enhance the electricity system’s flexibility across different time scales. Figure 5.4 illustrates the contributions of dis-



(a)



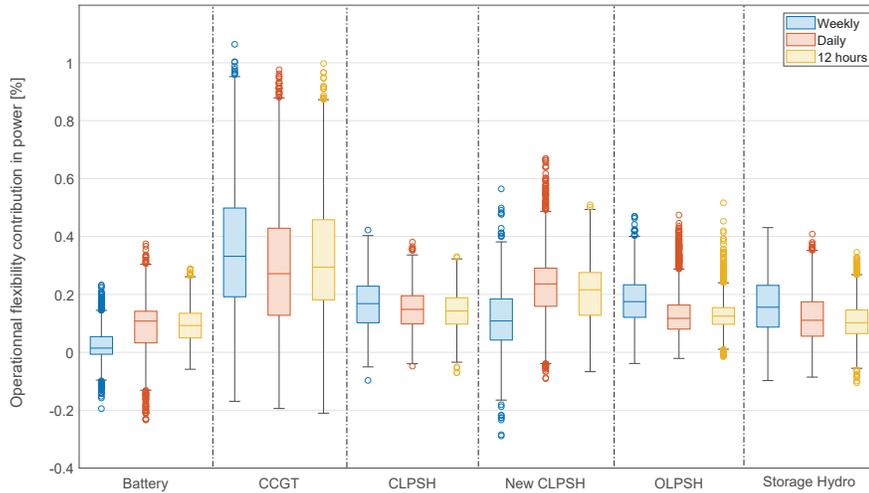
(b)

Figure 5.3: Hourly output of technologies during the two weeks when demand is the highest for the *BC* (5.3a) and the *Dunkelflaute* scenario (5.3b)

Table 5.5: Shares of technologies in supplying operating reserves upward and downward for the *BC*

| | Up | Down |
|---------------|-----|------|
| CCGT | 8% | 16% |
| Hydro Storage | 17% | 17% |
| OLPSH | 19% | 12% |
| CLPSH | 18% | 17% |
| New CLPSH | 22% | 20% |
| Battery | 16% | 17% |

patchable technologies to operational flexibility in response to power shortages for the *BC* scenario.

Figure 5.4: Contributions of dispatchable technologies to operational flexibility in power, correlating with net load variations for the *BC*

As depicted in Figure 5.4, each technology exhibits a unique ranking in its contribution to flexibility across time scales. Hydro Storage, existing CLPSH, OLPSH, and CCGT demonstrate more outstanding flexibility contributions in the weekly signal compared to the daily and 12-hour signals. In contrast, new CLPSHs and batteries show heightened contributions on daily and 12-hour time scales. The disparity in flexibility contributions among ESS primarily stems from their respective discharge cycles. Hydro Storage,

existing CLPSH, and OLPSH possess discharge cycles ranging from one day to a season, while batteries have a daily cycle, and new CLPSHs extend from hours to several days (i.e., less than one week). These discharge cycles consequently restrict the energy reserve management of ESS, thereby influencing their flexibility contributions.

Moreover, when comparing all technologies, it is noteworthy that battery technology contributes the least to operational flexibility in power scarcity situations despite its limited installed capacity. Conversely, as noted in [4], CCGT exhibits the most significant power modulation across all three time scales. Other dispatchable technologies, such as existing CLPSH, OLPSH, and Hydro Storage, offer similar contributions to operational flexibility.

It is essential to mention that the results about the contributions of these technologies to operational flexibility across various time scales in the sensitivity scenarios need to be presented, as no significant differences were observed.

5.2.3 Sensitivity Analysis: Wholesale System Services

Figure 5.5 presents the average daily battery dispatch for both the *BC* and *RS* scenarios alongside the normalized average daily net load, where normalization is based on the maximum hourly value for clarity.

The data in Figure 5.5 indicates that battery participation in system flexibility is markedly higher in scenarios involving ramping services. This is evidenced by batteries engaging in more substantial energy volume transactions on a daily basis. Incorporating ramping services in the model facilitates more significant intraday energy movement by batteries, thereby augmenting the flexibility provided by battery technology. Additionally, Figure 5.5 reveals that the peak production period of batteries (i.e., 18-19 h) does not coincide with the period of maximum net load demand (i.e., 21-22 h). This discrepancy highlights the critical role of batteries in alleviating the late afternoon net load ramp increase, which typically arises during the transition from solar production to peak demand periods.

