Impact of climate change on hydropower plant's role in the Iberian electricity market

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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ABSTRACT

In the face of the urgent global issue of climate change, the Iberian Peninsula stands at the crossroads of renewable energy expansion and the climate-induced transformation of its water resources. In this critical scenario, hydropower is essential in the transition to a sustainable, low-carbon energy future. This study examines the effects of climate change on the role of hydropower in the Iberian power system, focusing on its impact on generation, energy security, and market dynamics in the context of increasing renewable energy capacities. The research conducts comprehensive EnergyPLAN simulations for the year 2030, encompassing both technical and economic scenarios. A gradient boosting algorithm is employed for electricity price forecasting, enhancing economic analysis and market dynamics integration. The study reveals a promising trajectory for renewable energy growth in the Iberian Peninsula but emphasizes vulnerability to drier years, significantly affecting hydropower generation. The importance of pumped storage emerges, promoting dammed hydropower as a vital dispatchable source. Economic simulations reveal favourable prospects for Portugal, emphasizing the value of imports in a renewable-dominated environment and highlighting the importance of strategic water resource management. The study concludes that hydropower, particularly dammed hydropower, will shift from a contributor to a central regulatory role in the power system. Hydro-pumped storage diminishes reliance on non-renewable sources, with alterations in pumping and generation patterns aligned with solar availability and market prices. This research provides indispensable insights into hydropower's evolving role in a changing climate, offering essential considerations for policymakers, energy stakeholders, and researchers engaged in the Iberian energy landscape.

Key-words: climate change; renewables; hydropower; energy transition; pump-storage

RESUMO

No contexto do desafio das mudanças climáticas, a Península Ibérica encontra-se na encruzilhada da expansão de energia renovável e da influência climática sobre os recursos hídricos. Neste panorama de mudança, a energia hidroelétrica é essencial na transição para um futuro energético sustentável e com baixas emissões de carbono. Este estudo examina os efeitos das mudanças climáticas no papel da hídrica no sistema electroprodutor ibérico, com foco no impacto na geração, segurança energética e dinâmica de mercado. Diversas simulações através da ferramenta EnergyPLAN para o ano de 2030 são realizadas, abrangendo cenários técnicos e econômicos. Um algoritmo gradient boosting é utilizado na previsão dos preços de eletricidade, possibilitando a análise econômica e a integração da dinâmica do mercado Ibérico. O estudo revela uma trajetória promissora para o crescimento de geração renovável na Península Ibérica, mas realça a vulnerabilidade a anos mais secos, afetando significativamente a geração hídrica. A importância do armazenamento através da hídrica de bombagem é evidenciado, promovendo a energia hidroelétrica como uma fonte vital de geração despachável. Simulações econômicas realçam o valor das importações num ambiente dominado por energias renováveis e destacam a importância da gestão estratégica dos recursos hídricos. O estudo conclui que a energia hidroelétrica passará a desempenhar um papel central de regulação. A bombagem hídrica irá exibir alterações nos padrões de bombagem e geração alinhados com a disponibilidade solar e os preços de mercado. Este estudo fornece informações sobre a evolução da hídrica, oferecendo considerações essenciais para responsáveis políticos e investigadores envolvidos no cenário energético Ibérico.

Palavras-chave: alterações climáticas; renováveis; hidroenergia; transição energética; hídrica de bombagem

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1 Introduction

1.1 Motivation

The current decade is marked by an unprecedented global challenge – climate change. As highlighted by the Intergovernmental Panel on Climate Change (IPCC) and numerous scientific studies, the Earth's climate is undergoing rapid and profound alterations (Calvin et al. 2023). The observed global mean surface temperature has been rising over the past century, and projections indicate this trend will persist, with potential increases ranging from 1.4 to 4.4°C by the end of the 21st century. These changes are primarily driven by the atmospheric accumulation of greenhouse gases, making climate change one of the most urgent issues of our time.

A significant contributor to the increase in greenhouse gas emissions is the energy sector (Ritchie et al. 2020). It is, therefore, imperative to decarbonize this sector by increasing the share of renewable energy sources. Hydropower, a clean and mature source of energy, will play a pivotal role in this strategy. This source is the backbone of low-carbon electricity generation, providing almost half of current clean energy worldwide today. Hydropower’s contribution is 55% higher than nuclear’s and is still larger than that of all other renewables combined, including wind, solar PV, bioenergy, and geothermal (IRENA 2023). In 2020, hydropower supplied 17% of global electricity generation, the third largest source, after coal and natural gas. Over the last 20 years, hydropower’s total capacity rose 70% globally, but its share of total generation stayed stable due to the growth of wind, solar PV, coal, and natural gas (IEA 2021).

What sets hydropower apart is its dispatchable capacity in facilities equipped with reservoirs, commonly known as dammed hydropower. This feature distinguishes it from other renewables, including run-of-river facilities, which are highly dependent on the fluctuating nature of their energy supply (Ramião et al. 2023). Hydropower plants with reservoirs can improve energy supply security and reliability. In addition, hydropower is by far the most effective technology for energy storage in the form of pumped storage power plants, representing 97.5% of the global energy storage capacity (Fairley 2015). Despite possible methane emissions from the impounded areas, carbon emissions are relatively low in comparison to other technologies (Lu et al. 2020). It is, therefore, considered an essential element of the future energy mix as the global energy system moves towards a less carbon-intensive and sustainable future.

Despite its significance in the drive towards sustainability, hydropower exhibits a dual relationship with climate change. On one hand, it's a crucial component in achieving sustainability goals and reducing greenhouse gas emissions. On the other, it's uniquely susceptible to climate change impacts (Kumar et al. 2011). Climate change is poised to induce profound shifts in global water resources and, by extension, hydropower generation. These transformations encompass variations in the timing, magnitude, and geographical distribution of precipitation, along with adjustments in runoff patterns (Hamududu et al. 2012; Ramião et al. 2023; Rasilla et al. 2013). However, these effects exhibit notable variations depending on geographical locations, influenced by several natural factors (Lehner et al. 2005). The IPCC's Sixth Assessment Report (AR6) anticipates an augmentation of water resources at high and mid-latitudes, along with many equatorial areas. Conversely, subtropical regions are expected to face reduced water resources. Furthermore, the report suggests that climate change will likely amplify flood magnitude and frequency due to concentrated precipitation in various regions while diminishing low flows pose a potential threat to water resource quality (Calvin et al. 2023).

The Iberian Peninsula is projected to experience a substantial decline of up to 40% in hydropower generation by the year 2070, particularly in its southern region (Andrade et al. 2021; Lehner et al. 2005; Rasilla, Garmendia et al. 2013; Teotónio et al. 2017). This significant impact is closely linked to the Mediterranean climatic conditions that dominate the area. The Mediterranean Basin is considered a climate change "hot spot" due to its heightened vulnerability to rising temperatures, prolonged droughts, and alterations in precipitation patterns, which collectively amplify the challenges posed by climate change (Fernandez et al. 2017; De Luis et al. 2009).

Understanding the consequences of climate change on hydropower in the Iberian Peninsula is of utmost importance for several reasons. Firstly, it affects the region's energy security, as hydropower has traditionally acted as a natural buffer during periods of high demand or energy supply shortages. Secondly, the reliance on hydropower has significant implications for the Iberian electricity market's overall resilience, price dynamics, and long-term sustainability. Thirdly, this research can contribute valuable insights for policymakers, energy stakeholders, and the wider scientific community as they grapple with the urgent need to transition to a more sustainable, climate-resilient energy system.

1.2 Objectives

Notwithstanding hydropower's vulnerability to climate change, it's crucial to highlight its growing role in managing the fluctuations brought by the increasing penetration of intermittent renewable sources like wind and solar. By taking advantage of its pump storage capacity, hydropower serves as a dynamic solution to balance electricity supply and demand. During surplus periods of wind and solar power generation, excess energy can be used to pump water back into storage. This stored water can then be readily converted into hydropower when demand spikes, ensuring a reliable, flexible, and clean energy supply in a transitioning power system (IHA 2022). Additionally, strategies such as cascade effects, which maximize the utilization of the same water body, and emerging technologies like floating PV that reduce evaporation rates from reservoirs, must be considered as solutions to mitigate the effects of climate change on hydropower (IHA 2022; Teotónio et al. 2017). The solution is not to cease hydropower but to adapt it to this new reality.

The primary objective of this thesis is to assess the resilience of the Iberian power system in the face of extreme hydrological scenarios, which are representative of future climate conditions. This assessment will focus on hydropower generation and pump consumption patterns, emphasizing their technical and economic significance. As mentioned previously, pump consumption is anticipated to have a significant impact on a power system increasingly dominated by renewables. With the impacts of climate change on water resources, it is predicted that the role of pump storage and the interplay between turbine generation and pumping will become even more critical.

To address these complex questions, this thesis adopts a multidisciplinary approach, encompassing data collection, analysis, Iberian power system modelling, simulation of future scenarios, and market price forecasting. The specific objectives of the thesis are as follows:

- **Historical Data Acquisition:** Gather historical data to gain a comprehensive understanding of hydropower's historical role and patterns in the Iberian power system.

- **Energy Mix Projection for 2030:** Project the composition of the energy mix in the Iberian power system for the year 2030, considering the evolving influence of renewable energy sources.
- **Storage Capacity Utilization:** Project the utilization of storage capacity, with a particular focus on the energy consumed by pumped hydro storage (PHS).
- **CO2 Emissions and Renewable Energy Utilization:** Assess the future levels of CO2 emissions and the percentage of renewable energy sources (RES) utilization within the Iberian power system.
- **Identify Distinct Patterns:** Investigate potential unique patterns in generation and pump consumption for hydropower within the Iberian power system, providing insights into their historical trends and future implications.
- **Evaluation of Future Storage Needs:** Determine the future requirements for additional storage capacity, which may include an expansion of pumped hydro capacity or the incorporation of batteries. This evaluation aims to ascertain whether the planned or expected storage capacity for 2030 is adequate or if further capacity enhancements are necessary for the sustainable functioning of the system.