Figure 5.6 displays the distribution of total operating reserves among different dispatchable technologies (i.e., ESSs and CCGT) under the *BC* and *RS* scenarios. A critical insight from this figure is the differential impact of ramping services on various ESSs. While batteries and new CLPSH technologies show an increased involvement in operating reserves under the *RS* scenario, other ESSs demonstrate a decrease in contribution. Consequently,

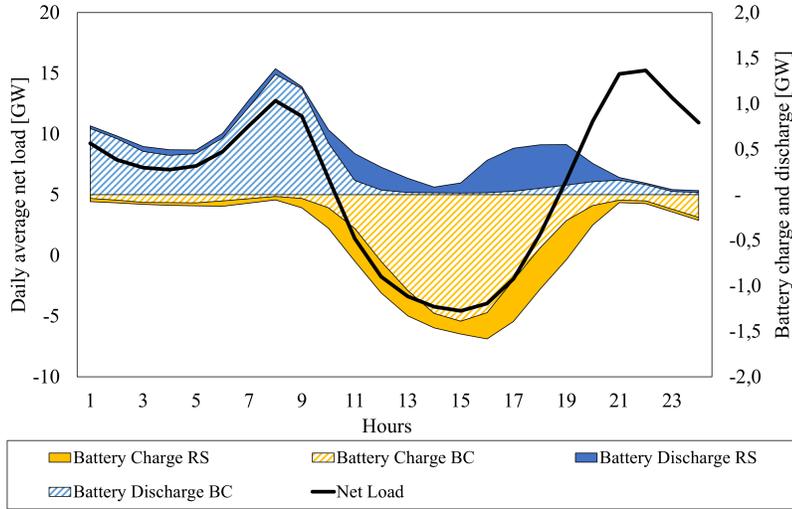


Figure 5.5: Comparison of daily average battery dispatch (represented in blue and yellow) with normalized daily average net load (depicted by the black line) in the *BC* and *RS* scenarios

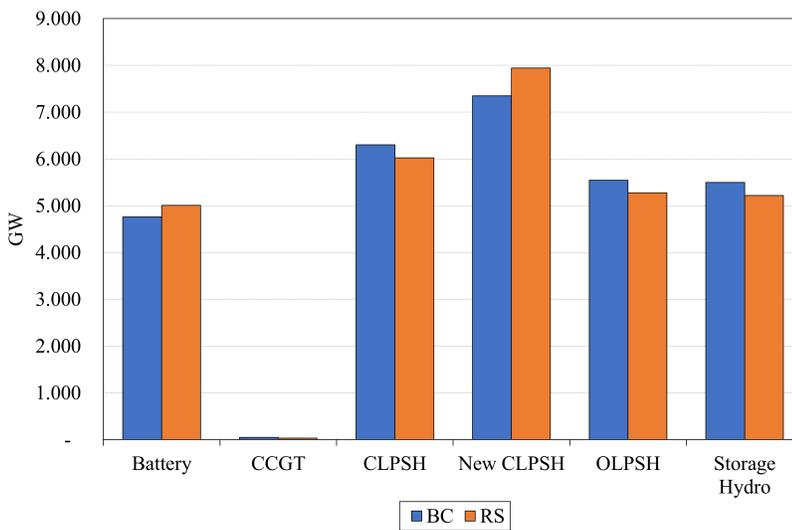


Figure 5.6: Provision of total operating reserves by dispatchable technologies in the *BC* and *RS* scenarios

as Figure 5.6 suggests, the introduction of ramping services generally favors ESSs with superior conversion efficiencies regarding their contribution to operating reserves. Despite this, it is evident that all ESSs contribute to operating reserves, albeit to varying extents.

Table 5.6: Technologies providing ramping services according to results of *RS* scenario

| | CCGT | OLPSH | Hydro Storage | CLPSH | New CLPSH | Battery |
|--------------------------|------|-------|---------------|-------|-----------|---------|
| Downward Ramping service | 0,0% | 10,6% | 69,5% | 0,0% | 0,2% | 19,6% |
| Upward Ramping Service | 0,0% | 9,6% | 69,2% | 0,0% | 0,2% | 21,0% |

Table 5.6 delineates the specific roles of various technologies in providing ramping services. According to the data in Table 5.6, Hydro Storage emerges as the predominant contributor to both the downward and upward ramping services, with batteries and OLPSH also playing significant roles.

Figure 5.7 illustrates the shifts in the engagement of dispatchable technologies within wholesale system services, specifically focusing on energy and operating reserves, as a result of incorporating ramping services. This figure, in conjunction with Table 5.6, allows for an analysis of the evolving synergies and trade-offs among different technologies, particularly in allocating resources for distinct services.

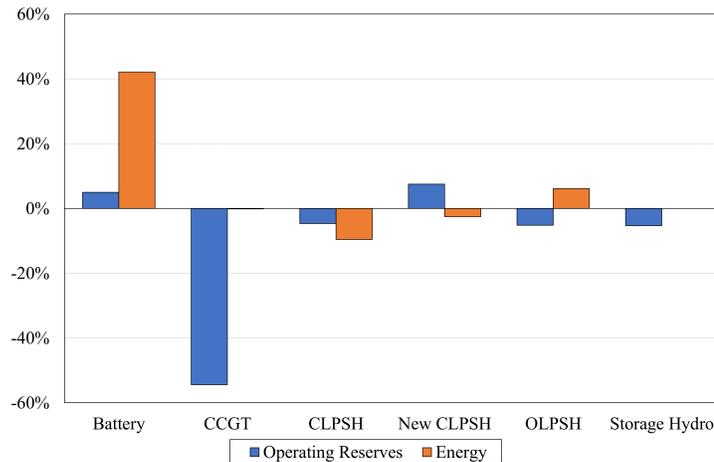


Figure 5.7: Differential contributions of dispatchable technologies to operating reserves (blue) and energy (orange) in the transition from *BC* to *RS* scenarios.

The insights derived from these findings elucidate the adaptive strategies of ESSs in response to the evolving landscape of market operations. The introduction of ramping services significantly enhances the deployment strategies of batteries in meeting energy demands and ramping service requirements. OLPSH, known for its weekly charging cycles and substantial capacity, demonstrates effective energy transfer over prolonged periods. This capability is instrumental in its increased role in ramping services and load demand fulfillment, simultaneously leading to a reduced engagement in operating reserves. In contrast, Hydro Storage maintains consistent involvement in energy services in both the *RS* and *BC* scenarios. However, there is a notable shift from its participation in operating reserves to a more dominant role in ramping services. Notably, Figure 5.7 also indicates a significant, nearly 50% decrease in CCGT's involvement in operating reserves. This change is relatively minor, considering CCGT's limited role in these services, as illustrated in Figure 5.6.

Subsequent sections offer an in-depth analysis of the competition within wholesale system services, focusing on the contributions of dispatchable technologies toward system adequacy.

5.3 Contributions to Adequacy

5.3.1 Capacity Value

Several methods exist for assessing peaking capacity resources [5], but they are not directly applicable to deterministic analysis in an operation model that does not consider investments. Hence, this analysis adopts a different approach, utilizing the average capacity factor of the technology during critical periods to evaluate the peaking capacity of ESS technologies, indicating their contribution to the adequacy of the power system [6]. A technology's presence during critical periods indicates its ability to contribute to the system's supply guarantee.

The assessment of technological contributions towards system adequacy utilizes the capacity factor approximation-based methodology, as outlined in [6]. This study explicitly investigates the role of various technologies in ensuring adequacy within contexts characterized by high VRES penetration. The chosen method correlates closely with instances of peak net demand, thereby focusing on critical periods where the likelihood of high demand

coinciding with low VRES generation is greatest. Table 5.7 enumerates the capacity values for dispatchable technologies, calculated for the top 100, 200, and 400 hours of peak net demand (i.e., referred to as critical hours) in the *BC*.

Table 5.7: Capacity value of technologies according to different time ranges for the *BC*

| | Battery | CLPSH | OLPSH | NEW CLPSH | CCGT | Hydro | Storage |
|--------------------|---------|-------|-------|-----------|------|-------|---------|
| 100 critical hours | 6% | 63% | 88% | 27% | 74% | | 98% |
| 200 critical hours | 7% | 62% | 82% | 34% | 66% | | 94% |
| 400 critical hours | 13% | 58% | 77% | 40% | 57% | | 89% |

The data presented in Table 5.7 is derived from the *BC* and the underlying modeling assumptions. As delineated in Table 5.7, batteries emerge as the final dispatchable technology contributing to adequacy during critical periods. Furthermore, the adequacy contribution of new CLPSH units is inferior to that of existing units. Notably, new CLPSH units exhibit superior round-trip efficiency compared to their older counterparts, yet they are characterized by a shorter discharge cycle and reduced energy storage capacity. Consequently, there appears to be a correlation between energy storage capacity and adequacy contribution, as exemplified by existing CLPSH units offering 33 hours of full-power discharge and achieving 63%-58% contribution to the adequacy, compared to new CLPSH units with 8 hours of discharge and 27%-40% adequacy contribution. Although the input data might influence this observation, it aligns with findings reported in [7]. Additionally, as Table 5.8 illustrates, the capacity value of some technologies fluctuates across different scenarios. A decrease in the range of critical hours for capacity value calculation, resulting in an increased capacity value, indicates the reliability of specific technologies during critical demand periods.

Table 5.8 also provides the average capacity values of technologies across the 100 to 400 critical hours for scenarios such as *Dunkelflaute*, *Dry Case*, and *Wet Case*. Batteries consistently rank as the last technology available during these critical hours. Nevertheless, they exhibit the slightest variation in capacity value across different sensitivity scenarios. This stability is attributed to batteries' relatively lower energy storage capacity than other ESSs.