1.3 Structure of the thesis

The thesis is organized into six chapters to provide a comprehensive exploration of the research topic. The first chapter serves as an introduction to the thesis, outlining the motivation behind the chosen theme and articulating the objectives that the research aims to achieve. Chapter 2 undertakes a comprehensive literature review to provide readers with a deep understanding of the existing body of knowledge and research related to the chosen topic. In Chapter 3, a broader perspective is offered, encompassing hydropower on a global scale and within the context of the Iberian power system. The chapter delves into the historical and current status of hydropower worldwide, examines its role in the Iberian power system, and investigates the impacts of climate change on this energy source. This chapter also serves as a bridge to the Iberian electricity market. Chapter 4 elaborates on the various phases of the methodology employed in the research, including an overview of the software tools used for conducting the analysis. Chapter 5 presents and discusses the research findings, offering insights into the implications and significance of the results. The final chapter, Chapter 6, consolidates the thesis by summarizing the conclusions drawn from the research and providing a final set of considerations. In the appendices, readers can access supplementary figures, tables, and data that complement and enhance the understanding of the research findings presented in the main chapters.

2 Background

2.1 Climate Change

The phenomenon of global climate change presents an unparalleled threat to both human societies and natural ecosystems. This transformation in climate mainly results from human-induced activities through the release of greenhouse gases into the atmosphere and significant changes in land use (Santos FD et al. 2001).

Describing the weather at a specific time and location implies the knowledge of meteorological variables, such as temperature, precipitation, wind, pressure, and humidity. The ensemble of weather events at a given site defines its climate. More formally, climate constitutes a statistical portrayal of meteorological variables' means and variability over a span ranging from months to millions of years, with a minimum period of 30 years set by the World Meteorological Organization (World Meteorological Organization (WMO) 2017). Climate change implies significant alterations in either the mean state of the climate or its variability, persisting for an extended duration, often decades or longer, as defined by the Intergovernmental Panel on Climate Change (IPCC) (Kumar et al. 2011).

Climate change arises from natural internal processes, external forces, and anthropogenic factors, manifesting as changes in atmospheric composition and land utilization. Notable natural external forces include changes in solar luminosity and earth-sun orbit parameters, affecting the planet's energy balance over extended periods. Human-induced climate change primarily results from changes in greenhouse gas concentrations, especially carbon dioxide (CO2), with higher concentrations leading to increased temperature due to the trapping of emitted infrared radiation near the surface (Berga 2016). The buildup of CO2, constituting 76% of total greenhouse gas emissions, has escalated from approximately 277 ppm in 1750 to 419 ppm in 2022, signifying a 51% increment (Tiseo 2023). The emissions result predominantly from activities like burning fossil fuels for energy generation and land-use changes like deforestation.

Global efforts to counteract greenhouse gas emissions and address climate change began with the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. The UNFCCC aims to stabilize atmospheric greenhouse gas concentrations to prevent detrimental interference with the climate system. The 21st session of the Conference of the Parties (COP21) in Paris in 2015 was an important milestone. The Paris Agreement aims to limit global temperature increases to well below 2°C above pre-industrial levels and to pursue efforts for a 1.5°C limit. While progress has been made, many Intended Nationally Determined Contributions (INDCs) for mitigation efforts only extend to 2030, implying a potential temperature rise of around 3°C (UNFCCC 2015). Consequently, post-2030 actions are essential. A consensus has formed around key aspects of curbing electricity-related emissions. This involves fostering renewable energy sources, improving supply efficiency, transitioning from coal to gas, exploring nuclear power and combined heat and power systems, and implementing early CO2 capture methods. Furthermore, the COP21 Paris Agreement acknowledges the imperative of universal access to sustainable energy, particularly in developing regions like Africa, through the expanded deployment of renewable energy technologies.

To model future climate, it is essential to develop comprehensive models that consider key physical principles and processes. General Circulation Models (GCMs) are among the most comprehensive climate models, coupling the atmosphere, ocean, and sea ice to simulate global climatic variables' evolution. The efficacy of GCMs can be assessed by evaluating their ability to replicate past and present conditions, thereby increasing our confidence in their predictions (Santos FD et al. 2001). These models are usually coupled with emission scenarios, which consider factors like technological advancements, economic development, energy consumption patterns, and policy measures. Such scenarios project potential changes in emissions over time and explore the impacts of varying greenhouse gas emission levels on the Earth's climate system. By integrating these emission scenarios with GCMs, researchers can generate a spectrum of potential future climate outcomes, providing valuable insights into the consequences of different human activity pathways on our planet's climate.

Due to the coarse spatial resolution of GCMs, regional studies must use pre-established regional climate models RGMs or scale reduction techniques normally called downscaling or regionalization. Several studies have suggested that global circulation models (GCM) uncertainty is the largest (dominant) source of uncertainty in climate change impact assessments (Kay et al. 2009; Prudhomme et al. 2010) so constant improvements have been made regarding climate models and regionalization/ downscaling such as double-downscaling processes and bias-correction (Chirivella 2010; Versini et al. 2016). The same applies to the socio-economic scenarios, which should be analyzed and changed according to the future projections for a specific country/ region.

According to the Intergovernmental Panel on Climate Change (IPCC), there has been a consistent increase in air temperatures across most regions of the world over the past century, a trend that is anticipated to persist in the coming years. The most recent IPCC Sixth Assessment Report (Calvin et al. 2023) projects a global temperature increase of 0.8°C to 2.6°C by 2050 and 1.4°C to 4.4°C by 2100. This trend is widespread and affects every corner of the planet. Global warming serves as the primary driver for other consequential climate alterations including shifts in precipitation, runoff patterns, and humidity levels. However, the effects of these climate factors exhibit notable variations depending on geographical locations (Lehner et al. 2005). This variation is influenced by several factors, including the proximity to the ocean, the presence of mountains, snow cover, land-use practices, and more. These natural features play a crucial role in shaping the regional distribution of climate impacts, adding intricate layers of complexity to the broader understanding of climate change effects.

Climate change is anticipated to bring about complex shifts in precipitation patterns across different world regions. High and mid-latitudes, along with many equatorial areas, are projected to experience an increase in annual precipitation. Inversely, subtropical regions are expected to face a general decrease in annual precipitation. This alteration in precipitation patterns is likely to lead to a rise in flood magnitudes and frequencies, primarily due to the concentration of precipitation during winter in numerous global regions.

Simultaneously, rising temperatures are expected to trigger a decrease in runoff levels in various regions, posing a significant threat to the quality and availability of water resources. Regarding the consequences of climate change in Europe, findings from IPCC studies indicate that Southern Europe, including the Mediterranean region, will experience pronounced negative effects. This scenario is especially true for the Iberian Peninsula, particularly south of the River Tagus. Projections for the year 2100 indicate a significant rise in temperatures coupled with a decline in both precipitation and runoff.

2.2 Introduction to Hydropower

Hydropower is a renewable energy source that is derived from the ongoing movement of water within the Earth’s hydrological cycle, which is triggered by solar radiation. Solar radiation that reaches the Earth's surface is absorbed by land and seas, resulting in surface heating and subsequent evaporation wherever water is present. Nearly 50% of the solar radiation reaching the Earth is devoted to this water-evaporation process. Within this cycle lies an immense potential energy reserve; however, only a fraction of it can be feasibly developed.

Evaporated water ascends into the atmosphere, increasing the atmospheric water vapour content. Both air and vapour are then transported across the globe by wind patterns (also generated and maintained by solar energy inputs). Ultimately, this vapour condenses to form precipitation, with around 78% falling over the oceans and the remaining 22% onto land. This process results in a net transport of water from the oceans to the land surface and an equally large flow of water returning to the oceans through river and groundwater runoff.

The essence of hydropower generation revolves around the flow of water within rivers, or more precisely, the potential energy harnessed from water's gravitational movement from higher elevations to lower elevations, eventually reaching the ocean. This gravitational force drives the movement of water, offering a renewable source of energy that can be effectively converted into hydropower (Kumar et al. 2011).

The key principle behind hydropower is the conversion of potential energy (in the elevated water) into kinetic energy (as the water flows downhill) then into mechanical energy (the spinning turbine) and finally into electrical energy (through the generator). Water is released from the reservoir or diverted from the river and directed into a large pipe or conduit called a penstock. As the water flows through the penstock, it gains kinetic energy due to its motion and gravitational potential energy due to the elevation difference created by the dam. At the end of the penstock, the high-velocity water is directed onto a turbine. The kinetic energy of the flowing water causes the turbine blades to spin. Turbines are designed to capture as much kinetic energy as possible from the water. The rotating turbine is connected to a generator. As the turbine spins, it turns the generator, which consists of a rotor and a stator. This rotation of the generator creates an electromagnetic field, inducing an electric current in the generator's coils (Castro 2011).

Hydropower stands as a well-established, reliable, and often cost-competitive energy technology. Renowned for its efficiency, it boasts one of the highest conversion rates among all energy sources, at approximately 90% efficiency. While the initial investment can be relatively substantial, hydropower systems offer extended lifespans with minimal operational and maintenance costs. The levelized cost of electricity for hydropower projects varies depending on conditions, but in favourable circumstances, it can drop as low as 0.044 €/kWh (IRENA 2023). These systems encompass various project types, categorised based on design, system, head, or purpose, allowing for tailored solutions to specific requirements and site conditions. The primary types of hydropower projects include run-of-river, storage-based (reservoir) and pumped storage (Kumar et al. 2011).

Hydropower is a low-carbon, renewable electricity source. However, its advantages are not limited to power generation (IHA 2022). In fact, many of its other services are becoming increasingly important in the context of the energy transition and climate change. Hydropower plants offer a broad range of services to the grid that includes balancing and ancillary services and enjoy a high capacity factor relative to some other renewable energy sources (Berga 2016; Kumar et al. 2011; Ramião et al. 2023). Additionally, hydropower can provide water services such as flood control, irrigation control, water distribution and wastewater control. Finally, water storage areas can offer recreational value through facilities such as boat ramps, beaches, picnic areas and trail systems (Berga 2016; Kumar et al. 2011; Santos FD et al. 2007).

2.2.1 Run of River

A Run-of-River (RoR) hydropower plant harnesses the dynamic energy flow of a river to generate electricity. Unlike some hydropower systems, RoR plants primarily derive their power from the river's natural flow, with only limited short-term storage capacity, often spanning hourly to daily intervals. This unique characteristic means that RoR plants are inherently responsive to the river's flow, resulting in electricity generation profiles heavily influenced by local river conditions (IHA 2022). The generation output of RoR hydropower plants is tied to factors such as precipitation and runoff, contributing to pronounced variations on daily, monthly, and seasonal scales. In cases where these plants lack short-term storage capabilities, their generation profiles become even more variable. This is particularly noticeable when RoR hydropower stations are situated along small rivers or streams, where flow fluctuations can be substantial (Kumar et al. 2011). RoR hydropower installations employ a straightforward approach as illustrated in Figure 1. A portion of the river's water is diverted through a channel or pipeline, commonly referred to as a penstock. This redirected water is then directed toward a hydraulic turbine directly connected to an electricity generator (IRENA 2023). RoR hydropower projects may be arranged as cascades (cascade-effect) along a river valley. These cascades can include a combination of RoR stations and larger reservoir-type hydropower plants, particularly in the valley's upper reaches. This strategy allows these projects to collectively leverage the cumulative capacity of the various power stations within the cascade (Kumar et al. 2011). One of the key advantages of RoR hydropower is its relatively low installation cost compared to some other hydropower technologies. Moreover, RoR plants tend to exhibit lower environmental impacts, particularly when compared to similarly sized storage hydropower plants.