Table 5.8: Capacity value of technologies according to the average of 100 - 400 critical hours of net demand for the *BC* and sensitivity scenarios

| | Battery | CLPSH | OLPSH | New CLPSH | CCGT | Hydro Storage |
|---------------------|---------|-------|-------|-----------|------|---------------|
| <i>Ref Case</i> | 9% | 61% | 82% | 35% | 65% | 93% |
| <i>Dunkelflaute</i> | 12% | 56% | 81% | 35% | 69% | 93% |
| <i>Dry Case</i> | 9% | 60% | 69% | 34% | 71% | 79% |
| <i>Wet Case</i> | 9% | 66% | 93% | 36% | 62% | 92% |

5.3.2 Behavior of ESS during critical events

In evaluating the operational competitiveness and role of different ESS technologies, their contribution to the system's adequacy is an essential factor. This contribution, crucial for supply assurance, is typically remunerated in capacity markets. As such, it becomes a significant aspect in assessing the competitiveness and role of generation technologies and ESSs. Although stochastic models ideally address this, deterministic operation models like the one employed in this study can provide valuable insights into the comparative roles of ESSs in this context.

This consideration gains even more importance in systems predominantly powered by intermittent generation sources. Such systems can expect a higher frequency and duration of critical events, necessitating robust responses from non-dispatchable resources. In these scenarios, thermal generation and ESSs become key players. Critical hours are primarily linked to periods of exceptionally high demand in electricity systems dominated by thermal generation. However, in systems with a significant proportion of non-dispatchable VRES, one may observe sequences of many consecutive critical hours. Thus, examining the behavior of ESS technologies during these critical events is crucial to understanding their roles. This section, therefore, focuses on evaluating the contribution of PSH units during the most critical hours in terms of their production level.

The reliability of a technology during peak demand hours is gauged by a measure that approaches one. However, determining the number of critical hours to consider remains crucial. A high number of critical hours might lead to an average annual load factor for each technology, as fewer critical hours are included in the analysis. Conversely, fewer hours might fail to account for longer critical events, potentially leading to overestimation or underestimation of some ESSs. Consequently, a sensitivity analysis was conducted,

considering a range of 100 to 400 hours, focusing on periods with the highest net demand after accounting for intermittent VRES production.

In Tables 5.8 and 5.7, the capacity factors align with the annual mean of the demand-based capacity factor, especially for the critical 400-hour range. Moreover, the net demand-based capacity factor exceeds the demand-based factor, suggesting better ESS availability when demand is high and non-dispatchable VRES production is low. These observations imply that (1) defining critical system hours should consider both non-dispatchable VRES production and load demand; (2) an overly broad time window could lead to misleading interpretations, shifting focus from technology availability in critical periods to its annual average capacity factor.

Another notable point in Tables 5.8 and 5.7 is the apparent link between the availability of ESSs and the capacity of their energy reservoirs. The ranking of ESS availability at peak hours correlates with the size of each ESS's energy reservoir. As the critical hours range narrows, the availability of OLPSH and existing CLPSH increases while that of new CLPSH and batteries decreases. Note that this correlation should be viewed cautiously as it is subject to the specifics of the technology data, modeling assumptions, and the power system under consideration. The fewer critical hours considered, the fewer ESSs with smaller energy reservoirs are available due to the higher net demand values.

Despite their high round-trip efficiency, as shown in Figure 5.8, batteries would not be available during the 100-hour or 300-hour highest net demand values. This limitation stems from the batteries' maximum discharge time of 4 hours.

Figure 5.8 indicates that the most prolonged critical period observed is 7 hours. In the 100-hour highest net demand scenario, 4-hour and 5-hour events occur with similar frequency, while in the 300-hour scenario, 5-hour events are more frequent. Despite some periods matching the maximum discharge time of batteries, numerous critical hours occur consecutively or in close succession, such as on consecutive days. Given their limited storage capacity, batteries cannot sustain availability at the same level as other ESSs.

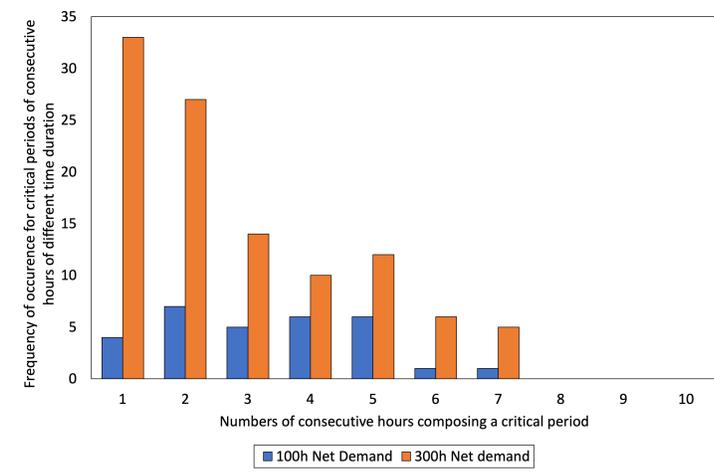


Figure 5.8: Occurrence frequency of critical events with various durations for the *BC* scenario, considering 100 and 300 hours of highest net demand.

5.4 Economic Analysis of Wholesale System services

5.4.1 Income according to wholesale system services

Figures 5.9a and 5.9b display the total revenue per installed capacity for dispatchable technologies in the *BC* and *RS* scenarios. This measure aggregates all income from provided services, normalized by each technology's installed capacity, and examines income distribution across different services.

Figure 5.9a indicates that in the *RS* scenario, the income per capacity for all ESS technologies increases, except for existing and new CLPSH, which see a decrease of 12.3% and 3%, respectively. Despite reduced revenue for CLPSH units due to ramping services, their crucial role in demand fulfillment and system adequacy maintenance remains intact. Batteries, in particular, exhibit the most significant increase in revenue, with a 23% rise in the *RS* scenario compared to the *BC* scenario.

Figure 5.10 elucidates the impact of ramping services on the income of dispatchable technologies across different wholesale system services, including energy and operating reserves. Despite their augmented role in energy and operating reserves, batteries' revenue from the latter declines upon the introduction of ramping services. Conversely, Hydro Storage sees a decrease

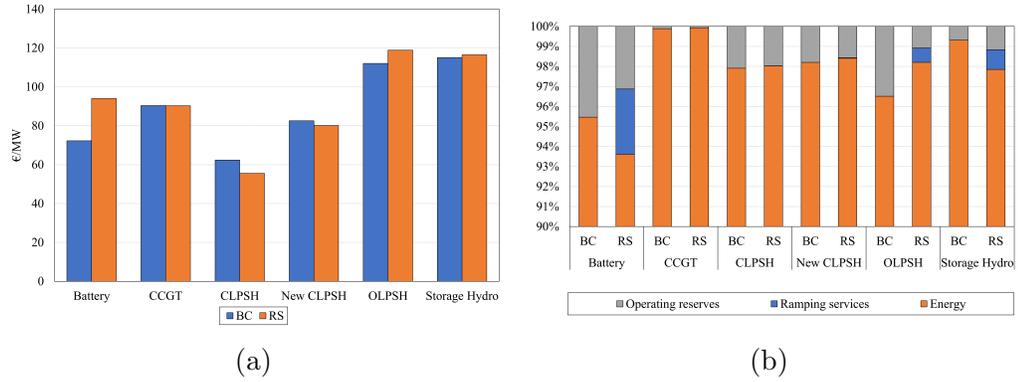


Figure 5.9: (a) Per-capacity income (€/MW) of dispatchable technologies for wholesale system services in the *BC* and *RS* scenarios. (b) Distribution of income by service type in the *BC* and *RS* scenarios.

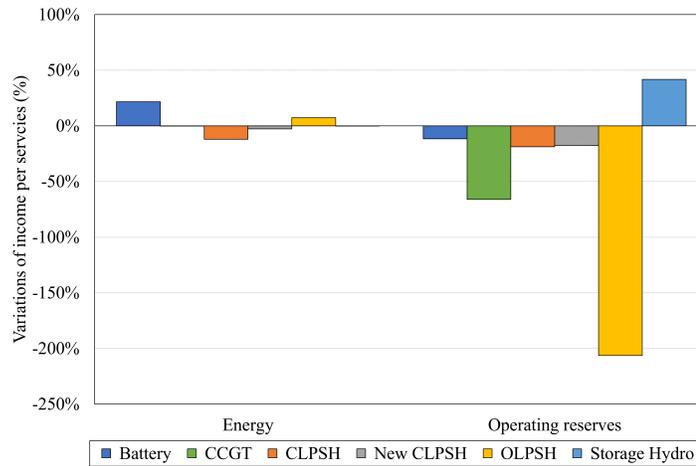


Figure 5.10: Variation in income for ESS technologies by service type (left: Energy services; right: Operating reserves) with the inclusion of ramping services.

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in its engagement in operating reserves but an increase in associated revenue. This pattern reflects the marginal electricity market principle in ideal market conditions and the reassignment of roles among technologies based on their specific characteristics. The figure also highlights the economic competition among technologies in optimizing their contributions to system services and the overall cost efficiency in electric system operation.

The findings underscore the importance of ramping services for technologies adept at rapidly adapting to fluctuations in net load demand. With its high ramping capacity and minimal technical output constraints, battery technology becomes increasingly viable for ramping service requirements, as discussed in [3]. The incorporation of ramping services ensures sufficient ramping availability, enhancing batteries' role in meeting daily flexibility needs. As a result, batteries provide ramping and operating reserves and significantly contribute to meeting demand. This necessitates reducing CLPSH and new CLPSH production, allowing these units to reserve energy to maintain system adequacy during peak periods.

5.4.2 Sensitivity analysis

This section investigates the influence of extreme scenarios dictated by water inflow variations on operation dispatch, system flexibility, adequacy, and the revenue of technologies, particularly under the implementation of ramping services.

Table 5.9 elucidates the results for these scenarios, analyzed through various power system indicators.