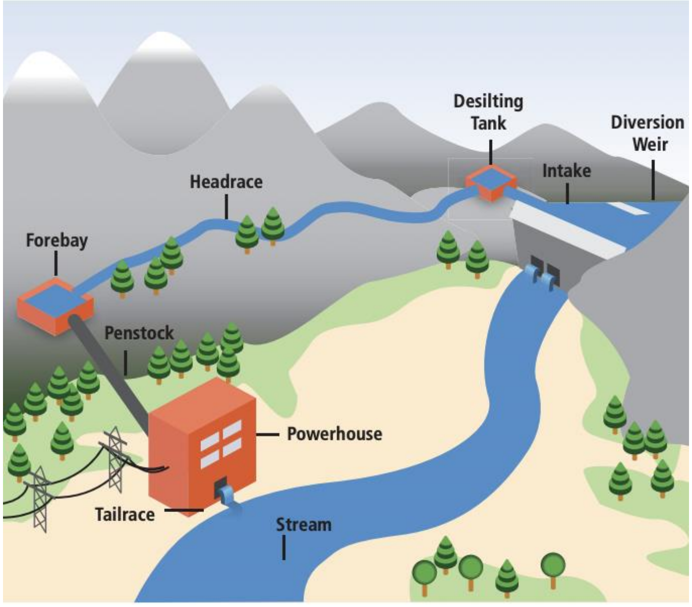


Figure 1. Schematic run-of-river hydropower plant (Kumar et al. 2011)**.**

2.2.2 Storage Hydropower

Storage Hydropower, also known as reservoir hydropower, represents one of the most prevalent and versatile forms of hydropower generation. This technology involves the creation of a reservoir, typically formed by a dam, for the purpose of storing water. The primary advantage of this approach is its capacity to mitigate the reliance on the natural variability of inflow, thereby ensuring a more consistent and reliable source of energy (IRENA 2023). The actual power generation occurs at stations strategically positioned either at the base of the dam or further downstream, linked to the reservoir through a network of tunnels or pipelines (as illustrated in Figure 2). The specific design and characteristics of the reservoir are determined by the local topography and in many parts of the world are inundated river valleys where the reservoir is an artificial lake. In certain regions, it's even possible to preserve the natural landscape by using original lakes or the ocean as natural reservoirs for hydropower generation (Kumar et al. 2011). This capacity for water storage and controlled release gives storage hydropower unique advantages. It can operate as a consistent source of "base load" electricity, while also possessing the capability to swiftly respond to fluctuations in demand, thus serving as a source of "peak load" power. Additionally, storage hydropower systems can offer substantial storage capacity, allowing them to operate independently of the variability in hydrological inflow for extended periods, ranging from weeks to months. Furthermore, the water stored in the reservoir can serve multiple purposes beyond electricity generation, including fulfilling irrigation requirements and meeting various water consumption needs (IHA 2022).

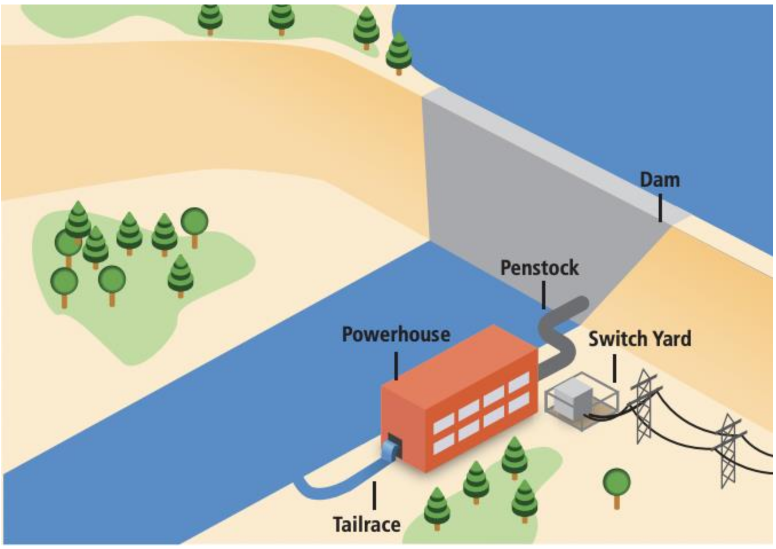


Figure 2. Schematic representation of a hydropower plant with storage capacity (Kumar et al. 2011)**.**

2.2.3 Pumped Storage

Pumped storage technology, one of the world's most widely used and oldest energy storage methods, serves as an essential energy storage system. It is distinct from energy sources and rather functions as a storage mechanism. Pumped storage plants consist of two reservoirs at different elevations (see Figure 3): a lower and an upper reservoir. During times of high electricity demand, water is released from the upper reservoir into the lower reservoir through a reversible pump turbine, generating electricity. Conversely, during periods of low demand, surplus energy from the system is employed to pump water back into the upper reservoir. Pumped storage systems come in two primary configurations: open-loop and closed-loop. Open-loop systems employ a natural water source as their lower reservoir, while closed-loop systems do not. Typically, both reservoirs are located "off-river" or off-channel, but closed-loop systems tend to have fewer environmental impacts (IRENA 2023).

While the energy losses associated with the pumping process render these plants net energy consumers overall, their capacity for large-scale energy storage delivers significant system benefits, making pumped storage technology the most extensive form of readily available grid energy storage on a global scale. The major advantages include high cycle efficiency (above 75%), ample storage capacity with appropriate and flexible response times, mature technology widely deployed worldwide, and the potential for integration into existing hydropower facilities. In addition, pumped storage hydropower plays a pivotal role in providing flexible power storage for future energy systems, facilitating the increased integration of variable renewable energy sources such as wind and solar (Ferrão et al. 2022). Overall, pumped storage technology functions as a reservoir facility with the added benefit of recovering the water used during electricity generation, enabling more effective water resource management—a crucial factor for the future of sustainable energy and environmental conservation.

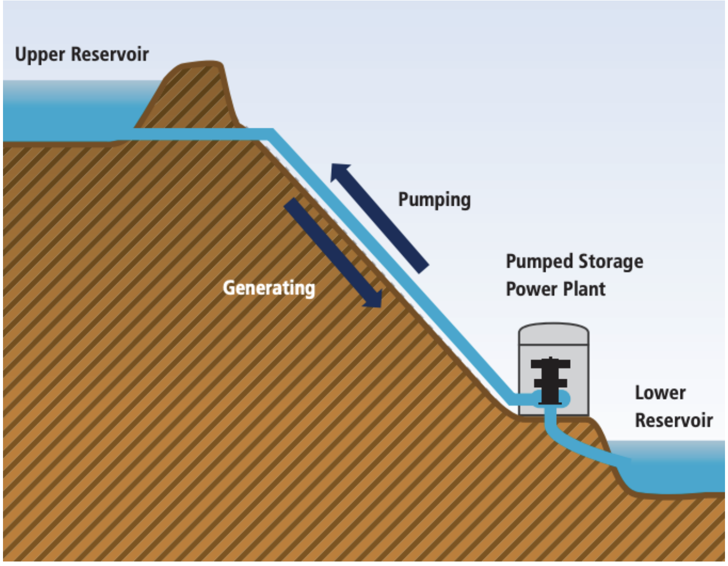


Figure 3. Schematic representation of a Pumped hydropower plant (Kumar et al. 2011)**.**

2.3 Hydropower status worldwide

2.3.1 Current installed capacity

Hydropower, a sustainable and eco-friendly energy source, plays a significant role in global electricity generation, contributing over 15% of the world's total electricity. In 2022, hydropower production witnessed a nearly 2% increase, reaching 4408 TWh, marking its dominance as the largest renewable source of electricity, surpassing all other renewable energy technologies combined (IEA 2023).

Global hydro capacity is 1397 GW (2,7% increase in relation to 2021), of which 175 GW are pumped storage (6% increase in relation to 2021). East Asia and the Pacific, predominantly China, lead the installed hydropower capacity with a remarkable 523 GW. Europe follows closely with 255 GW, and North and Central America with 205 GW. South America and South and Central Asia also contribute significantly to global capacity, presenting similar installed values (IHA 2022). In contrast, Africa presents a unique case, with only 7% of its economically viable hydropower potential developed, resulting in a limited 38 GW installed capacity (Berga 2016).

China maintains its prominent position in capacity additions, accounting for 24 GW of new capacity in 2022, a staggering three-quarters of the global increase. Although hydropower is still a key component of China's 14th Five-Year Plan for Renewable Energy, future capacity additions may slow down due to a shortage of suitable sites and environmental concerns. Central and Southern Asia, specifically India and Pakistan, continue to develop several substantial hydropower projects, anticipating significant capacity growth in the near future. Achieving the commitment to attain 500 GW of non-fossil electricity capacity by 2030 relies heavily on hydropower as a vital technology.

In Europe, a notable development occurred in 2022 as nearly 2 GW of pumped storage hydropower capacity was commissioned, the highest level recorded since at least 1990. Projects in Switzerland and Portugal aimed to enhance the integration of solar PV and wind power into the grid.

Both North and South America collectively added over 1 GW of new hydropower capacity in 2022, with significant contributions from Canada, Colombia, and Chile (477 MW). In August 2022, the United States introduced the Inflation Reduction Act, which extends and enhances tax credits for hydropower technologies, further boosting the sector's growth (IEA 2023).

2.3.2 Future hydropower development

The global pipeline for hydropower projects is robust, with approximately 131 GW currently under construction, and more than 460 GW planned or awaiting approval. East Asia and the Pacific, predominantly China, host the majority of these projects, with a noteworthy 32% dedicated to pumped storage stations. In Africa, 120 GW of hydropower capacity is in development, with most projects having received regulatory approval, although less capacity is currently under construction. Africa's urgent need for electrification is driving these developments, with conventional hydropower projects dominating the pipeline. Furthermore, about 84 GW (excluding closed-loop pumped storage) are in an advanced development stage, suggesting the potential for significant acceleration in development over the next decade. However, barriers such as financing challenges and slow procurement processes have historically delayed projects. Accelerating access to financing and sustainable construction is essential for Africa's hydropower growth (IEA 2021; IHA 2022).

In Europe, the pipeline comprises fewer projects, reflecting the region's well-established hydropower fleet. Over 90% of these future projects are pumped storage initiatives, aimed at addressing the increased demand for storage capacity resulting from the rapid expansion of wind and solar deployments.

North and Central America, while making progress in hydropower projects, experience longer regulatory processes compared to other regions. Over 90% of their future projects are also pumped storage. This focus on storage is crucial as governments prioritize the extensive deployment of variable renewable energy sources.

South America, meanwhile, has a substantial volume of smaller hydropower projects in the pipeline, predominantly run-of-river or small-scale reservoir storage. These projects are ready but await financial support.

South and Central Asia, including India, Pakistan, Nepal, and Bhutan, are actively planning numerous hydropower projects, with many awaiting permissions. The pipeline indicates a significant volume of small hydropower projects in development (IHA 2022).

The global hydropower environment presents a varied scenario. Developed countries have largely harnessed their hydropower potential, with more than 50% of their technical feasible potential exploited. Emerging economies have tapped between 20% and 30% of their potential, indicating substantial growth opportunities. Developing nations still possess considerable unexplored hydropower potential, offering significant room for expansion (Berga 2016).

2.4 Iberian Power System

The Iberian Peninsula, consisting primarily of mainland Portugal and Spain, possesses a unique energy landscape within Europe. Its power system operates on a market-based model, with private ownership governing most activities. The predominant market entity is Operador del Mercado Iberico (OMIE), jointly owned by the two countries (OMI 2023). Each country has its Transmission System Operator (TSO), namely Redes Energéticas Nacionais (REN) in Portugal and Red Electrica de España (REE) in Spain. OMIE oversees the financial aspects of the market, while REN and REE manage the technical feasibility of the system, encompassing both generation and transmission. This collaborative effort between the Portuguese and Spanish Governments has not only led to the establishment of an Iberian Electricity Market (MIBEL) but has also contributed significantly to the development of a broader European Internal Energy Market (MIBEL 2023).

Established on July 1, 2007, MIBEL was created with the primary objective of integrating the electrical systems of both countries to benefit consumers in both regions. This integration allows Iberian consumers to source electricity from any producer operating in Portugal or Spain, providing the option to engage with competitive commercial agreements. In the case of MIBEL, and indeed all European markets, the marginal cost model is employed. In this model, electricity producers submit offers based on their marginal production costs, encompassing factors like fuel costs, emissions costs, variable operational and maintenance expenses, and taxes. These offers are then arranged in ascending order. On the other hand, suppliers' bids for energy purchases are ranked by purchase price, in descending order. The energy production price for all producers is determined by the intersection point between supply and demand, representing the marginal production cost of the last producer meeting demand during the bidding period. This approach ensures efficient market operation and fair pricing for consumers (EDP 2022).

Historically, the primary factors driving grid development in the Iberian Peninsula within the broader European context have included:

- **The insufficient cross-border capacity**. The need to enhance cross-border capacity has been essential to facilitate the full realization of the Iberian Electricity Market (MIBEL), through the reinforcement of the Portugal–Spain interconnection, and to integrate the Iberian Peninsula into the wider European continental market, through the development of the France–Spain interconnection.
- **The Renewable Energy Sources (RES) integration**. The Iberian Peninsula has been at the forefront of adopting RES technologies (hydro, onshore wind and solar), and in the integration of this production into the system, with significant investments in new network infrastructure in Portugal and Spain and smart management such as the Spanish renewable control centre (CECRE).

As the region advances towards a decarbonised power system, both issues remain a challenge in the short and long term, as the most recent studies demonstrate. According to a study made by the European Networks of Transmission System Operators for Electricity (ENTSOE), different projections preview the evolution of the power grid until 2040 for every country in the EU. The Ten-Year Network Development Plan analyses these projections and presents an interpretation of the results (ENTSOE 2022). For the Iberian Peninsula, is expected:

- **Change in the generation portfolio towards a more carbon-free system**. The transition from thermal to renewable generation and a complete phase-out of coal in the Iberian Peninsula will lead to significant increases in RES technologies, primarily solar energy.
- **The need for further market integration in the region, with a special focus on the isolation of the Iberian Peninsula**. Despite the strong efforts, Spain has not fulfilled the 10% interconnection ratio objective for 2020 as recommended and will be unable to fulfil it in the midterm. Moreover, this objective has been increased to 15% for the 2030 horizon.
- **The RES integration will pose a challenge, and it will not have a unique solution.** A high amount of RES curtailment is expected for the region in the event of no grid development beyond 2025. The solution for this RES integration challenge should be a mixture of internal reinforcements, the development of interconnections, new storage, power to gas, and so forth.
- **The system will experience new power flow patterns and important investment needs.** The increasing use of renewables in the Iberian Peninsula, along with anticipated higher electricity flows between the Iberian Peninsula, France, and Central Europe, will require both internal grid improvements and increased cross-border capacity to maintain reliability.
- **The security of supply will have a new dimension.** Securing future energy supply extends beyond traditional considerations of generation capacity and transmission congestion. Factors such as flexibility, dynamic response, system inertia, and demand-side management will become increasingly critical for ensuring energy security.

Expanding cross-border connection capacity and investing in storage solutions will have a profound impact on the electrical system and society. These developments promise a range of significant benefits, including a reduction in the annual average marginal cost of electricity and a decrease in CO2 emissions. Furthermore, they enable the seamless integration of a more substantial share of renewable energy sources, which would otherwise face limitations (ENTSOE 2022). With this in mind, cross-border projects are already addressing this need in the 2030 horizon. The direct current interconnection under construction through the Gulf of Biscay (expected to be completed in the third quarter of 2027), will nearly double the interconnection capacity between Spain and France to 5 GW. The construction of a new interconnection between Portugal and Spain is in the planning phase; once completed, it would increase the exchange capacity between Spain and Portugal to 3 GW (IEA 2022).

It's important to note that alongside increased cross-border connectivity, the expansion of energy storage solutions will be equally critical. Pumped hydro storage, with its mature technology, is expected to play an active role in this regard (In 2022, Portugal's Gouvães power plant, with an 880 MW pumped storage capacity, ranked fourth globally for capacity added) (IHA 2022). Additionally, battery storage and hydrogen-based storage solutions offer promising options to further enhance the flexibility and resilience of the electrical system while facilitating the integration of renewables.

In terms of physical size, Portugal's mainland is just a fifth of Spain's, which significantly influences its energy demand and production scale. As of 2022, Portugal had an installed power capacity of 20.7 GW, with renewables accounting for 78% of this capacity, led by hydro (8.2 GW) and wind (5.3 GW). Non-renewable capacity is mainly comprised of natural combined cycle and cogeneration, totalling 4.5 GW. Regarding new additions, the Alto Tâmega complex saw the introduction of new facilities, including Gouvães with four reversible groups totalling 880 MW and Daivões with 118 MW, along with around 500 MW of new photovoltaic installations (REN 2022b).

In 2022, the Portuguese national renewable generation supplied 49% of consumption, a figure that typically reaches around 62% in average weather conditions. Hydropower, accounting for 51% of the country's renewable capacity, significantly influences these figures, with a low capability index (the deviation between the total power produced over the amount of energy produced in an average year) of 0.63 in 2022, indicating a dry year. In contrast, solar and wind energy exhibit more stable capability indexes. Wind power, the primary renewable source, supplied 25% of the total consumption, with a capability index of 0.99. Other renewable sources, including biomass (7%) and photovoltaics (5%), made notable contributions. Non-renewables still play an active role with natural gas, including combined cycle and cogeneration, providing around one-third of the consumption. The trade balance with foreign countries (mainly Spain) favoured imports for the fourth consecutive year, representing 18% of domestic consumption (REN 2022b). Compared with 2021, a wetter year characterized by a hydro capability index of 0.93, the hydropower generation decreased by 10%, promptly increasing the reliance on natural gas generation and import inflow to compensate for the reduction in hydropower output (see Figure 4).

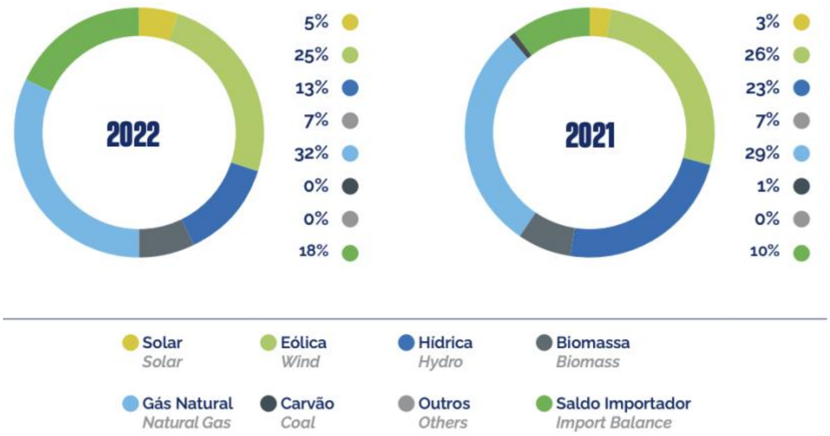
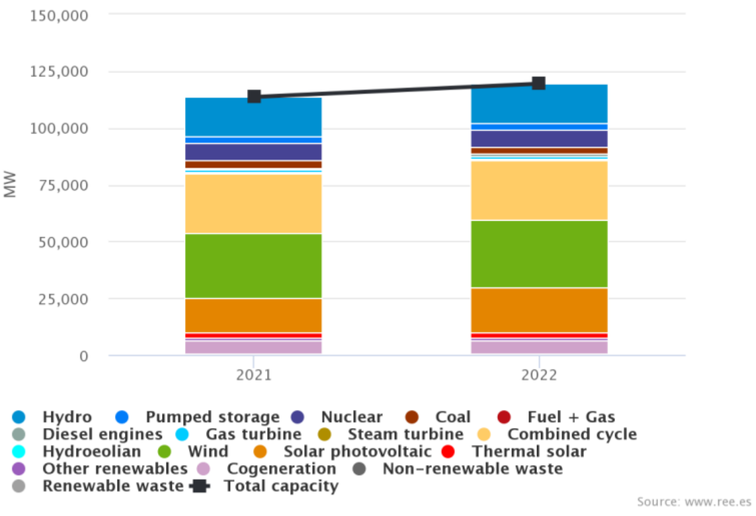


Figure 4. Generation breakdown for 2021 and 2022 (REN 2022b).