Table 5.9: Indicators of power system operations for the *BC Wet*, *RS Wet*, *BC Dry* and the *RS Dry* scenarios

| | | BC Wet | RS Wet | % | BC Dry | RS Dry | % |
|----------------------|-------------------|--------|--------|-------|--------|--------|-------|
| Total Operation Cost | M€ | 3182,4 | 3171,8 | -0,33 | 4048,2 | 4046,8 | -0,03 |
| Total Emission | MtCO ₂ | 19,2 | 19,2 | -0,23 | 23,5 | 23,5 | -0,03 |
| Average SRMC | €/MWh | 39,7 | 39,7 | 0,11 | 47,0 | 47,3 | 0,52 |
| Max SRMC | €/MWh | 89,5 | 84,6 | -5,80 | 84,7 | 84,3 | -0,55 |
| Std SRMC | €/MWh | 30,6 | 30,6 | -0,22 | 28,3 | 28,2 | -0,55 |
| ENS | GWh | 0 | 0 | | 0 | 0 | |

The analysis in Table 5.9 demonstrates that in the *BC Dry* and *RS Dry* scenarios, integrating ramping services results in reduced variability and peak

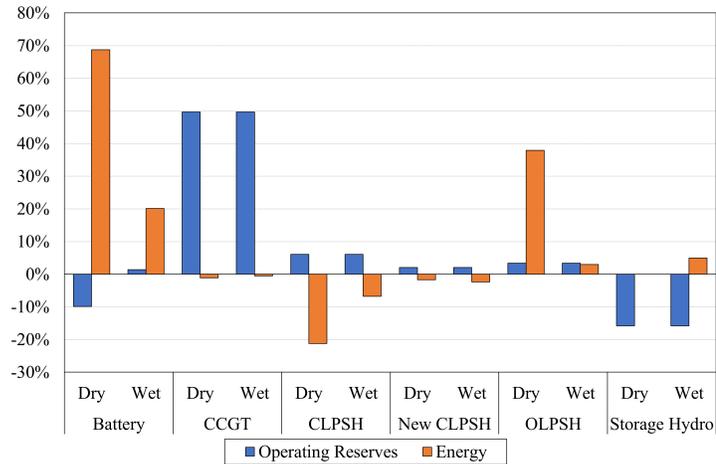


Figure 5.11: Variations in income per service for ESS technologies across *BC Wet* versus *RS Wet*, and *BC Dry* versus *RS Dry* scenarios.

values in the Short-Run Marginal Cost (SRMC). Figure 5.11 complements this analysis by depicting the shifts in dispatchable technologies' participation in wholesale system services (energy and operating reserves) under extreme conditions with ramping services. The figure reveals that implementing additional services enhances the operational efficiency of ESS technologies, notably batteries, even in these extreme scenarios. It also shows the varying value of ESSs in different scenarios (Dry or Wet), indicating resource-dependent trade-offs.

Figure 5.12 assesses the income per installed capacity of dispatchable technologies in various scenarios. Technologies independent of water inflows show divergent income patterns based on the scenario's wetness or dryness. In dry conditions, batteries and new CLPSH units enhance their income, compensating for the reduced availability of OLPSH and Hydro Storage resources. The introduction of ramping services boosts revenue for batteries, OLPSH, and Hydro Storage while reducing it for CLPSH units.

5.4. ECONOMIC ANALYSIS OF WHOLESALE SYSTEM SERVICES¹²¹

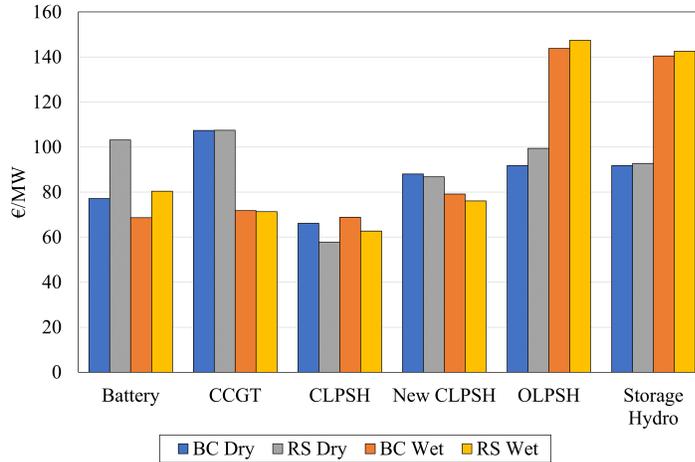


Figure 5.12: Per-capacity income (€/MW) of dispatchable technologies in providing wholesale system services across *BC Wet*, *RS Wet*, *BC Dry*, and *RS Dry* scenarios.