In Spain, the total installed power capacity at the end of 2022 accounts for 113.6 GW, with renewable power capacity witnessing an additional increase of 5.9 GW, primarily in wind and solar technologies (see Figure 5). Consequently, Spain now boasts a total installed capacity of 70.5 GW in renewable energy generation, comprising 59.2% of the overall installed capacity. Wind power remains the dominant renewable energy technology in Spain, contributing a total capacity of 29.4 GW. Combined cycle power generation takes second place with 24.5 GW of installed capacity. Solar photovoltaic capacity experienced significant growth, with an addition of approximately 4,400 MW. Notably, in 2022, solar photovoltaics surpassed hydropower, ranking as the third-largest power source with 17.0% of the total installed capacity. Hydropower retains its position as the fourth-largest technology in terms of installed capacity, with approximately 17 GW. Conversely, non-renewable power capacity on the peninsula decreased by 0.8%, primarily due to an 8.5% reduction in installed coal power (REE 2023b).



Source: www.ree.es

Figure 5. Installed Capacity in Spain 2021-2022 (REE 2023b).

In the context of electricity generation in peninsular Spain, which accounts for approximately 95% of the nation's total electricity production, there was a notable 6.1% increase in 2022, resulting in a total generation of 261,955 GWh. The most significant changes compared to the previous year were observed in combined cycle and solar photovoltaic generation, which saw substantial increases of 61.1% and 32.9%, respectively. In contrast, hydropower production declined by 39.7% (REE 2023a).

Examining the breakdown of electricity generation by energy type in the national electrical system, renewable energy sources experienced a 4.0% reduction in production in 2022, primarily due to decreased hydropower output. Throughout the fiscal year 2022, renewable energy's contribution to the national energy mix stood at 42.2%, compared to the 46.7% achieved in 2021. In contrast, non-renewable energy sources expanded their share to 57.8% (compared to 53.3% in 2021). This growth in non-renewable generation was primarily driven by increased output from coal-fired plants and combined cycle facilities, which generated 55.6% and 61.1% more electricity than in 2021, respectively (REE 2023a).

In 2022, Spain experienced a notable shift in its electricity balance, transitioning from being a net importer as it was in the previous year (1,462 GWh), to becoming a net exporter with a historically high export value of 19,841 GWh. This marked the first time Spain had achieved a net export status since 2015. The change in balance direction towards export can be primarily attributed to two factors: the increased penetration of renewable energy sources in the Spanish energy system and the elevated electricity prices in France. Throughout the year, electricity prices in France consistently exceeded those in Spain due to high nuclear unavailability in France and the Iberian mechanism for capping high gas prices across Europe. These factors contributed to significant price disparities between the two regions (REE 2023c).

Overall, the reduced production of hydroelectric energy had a direct impact on the generation mix in both Portugal and Spain, leading to an upsurge in non-renewable generation and an increased flow of electricity imports (see Figure 6).

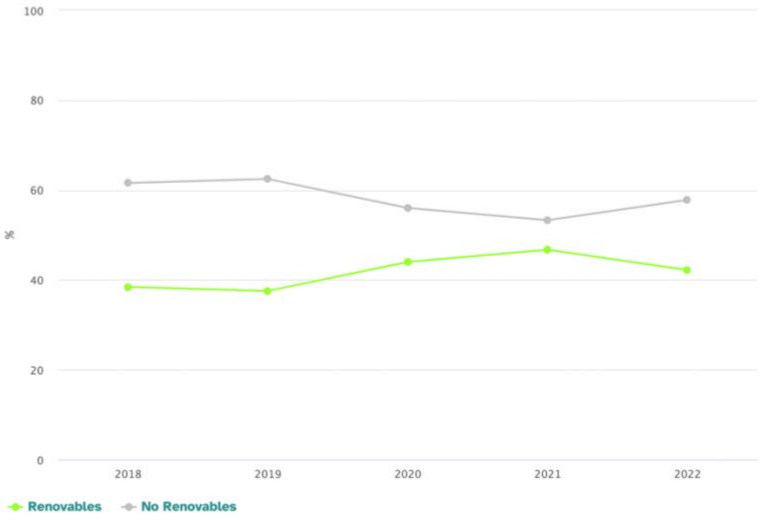


Figure 6. Renewables vs Non-Renewables evolution in Spain

2.4.1 Exceptional Market Situations in the Iberian Power System

2.4.1.1 Negative prices in Electricity Markets

Negative electricity prices can occur in various segments of the electricity market, including both intraday and day-ahead markets (more prevalent in the intraday market since for the day-ahead market the prices are typically set to zero during this situation). The occurrence of negative prices primarily results from a temporary oversupply of electricity relative to demand. A combination of factors contributes to negative prices (Pereira da Silva et al. 2019):

- **Excess Generation:** Negative prices can emerge when there is an oversupply of electricity production compared to forecasted demand. This often happens when renewable energy sources generate more electricity than needed. Operators may choose to sell excess electricity at negative prices to avoid waste.
- **Maintenance Considerations:** Power plants may prefer to operate at negative prices rather than undergo maintenance shutdowns, considering the cost and time associated with shutting down and restarting operations.
- **Integration of Renewable Energies:** The integration of intermittent renewable energy sources introduces variability in electricity generation, leading to fluctuations in electricity prices, including negative values.

2.4.1.2 Market decoupling

The internal decoupling of the Iberian electricity market, or MIBEL, occurs when technical limitations or constraints on the cross-border interconnections between Portugal and Spain, such as reaching the maximum transmission capacity, prevent the seamless flow of electricity between the two countries. During this period, typically lasting a few hours, the markets in Portugal and Spain operate independently, potentially leading to divergent electricity prices due to differences in supply and demand conditions (see Figure 7). The main purpose of this temporary separation is to safeguard the stability of the electrical grid and to prevent any market manipulation. It's important to note that this decoupling is implemented as a last resort, and the primary aim of MIBEL is to maintain an integrated and efficient Iberian electricity market that fosters continuous electricity trading between the two nations (Figueiredo et al. 2015).

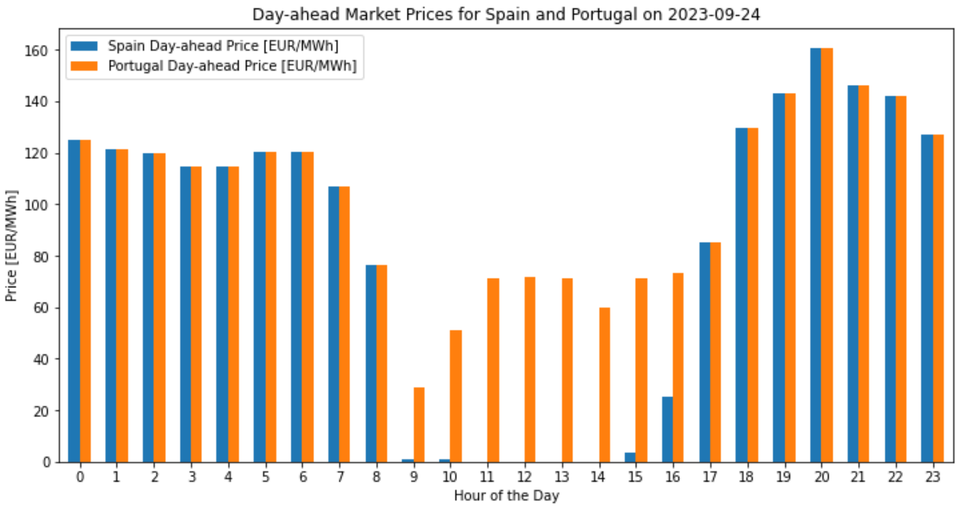


Figure 7. Example of market decoupling which happened on 24-09-2023.

2.4.1.3 Influence of economic and strategic factors in the interconnected markets

During periods of energy surplus in Spain, Portuguese operators may choose to import electricity at competitive prices rather than generating it locally from other sources. This economic strategy can extend to importing for purposes such as energy storage for later resale at higher prices, leveraging the storage capacity of hydroelectric plants, or ensuring strategic water reserves. As shown in Figure 8, which provides a breakdown of Portuguese electricity generation on October 26, 2023, imports during periods of renewable energy abundance, particularly solar power from Spain, not only meet demand but are also employed for pump consumption. This dynamic underscores how decisions about electricity import and generation in interconnected markets can be influenced by economic and strategic factors (António Vidigal 2023).

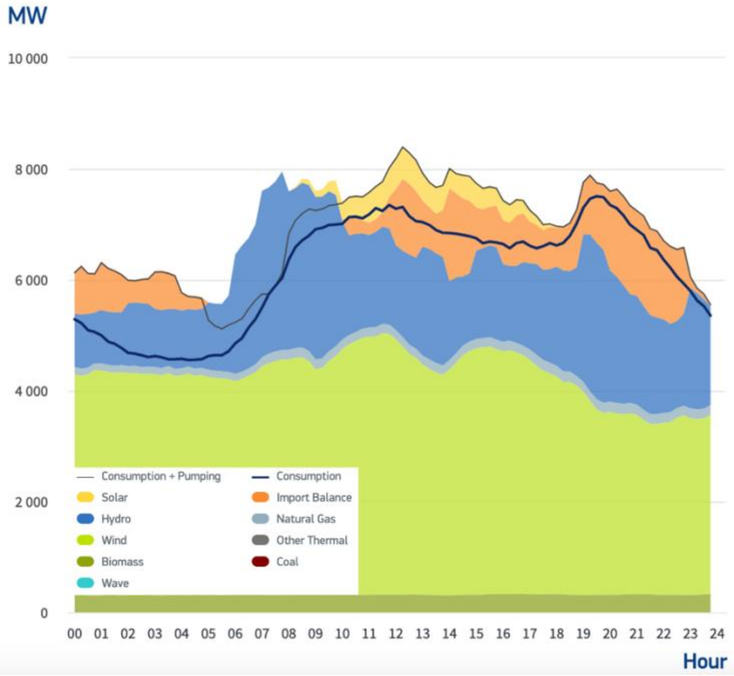


Figure 8. Breakdown of Portuguese electicity generation on October 26, 2023 (REN 2023)**.**

2.5 Iberian Peninsula hydropower system

Water administration in the Spanish part of the Iberian Peninsula is organised by River Basin Districts or catchments (Fernandez et al. 2017):

— Spanish territory of the Eastern Cantabrian River Basin District (Cantábrico Oriental).