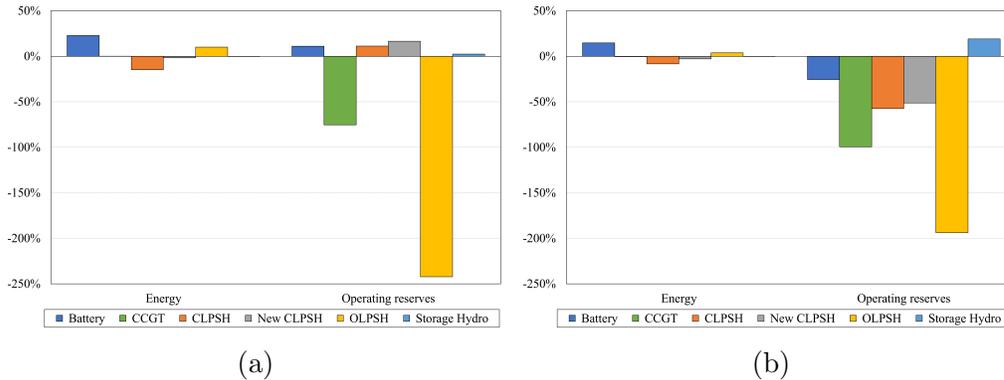


Figure 5.13: Revenue shifts in dispatchable technologies for different wholesale system services in *BC Wet*, *RS Wet* (a), *BC Dry*, and *RS Dry* (b) scenarios.

Figure 5.13 illustrates the incomes of dispatchable technologies across different wholesale system services, factoring in ramping services in Dry and Wet scenarios. Regardless of the scenario type, the introduction of ramping services yields consistent effects on technology income related to energy service: an increase for batteries and OLPSH. In contrast, other technologies face a decrease or negligible impact.

Additionally, introducing operating reserves and ramping services consistently augments Hydro Storage's income across both Wet and Dry scenarios. This trend is distinct from OLPSH, which, due to its inability to pump water, strategically limits its participation in ramping services under constrained water inflow conditions, prioritizing energy storage for critical demand periods.

Notably, Figure 5.13a reveals that OLPSH is the only ESS technology experiencing reduced revenue from operating reserves upon the addition of ramping services. In contrast, other technologies, including CLPSH units, Hydro Storage, and batteries, exhibit an uptick in revenue. This differential response highlights OLPSH's strategic adaptation to limited water resources, conserving its capacity for periods of heightened net demand.

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Chapter 6

Conclusions

6.1 Main Conclusions

This thesis presents an in-depth analysis of the Spanish electricity system's medium-term operation under scenarios with a high VRES share by 2030. Central to this analysis is the role of ESS, particularly batteries and PSH. These systems are crucial in ensuring the security of supply and flexibility in the electricity system. The medium-term operational model developed in the research highlights the significant role of ESS in maintaining adequacy, especially during critical events. Notably, batteries, despite their smaller energy capacity, emerge as substantial contributors to the reserve market, effectively balancing the system's reliability needs.

Another significant aspect of the research is the integration of ramping services into the medium-term operational model. This addition reveals the nuanced roles of dispatchable technologies in providing various power system services. The integration of ramping services leads to a notable shift in the operation of batteries, enhancing their contribution to energy and ramping services. This shift allows OLPSH to increase its availability during critical periods to provide adequacy, demonstrating the complex interdependencies within the power system.

The research also emphasizes the importance of energy storage capacity in determining the adequacy contribution of ESS technologies. OLPSH, with its ability to pump water, demonstrates a superior contribution to system adequacy compared to CLPSH units, which have a lower energy storage capacity. This finding is significant as it highlights the varied roles that different

storage technologies can play in a renewable-dominated power system.

6.2 Contributions

The research presented in this thesis significantly contributes to the field of energy systems, particularly in understanding the role of storage technologies in renewable-dominated power systems. A notable contribution is developing a novel methodological framework and methodology to jointly assess the adequacy and operational flexibility of power systems with high shares of VRES. This framework provides a comprehensive approach to understanding the complex roles of ESSs in power systems transitioning toward renewable energy.

One of the primary enhancements in this research is incorporating mechanisms to consider operating reserves, encompassing balancing capacity and energy activation and integrating ramping services. These enhancements expand the model's applicability and improve its ability to represent power systems' operational flexibility accurately. Additionally, the model now accounts for discharging time, allowing for differentiation between various ESSs, which is critical for assessing their performance and value in different scenarios.

Another key contribution is the detailed analysis of different ESS under various critical scenarios, including dry and wet water inflow conditions. This analysis offers a deeper understanding of the complex roles that storage technologies play under different environmental and operational conditions. The study provides insights into how different storage technologies can complement and compete with each other, thereby enhancing the overall reliability and efficiency of the power system.

The research also examines the economic and operational impacts of ramping services, which is another significant contribution. This analysis provides insights into the complex interplay between various dispatchable technologies in the power system and the potential for revenue redistribution. The findings from this study underscore the importance of considering such services in the medium-term operational planning of power systems, particularly in scenarios with high VRES penetration. Introducing additional wholesale services to reinforce economic incentives for diverse technologies further emphasizes the importance of a holistic approach to system planning and operation.

Moreover, developing and applying a unique taxonomy to facilitate the analysis of balancing services as wholesale system services represents a methodological advancement. Grouping these services under a single umbrella term enables a more holistic examination of the diverse range of services that ESS can provide, including energy, operating reserves, ramping services, and significant contributions to overall system adequacy. This taxonomy enhances the clarity and depth of the analysis, allowing for a more nuanced understanding of how ESS can adapt and respond to the flexibility needs of a power system increasingly reliant on renewable sources.