— Western Cantabrian River Basin District (Cantábrico Occidental).

— Galicia-Coast River Basin District (Galicia Costa).

— Spanish territory of the Miño-Sil River Basin District (Miño-Sil).

— Spanish territory of the Duero River Basin District (Duero).

— Spanish territory of the Tagus River Basin District (Tajo).

— Spanish territory of the Guadiana River Basin District (Guadiana).

— Tinto, Odiel and Piedras River Basin District (Tinto, Odiel y Piedras).

— Guadalquivir River Basin District (Guadalquivir).

— Guadalete and Barbate River Basin District (Guadalete y Barbate).

— Andalusian Mediterranean Basin District (C.M. Andaluza).

— Segura River Basin District (Segura).

— Jucar River Basin District (Júcar).

— Spanish territory of the Ebro River Basin District (Ebro).

— Catalonia River Basin District (C.I. de Cataluña).

Water administration in the Portuguese part of the Iberian Peninsula is divided into 8 river basin districts (Fernandez et al. 2017):

— The Minho and Lima River Basin District.

— The Cávado, Ave and Leça River Basin District.

— Portuguese territory of the Douro River Basin District.

— The Vouga, Mondego, Lis, and Ribeiras do Oeste River Basin District.

— Portuguese territory of the Tejo River Basin District.

— The Sado and Mira River Basin District.

— Portuguese territory of the Guadiana River Basin District.

— The Ribeiras do Algarve River Basin District.

Both Portugal and Spain are not considered water-scarce countries, as demonstrated by various comparative studies that position them favourably in terms of average water availability when compared to other European countries or those in the Mediterranean basin (IHA 2022; Lehner et al. 2005; Santos et al. 2007). However, the climatic, geomorphological, geological, and socioeconomic characteristics of the Iberian Peninsula present a set of challenges. The availability of water resources varies significantly in space and time. The average annual precipitation is about five times higher in the North-Atlantic region than in the interior South, and annual precipitation can vary by about three times from year to year (Santos FD and Miranda P 2007). The disparity in rainfall between northern and southern regions can be attributed to geographical and climatic factors. The northern region, situated at a higher latitude and characterized by more mountainous terrain, receives more precipitation due to orographic lifting when moist oceanic air encounters the elevated landscape. Additionally, it is influenced by frontal systems from the Atlantic, whereas the southern region, with a Mediterranean climate, experiences hotter and drier summers and milder winters, resulting in lower overall rainfall.

This variability necessitates water storage solutions to address frequent water scarcity situations and the promotion of water management policies that reconcile the need for water with its availability.

Regarding water availability, it is also important to consider that almost 65% of the Portuguese territory falls within the major Luso-Spanish river basins, which have their upstream regions in Spain (Minho-Lima, Douro, Tejo, and Guadiana). As a result, approximately 60% of the annual runoff originates in the neighbouring country, requiring Portugal to find cooperative solutions that safeguard its interests in this area (Santos FD et al. 2007). From the Iberian Peninsula perspective, there are five additional transboundary river basins: Eastern Cantabrian, Ebro, and Catalonia are shared with France, while the Ebro is also shared with Andorra, and Ceuta and Melilla are shared with Morocco (Fernandez et al. 2017).

For better water use and management, Spain has around 1300 dams distributed across its territory (SPANCOLD 2022). The total reservoir capacity is equal to 56000 hm3 at the national level (MITECO 2023) and the gross part of it (around 75%) corresponds to the reservoir capacity in the Tajo, Guadiana, Guadalquivir, Ebro and Duero (Fernandez et al. 2017). According to the Portuguese Environment Agency (APA), Portugal has around 260 large dams distributed across its territory (APA 2022). The total reservoir capacity is equal to 13290 hm3 and the biggest reservoir capacities can be found for Guadiana and Tejo (SNIRH 2023a).

Existing dams serve various purposes, including irrigation, public water supply, and energy production. The distribution of dams across the territory is explained by the water usage needs and the uneven distribution of water availability, both in space and throughout the seasons, due to the country's geographic, climatic, and physiographic characteristics. In regions with more irregular water resources, especially in the south and interior, the use of reservoirs for irrigation and public water supply is more common. Irrigation is the primary use of water in the Iberian Peninsula, and sourcing water from reservoirs (for both irrigation and consumption) is essential in areas where aquifers and rivers are insufficient to meet the necessary flow rates. In the north, where water resources are more abundant and regular, a significant portion of hydroelectric projects for energy production have been developed (APA 2022; Fernandez et al. 2017).

Flood mitigation, through the available storage capacity in dams, is important in several regions. Dams do not prevent river floods but can mitigate their effects, especially for frequent and medium-frequency floods. Many of the reservoirs in large dams today serve multiple purposes. This is either because existing reservoirs have acquired new uses or because the evolving concept of integrated water resource planning has led to the gradual abandonment of large single-purpose developments (APA 2022).

The primary water consumption occurs in the agriculture sector in both Portugal and Spain, typically accounting for more than 75% of total water consumption (Fortes et al. 2022; Garriga J. 2022). The agriculture sector is followed by the energy sector, domestic purposes, industrial processes, and cooling needs, in that order (Fernandez et al. 2017). The population concentration around major urban centres presents additional challenges, leading to imbalances between water demand and availability, as well as issues related to the treatment and purification of domestic and industrial wastewater. Climate change may exacerbate all these situations and further complicate water management in the Iberian Peninsula.

3 Literature review

It is noteworthy that the hydropower potential, in many cases, depends on climate, and climate change will affect both hydropower resources and generation. The relationship between hydropower resources and climate change is a very complex interaction. Greater attention has been given to climate change impacts on water resources used for hydroelectricity since the late 20th Century. However, significant research on climate change impacts on hydropower is urgently needed to understand better and quantify the estimates and analyses of these potential effects. Several research findings published worldwide involve the climate change impacts on hydropower resources.

3.1 Impacts on Global Hydropower

Globally, the International Panel on Climate Change (IPCC) has been at the forefront of addressing the impacts of climate change since its establishment in 1988. The IPCC has released six assessment reports (1990, 1995, 2001, 2007, 2014, and 2023), providing comprehensive evaluations of climate change and its implications (Calvin et al. 2023). While not exclusively focused on the hydropower sector, the IPCC released a specific report in 2011 titled "Renewable Energy Sources and Climate Change Mitigation," which dedicates an entire chapter to hydropower (Kumar et al. 2011).

This report draws on the work of IPCC Working Group II, which includes an in-depth discussion of the impact of climate change on water resources, and the studies conducted by (Bates et al. 2008). Both these assessments have been essential in understanding the effects of climate change on hydropower and other renewable energy sources. Although the report was published a decade ago, its information remains up to date and aligns with the current assessments in the Working Group II contribution, "Climate Change 2022: Impacts, Adaptation, and Vulnerability" (Calvin et al. 2023).

3.1.1 Africa

In Africa, limited research exists regarding the impact of climate change on hydropower due to fewer resource applications. The primary regions for hydropower in Africa include the Nile, Congo, and Zambezi River basins, as well as smaller basins in sub-Saharan West Africa.

Click or tap here to enter text.In West Africa, the Niger, Volta, and Senegal River basins offer significant hydropower potential, but historical precipitation records show high variability (Roudier et al. 2014). The natural variability in West Africa is so pronounced that distinguishing the climate change signal from natural variability may only become possible after 2050 (Footitt et al. 2007). Still, predictions suggest a decrease of more than 10% in runoff in the Senegal, Gambia, and Guinea-Bissau River basins, whereas an increase of more than 10% in runoff is expected in the region covering Liberia and Côte d'Ivoire (Stanzel et al. 2018).

In East Africa, with the White Nile and Blue Nile Rivers, water levels have seen fluctuations, and projections suggest increased wet season precipitation (Onyutha et al. 2016). The Blue Nile, originating from Lake Tana, is expected to witness more frequent and severe floods and droughts (Tariku et al. 2021). Concerns arise with the construction of the Grand Ethiopian Renaissance Dam and associated reservoir surface evaporation, which could impact downstream flows, potentially affecting agriculture and water supply in Sudan and Egypt (International Non-partisan Eastern Nile Working Group et al. 2014).

In Southern Africa, the Zambezi River basin hosts significant hydropower facilities, but understanding climate change effects is complicated due to high variability and incomplete historical records. Simulations indicate potential future devastating floods or extreme dryness in the Zambezi basin, posing challenges for hydropower generation (Yamba et al. 2011). Tanzanian hydropower faces increasing challenges linked to streamflow variability, affecting its generation capacity (Loisulie 2010).

3.1.2 Asia

In Asia, studies have highlighted potential runoff changes, particularly impacting Himalayan countries. These regions face the risk of landslides and glacial lake outbursts, necessitating increased storage capacities to accommodate intensified seasonal precipitation.

West Asia, including the Tien Shan-Pamir-Karakoram and the primary sources of the Indus River, experiences varying climate change impacts on hydrological processes. Glacierized catchments witness increased summer and winter runoff (Sharif et al. 2013), while those with lower glacier coverage experience amplified interannual variation (Deng et al. 2019). Projections suggest a future increase in streamflow due to continued glacier melt and potentially heightened precipitation. However, the magnitude of this increase varies based on factors like climate models and glacial melt models (Lutz et al. 2019). Interannual variation could lead to conflicts between agriculture and hydropower water demands (Reyer et al. 2017).

In the central and eastern Himalayas, the Brahmaputra River basin has seen an increasing trend in streamflow alongside glacier melt. Projections suggest potential changes in monsoon precipitation, ranging from -20% to +50% (Ray et al. 2015). Most climate models anticipate a strengthened monsoon, leading to an overall annual increase in runoff (wet summers and dry winters) (Lutz et al. 2019). Himalayan hydropower projects also face the risk of Glacial Lake Outburst Floods, with an increased risk due to the planning of new projects closer to the headwaters (Zheng et al. 2021).

Northeast Asia, home to projects on the Yangtze and Yellow Rivers, faces challenges from glaciers melting in their glaciated headwaters, namely a projected increase in precipitation that will require modified reservoir operation (Zhao et al. 2021).

Southeast Asia has multipurpose storage reservoirs with ongoing development plans. The region's hydrological regime is influenced by monsoon precipitation, but future precipitation changes remain uncertain. Climate change, coupled with irrigation projects and new hydropower developments, may alter flow seasonality, potentially leading to increased droughts. This could reduce hydropower availability, prompting consideration of alternative sustainable energy options like solar power (Siala et al. 2021).