Completing this thesis journey and presenting the findings have not only culminated in significant academic contributions but have also been disseminated through several publications. The author of this thesis has led the following articles:

- **Huclin, S.**, et al. (2022). Exploring the roles of storage technologies in the Spanish electricity system with high share of renewable energy. *Energy Reports*, 8, 4041–4057. <https://doi.org/10.1016/j.egyр.2022.03.032>
- **Huclin, S.**, et al. (2023). A methodological approach for assessing flexibility and capacity value in renewable-dominated power systems: A Spanish case study in 2030. *Energy*, 285, 129491. <https://doi.org/10.1016/j.energy.2023.129491>
- **Huclin, S.**, et al. (2024). Evaluating the economics and competition of providing wholesale system services in a renewable-dominated power system: the Spanish case study. *Applied Energy* (*In revision*)

Furthermore, the author of this thesis has participated as co-author of the following articles:

- Ramos, A., **Huclin, S.**, Chaves, J. P. (2023). Analysis of different flexible technologies in the Spain NECP for 2030. *Frontiers in Built Environment*, 9. <https://doi.org/10.3389/fbuil.2023.1065998>
- Freire-Barceló, T., Martín-Martínez, F., Sánchez-Miralles, Á., Rivier, M., San Román, T. G., **Huclin, S.**, Ávila, J. P. C., Ramos, A. (2022). Storage and demand response contribution to firm capacity: Analysis of the Spanish electricity system. *Energy Reports*, 8, 10546–10560. <https://doi.org/10.1016/j.egyр.2022.08.014>

- Lumbreras, S.; Gómez, J.D.; Alvarez, E.F.; **Huclin, S.** (2022) The Human Factor in Transmission Network Expansion Planning: The Grid That a Sustainable Energy System Needs. *Sustainability* 2022, 14, 6746. <https://doi.org/10.3390/su14116746>

6.3 Future Works

Looking ahead, several avenues for future research are suggested to address the limitations and expand the scope of the current studies. One important direction is incorporating emerging technologies such as electric vehicles, power-to-X, demand response, and hydrogen-based systems. Including these technologies in future studies would provide a more comprehensive analysis of the power system's capabilities and limitations, particularly regarding flexibility and storage.

Integrating network constraints and adopting a finer temporal resolution would significantly enhance the accuracy and applicability of the operational models. Given the geographical isolation of the Iberian Peninsula and the increasing integration of VRES, the significance of interconnections with Portugal and France within the context of the Spanish power system continues to grow, particularly concerning the flexibility requirements. Therefore, modeling interconnections enhances the analysis of adequacy and flexibility, providing a comprehensive understanding of the roles played by various flexible technologies in the context of VRES integration. Additionally, incorporating topography to represent hydropower plants and hydrothermal constraints better would further improve the model's accuracy and reliability. These improvements would allow for a more detailed and nuanced understanding of the power system's operation, including the interactions between different technologies and the impacts of network limitations on power system adequacy and operational flexibility.

Extending the geographic scope of the studies beyond Spain and refining the use of the model to have a less clairvoyant operation of the power system would provide a more robust understanding of the impacts of storage technologies and ramping services across different power systems and under varying conditions. This broader perspective would be valuable for policy-makers and stakeholders in designing and implementing strategies for the transition to renewable energy.

Extending the geographic scope of the studies beyond Spain and refining

the use of the model to have a less clairvoyant operation of the power system would provide a more robust understanding of the impacts of storage technologies and ramping services across different power systems and under varying conditions. Furthermore, incorporating stochasticity to account for VRES uncertainty would enhance the model's ability to simulate real-world conditions and better assess technology's contribution to the power system flexibility. This broader perspective would be valuable for policymakers and stakeholders in designing and implementing strategies for the transition to renewable energy.

Another important future direction is expanding the models to include investment options and a more detailed economic analysis. This expansion would provide insights into the long-term implications of storage technologies and ramping services, including their impact on investment decisions and the evolution of the energy mix. Such an analysis would be crucial for understanding the economic drivers and barriers to deploying different technologies in a renewable-dominated power system. Considering investment options would also refine the calculation of adequacy contributions, offering a more precise assessment of the technology contribution to the power system adequacy.

In light of the emerging challenges posed by the integration of VRES, it becomes imperative to rethink and adapt electricity market regulations. This study underscores the necessity of integrating additional wholesale system services, such as ramping services, tailored to the unique needs of different power systems. These services should be introduced by a remuneration structure that recognizes and incentivizes the distinct value they add to the power system. Such a strategic approach is critical in enhancing the integration of VRES, as it would not only adapt investment signals for emerging technologies but also facilitate a smoother transition towards a renewables-based energy mix. Identifying and implementing the specific services required for each power system will be a cornerstone in achieving a more resilient, efficient, and sustainable energy future.