3.1.3 Europe

In Europe, there is an estimated potential decline of about 6% in hydropower by the 2070s. However, individual countries show varying trends, with some experiencing increases while others face decreases (Lehner et al. 2005).

The European Alps, which supply major river basins (such as the Danube, Rhine, Rhone, and Po), are experiencing glacier and snow-cover reductions due to global warming (Beniston et al. 2018). This has led to increased glacier melt in Switzerland temporarily boosting hydropower, but a decline of approximately 3% is projected due to shrinking glaciers (Schaefli et al. 2019). The Alps also see a loss in snowpack volume, potentially reducing hydropower generation in regions like the upper Rhone basin and some Italian Run-of-River projects. Changing streamflow seasonality (due to glacier melt), shifting from summer to winter, will certainly affect hydropower production differently depending on local conditions (Savelsberg et al. 2018).

In the Nordics and the Baltics, hydropower is vital, especially in Norway, where over 90% of electricity comes from hydropower (IHA 2021b). Recent increases in average streamflow have driven hydropower expansion in Norway, especially in the southern mountain region. Climate change brings more rain-on-snow events, earlier snowmelt, and projections of increased autumn discharge due to more precipitation. Case studies show a promising 9%-20% increase in energy generation, accompanied by an 11%-17% increase in annual inflow due to earlier peaks and larger spring flow (Chernet et al. 2013). The eastern Baltic countries (Lithuania, Latvia, Estonia) experience a shift in precipitation, with decreased total annual precipitation but increased winter precipitation. This leads to increased winter discharge and decreased spring floods (Jaagus et al. 2018).

In the Mediterranean, drier conditions have emerged over the past few decades. Studies in the Mediterranean Llobregat River basin suggest hydropower generation could drop by 5%-43% by 2070 (Bangash et al. 2013). In Turkey, a significant player in Europe's future hydropower, long-term drought conditions are affecting the eastern region. Projections indicate increased temperatures and decreased precipitation, intensifying drought episodes (Altın et al. 2020). Additionally, a study in the Aracthos River basin in Greece predicts a decrease in average annual precipitation and an increase in temperatures. Streamflow is expected to decrease by almost 20% in the worst emission scenario, with significant impacts on the riverine ecosystem, agriculture, and hydroelectric production (López-Ballesteros et al. 2020).

3.1.4 America

In North America, hydropower production is highly sensitive to total runoff and reservoir levels. Warmer weather can lead to increased precipitation and higher water levels, enabling hydroelectricity to meet peak demand. However, lower water levels can result in reduced hydropower production. In the Northeast region of North America, there's been a notable increase in flood magnitude and frequency, often linked to more frequent extreme precipitation events. Future projections indicate rising temperatures and winter precipitation, particularly along the northeast coast (Collins 2019). In recent decades, more rain and less snowfall in the Western region, especially the Pacific Northwest, have reduced the snowpack volume critical for recharging aquifers in dry summers. Early snowmelt, driven by rising temperatures, threatens summer flows and hydropower generation (Newton et al. 2019). Moreover, the region faces more intense multiyear droughts and higher cooling demands due to increased temperatures (Diffenbaugh et al. 2015). In the Southern region, the Tennessee Valley Authority operates numerous hydropower dams, and both annual and peak electricity demands are projected to increase with climate change. Modifying reservoir operating rules to accommodate these changes could mitigate operational penalties (Rungee and Kim 2017). However, some parts of the southern US and northwest Mexico have experienced significant decreases in precipitation, leading to droughts likely exacerbated by climate change (Cavazos et al. 2020).

In Central America, hydropower is a key electricity source, especially in Costa Rica, where it supplies over 80% of the country's energy needs. However, the region has observed changes in precipitation patterns, with increased winter rainfall and reduced summer rainfall during the El Niño Southern-Oscillation (ENSO) phases. This trend is expected to intensify in the future (Magrin et al. 2014). Additionally, rising maximum temperatures have been documented in Central America over recent decades (Behzadi et al. 2020). Evaluating future climate projections in this area, including Mexico and the Caribbean, is challenging due to limited ground-based meteorological data (Cavazos et al. 2020). According to an ensemble of 30 General Circulation Models (GCMs), median projections suggest potential declines in both precipitation (up to 5%-10%) and runoff (up to 10%-30%) in northern Central America from 2050 to 2099, accompanied by increased drought severity. These changes may impact the future of hydropower in the region (Hidalgo et al. 2013).

In South America, the climate is characterized by distinct wet and dry seasons, strongly influenced by ENSO, particularly in countries like Peru, Colombia, and northeast Brazil. Over recent decades, accelerated melting of glaciers in the Andes has been observed, resulting in losses through sublimation (Vuille et al. 2018). Future projections point to a continued reduction in river discharge during the dry season in glaciated areas of South America, primarily in Chile, Peru, and Bolivia, due to ongoing glacier shrinkage caused by warming (Seehaus et al. 2019). Brazil boasts the largest installed hydropower capacity in South America, with substantial potential for future expansion. While historical data in the Paraná River basin indicates positive trends in total annual rainfall, mainly driven by an increase in heavy rainfall events, future climate projections paint a different picture. These projections suggest reduced rainfall and higher temperatures during the peak rainy season, along with decreased precipitation in Northeast Brazil during the dry season (Marengo et al. 2017). Severe droughts have recently impacted the São Francisco River in Brazil, leading to decreased electricity generation in small hydropower projects in semi-arid regions. This is due to the allocation of limited water resources for irrigation and water supply purposes (Medeiros et al. 2021). Regionally, projections indicate increased precipitation in the northern Amazon and southern La Plata basin, alongside decreased precipitation in the northern La Plata basin by the close of the century (Gomes et al. 2022).

3.1.5 Oceania

In Oceania, low hydropower generation levels are primarily attributed to factors such as size, climate, and topography, which are distinct from the situation in Africa where large undeveloped hydropower potential exists. Australia has its hydropower facilities concentrated in the Southeast region. Future developments in the country are likely to prioritize small-scale hydroelectric projects, infrastructure upgrades, and potential investments in pumped storage projects (IHA 2021a). However, hydropower generation in Southeast Australia and Tasmania faces vulnerability to prolonged drought periods and diminishing rainfall, as exemplified by the Millennium Drought, which led to a significant decline in hydropower generation (Watterson 2010). Projections also indicate the likelihood of more frequent positive Indian Ocean Dipole events, resulting in drier conditions in the future. Modelling studies have suggested a potential reduction in future runoff in the region, with most results indicating decreased streamflow. This presents additional challenges for hydropower generation in Oceania. To ensure a sustainable energy supply, careful planning and adaptation strategies are crucial to address the impact of changing climate conditions on hydropower resources in Australia (Alexander and Arblaster 2017).

3.2 Impacts on Iberian Peninsula water resources

The Iberian Peninsula has been the subject of several studies over the last few years, investigating the impacts of climate change on the region. While many of these studies were conducted some time ago, their findings remain relevant and align with current perspectives and global research on climate change impacts, particularly in the context of the Mediterranean Area. IPCC assessments indicate that Southern Europe and the Mediterranean region are expected to face particularly detrimental effects. This is especially concerning for the Iberian Peninsula, especially for the region south of the River Tagus, where substantial temperature increases and diminished precipitation and runoff are forecasted by 2100 (Calvin et al. 2023; Kumar et al. 2011).

3.2.1 Portugal

In the context of Portugal (national scale), significant research efforts have been directed toward understanding the impacts of climate change. One noteworthy initiative is the SIAM project (Santos FD et al. 2001), which represents the first comprehensive assessment of climate change impacts and adaptation measures for Continental Portugal, and notably, the first such study conducted for a Southern European country. The report encompasses a thorough analysis of various sectors, including water resources. It combines Global Climate Models (GCMs) and Regional Climate Models (RCMs) under two different emission scenarios to feed a hydrological model (Temez), enabling a comprehensive evaluation of temperature, precipitation, and runoff changes. The basic scenario, commonly referred to as the control run, consists of simulating the conditions in the absence of any CO2 increase. The other scenario, referred to as a perturbed scenario, simulates the climate trend and variability associated with a given greenhouse gas emission scenario. Global results, when compared to the 1960-1999 period, reveal an anticipated increase in temperature between 2.0°C and 3.0°C by 2050, and between 3.5°C and 5.0°C by 2100, with even greater temperature rises expected during summers. Precipitation patterns are expected to decrease, leading to potential impacts on water availability in Portugal. However, these precipitation changes are not uniform across the country, with the Northern region (influenced by the Atlantic) expected to experience increases, while the Southern region (with Mediterranean influence) is likely to witness reductions. Projections range from -28% in the South to +11% in the North (Veiga et al. 2005).

These projections are strongly influenced by the climate model and scenarios employed. Similar studies conducted for the northern areas of Portugal and Spain (Estrela et al. 2012), such as Minho and Galicia, have indicated small decreases in both precipitation and runoff. Nonetheless, they are significantly smaller in magnitude when compared to the impacts observed in the southern parts of the countries.

Precipitation decreases are anticipated across all seasons, except for winter. These are in accordance with the findings conducted by APA (Agência Portuguesa do Ambiente) (APA 2013) and Pulquério et al. 2014. Similarly, the PRUDENCE (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) project estimates an annual decrease in precipitation of 6.1% per degree of global warming for Portugal, exhibiting a declining trend in all seasons except winter (Christensen 2005). The runoff regime in Portugal is significantly impacted by the seasonal and spatial distribution of precipitation, leading to considerable variation across different regions, with the wetter northern coastal river basins contrasting with the drier inland southern basins (Santos FD et al.

2001). In subsequent stages, the SIAM project extended its scope by integrating underground water resources and incorporating an expanded range of emission scenarios and socio-economic factors (Santos FD and Miranda P 2007). It is evident from various models employed in these studies that Portugal is projected to experience a general decrease in runoff across regions and seasons, despite inherent spatial and seasonal differences (Santos FD, Forbes K, and Moita R 2001; Santos FD and Miranda P 2007; Veiga et al. 2005).

These findings are consistent with regional studies that have focused on specific river basins in Portugal. Mourato et al. (2014) studied the Cobres basin in southern Portugal, forecasting a decrease in runoff ranging from -35% to -80% for the period 2071-2100 compared to 1961-1990. Kilsby et al. (2007) simulated mean monthly streamflow impacts for the Tagus and Guadiana basins, projecting changes between -49% and -20% for the Tagus and between -26% and -21% for the Guadiana by 2100. Similarly, Nunes et al. (2008) conducted a comparison of the Alentejo and Ribatejo basins, projecting a decrease in surface and subsurface runoff by more than 60% and 80%, respectively, due to reduced water availability from precipitation. Falloon et al. (2006) further forecasted a reduction of 40-55% in annual flow for the Douro River by 2080 compared to 1961-1990.

Given the transboundary nature of the larger Portuguese river basins, climate conditions in Spain also play a crucial role in shaping the hydrological regime in Portugal. Consequently, reduced runoff from Spanish sub-basins may amplify the decrease in water availability in Portuguese sub-basins. Additionally, the potential retention of water in the Spanish parts of the river basins could further exacerbate the negative impact on water availability across Portuguese sub-basins (APA 2013; Veiga et al. 2005). As a result, the competition for water resources between Portugal and Spain is likely to intensify in a climate change scenario, presenting an increasing challenge for policymakers.

3.2.2 Spain

In the past decades, Spain has witnessed a growing concern over the potential impacts of climate change on water resources. Several research projects have been conducted to assess these impacts, providing valuable insights for policymakers and water resource managers.

Ayala-Carcedo et al. (1996) conducted one of the first research projects in Spain, using a regional hydrological model to study the main Spanish river basins until 2060. Their study revealed a concerning 2.5°C increase in mean annual temperature and an 8% decrease in mean annual precipitation. These changes were projected to have a significant effect on water availability across the country, with the southern areas facing the most pronounced impacts.

The White Paper on Water in Spain (España Ministerio de Medio Ambiente 2000) systematically assessed the effects of climate change on water resources using a spatially distributed hydrological model. Three scenarios for 2030 were analyzed, indicating a clear reduction in total water resources. Under a simple scenario of a 5% decrease in mean annual precipitation and a 1°C increase in mean annual temperature, runoff was projected to decrease by 9% to 25% in different river basin districts. The study highlighted the regional variability of climate change impacts, with the arid and semi-arid regions of Spain, including the Guadiana, Canary Islands, Segura, Júcar, Guadalquivir River basins, the southern part of the country, and the Balearic Islands, being particularly vulnerable to water scarcity and drought.

In 2005, the Spanish Ministry of Environment led the ECCE project "Assessment Report of the Preliminary Impacts in Spain due to Climate Change" (José Manuel Moreno Rodríguez et al. 2005), which aimed to review and compile the state of the art on climate change impacts in Spain. The regional model used, PROMES, showed that by 2070-2100, there would be generalized warming all over Spain, with greater temperature increases in the southern and eastern areas (up to 5-7°C in summer). The study also projected general annual reductions in rainfall, with an irregular distribution across the seasons and among different regions of Spain, and a projected increase in demands for irrigation systems alongside a general decrease in water resources. These findings highlighted the need for improved monitoring networks, research in hydrological processes, and climate change adaptation strategies for water resources management.

In 2010, the Center for Hydrographic Studies of CEDEX conducted a comprehensive assessment of climate change impacts on natural regime water resources for the entire Spanish territory until 2100 (CEDEX 2010). The study combined the downscaling of several global circulation models under two IPCC emissions scenarios (A2 and B2). The projections indicated reductions in precipitation over the control period (1961-1990) of approximately 5%, 9%, and 17% during 2011-2040, 2041-2070, and 2071-2100, respectively, with slightly smaller reductions for scenario B2. Runoff reductions were also projected, with both scenarios leading to decreases of 8%, 11-16%, and 14-28% for the same respective periods. The regional variability of runoff reductions was evident, with the largest decreases occurring in river basins in southern Spain.

On a regional scale, several studies have been conducted in Spain to assess the specific impacts of climate change on water resources in different river basins. Hernández Barrios (2007) focused on the Júcar River basin, located in the eastern part of Spain near Valencia. The investigation involved evaluating available climate change scenarios for the period 2070-2100, which were based on results obtained from the HadCM3 model for A2 and B2 SRES (Special Report on Emission Scenarios from IPCC 2000). The findings revealed that the Júcar River basin is projected to experience a substantial global runoff reduction of 40%. However, the impact is not uniform across the basin, showing significant geographical variations. The inner zones of the basin are expected to face more severe reductions, with a staggering 50% decrease in runoff, while the coastal areas are likely to experience reductions of approximately 25%. Moreover, the study also examined the implications of reduced natural water resources and increased water needs for crops on the water resource systems in the basin. The results indicated a significant impact on the entire system, with substantial decreases in irrigation guarantees and potential emerging environmental issues in river ecosystems.

In a separate investigation, Chirivella (2010) characterized future climate scenarios in the Júcar River Basin District but under a slightly different emission scenario known as the A1B emission scenario, which was considered the most probable for Europe. The study projected a 19% reduction in water resources for the period 2010-2040 compared to the control period of 1990-2000. It is worth noting that this reduction is significantly higher than the estimates obtained in another study conducted by CEDEX (2010) for the same territorial scope using scenarios A2 (5%) and B2 (12%). The variation in the projected reduction may be attributed to the use of dynamic downscaling to represent the precipitation.

Additionally, Ceballos-Barbancho et al. (2008) examined the temporal trend of water supplies in a network of basins in the southwestern sector of the Spanish part of the Duero River basin, situated in northwest Spain. The research explored the relationship between the evolution of temperature, precipitation, and changes in plant cover over time. The results revealed a notable decrease in water supply, attributed to changes in the monthly distribution of water discharge due to alterations in the intra-annual distribution of precipitation and increased temperatures during spring and summer.

Versini et al. (2016) studied the impact of climate change on water resources in the Llobregat basin, a critical area in Catalonia. This basin is essential for supplying water to the Barcelona region and it is considered one of the most vulnerable areas in Mediterranean Spain due to its history of severe droughts and high population/ urbanization density. The study utilized various IPCC emission scenarios and a hydrological model to project future water availability. The findings revealed a potential decrease of up to 40% in annual water volume under the worst-case scenario, leading to more frequent and intense deficits. Despite acknowledging uncertainties arising from implicit hypotheses and limitations, such as those within the downscaling processes and the hydrological model's structure, the authors stress the importance of these findings in guiding decision-making processes for effective adaptation to the impacts of global climate change. These findings align with a study by Pascual et al. (2015), focusing on three neighbouring catchments. Despite using a different hydrological model, Pascual's work also showed reduced precipitation (5.9% to 6.9% short-term, 22.0% to 26.2% long-term) and a slight temperature increase (0.3°C to 0.7°C short-term, 3.4°C to 3.6°C by century's end). Streamflow may decrease by 22% to 39%, particularly pronounced in southern catchments farther from mountainous influences.

In southern Spain, Andreu et al. (2015) conducted research focused on the Sierra de las Cabras region. The study employed the RCP 4.5 and RCP 8.5 scenarios outlined by the IPCC to assess the potential impacts of climate change. The more severe RCP 8.5 scenario predicted significant long-term annual precipitation reductions of up to 30% and a substantial 7°C increase in summer temperatures. These changes could result in an approximate 50% decrease in water resources, impacting both surface and underground water bodies.

3.2.3 Peninsula

All these findings are in accordance with studies conducted for the Iberian Peninsula (IP). De Luis et al. (2009) projected a significant drop in mean annual precipitation by approximately 12.4% for the Iberian Peninsula (more pronounced in the southern Mediterranean-influenced regions than in the north). Variations in different seasons were observed, with increased precipitation variability during winter and summer (+ 23.5% and + 11.4%, respectively), and decreases in autumn and spring (-14.9% and -16.8%, respectively). The study also highlights potential socioeconomic challenges, such as population growth and greater irrigation needs, which will intensify pressure on water resources in the Iberian Peninsula.

Meanwhile, Andrade et al. (2021) utilized multiple regional climate models and emission scenarios to assess aridity until 2070. The results indicate growing aridity and dry conditions in central and southern Iberia by 2070, particularly under the RCP8.5 scenario. Areas significantly impacted include southern Portugal, Extremadura, Castilla-La Mancha, Comunidad de Madrid, Andalucía, Región de Murcia, Comunidad Valenciana, and some regions within the Aragón province. Temperature anomalies for 2041–2070 range from 1.6°C to 3.0°C under the worst-case scenario, coupled with a gradual reduction in mean annual precipitation. However, the changes in precipitation show substantial spatial variation and limited consistency across different periods and scenarios.

Rasilla et al. (2013) anticipate that rising temperatures will result in a more contrasting hydrological cycle. This will manifest as increased potential evapotranspiration, especially in the warmest months, alongside reduced annual precipitation. Consequently, springs and summers are expected to become drier, while winters may see heavier rainfall. Surface runoff is projected to decrease, primarily occurring during the cooler months. The consequences will vary spatially. Areas in the north or at higher altitudes may experience floods, while the Mediterranean region is expected to face severe droughts. Mountain basins that currently rely on snow will shift toward rain-dominated regimes. These changes, coupled with increased in-situ evaporation, are likely to exacerbate water stress and strain groundwater resources.

Pereira-Cardenal et al. (2014) forecasted temperature increases of approximately 1.1°C in spring and 3.6°C in late summer. They also projected a 13% increase in winter precipitation and a substantial 49% decrease in summer rainfall. Reference evapotranspiration is expected to rise by 9–18% throughout the year. Runoff is predicted to decrease by 19%, while higher evapotranspiration rates may boost total water demands by 13.3%.

3.3 Impacts on Hydropower in the Iberian Peninsula

Water resources and power systems are strongly linked since water is needed for many power generation technologies and electricity is required in most stages of water usage. Global warming, along with the expected trends in future precipitation patterns and the increase in evapotranspiration rates, will influence runoff, consequently affecting hydropower generation. Climate change is expected to have a negative impact on the Iberian Peninsula (IP). The hydropower potential in Spain and Portugal will likely decrease due to reduced runoff (Lehner et al. 2005), while higher temperatures will likely decrease (increase) winter (summer) electricity demand (Giannakopoulos et al. 2009).

Lehner et al. (2005) addressed the impact of global change on the hydropower potential in Europe by applying the global water model WaterGAP under different General Circulation Models (GCMs). The main results have shown that one of the regions most prone to a decrease in developed hydropower potential is the Iberian Peninsula. The worst-case scenario estimates a developed hydropower potential reduction of 44% for Portugal and 34.7% for Spain by 2070. Both high and low flows may get more extreme, thus leading to strong reductions in the potential for run-of-river stations but a more moderate balance for reservoirs.

Pereira-Cardenal et al. (2014) combined a rainfall-runoff model under A1B (different RCMs) and a power system model to assess the climate change impacts on the Iberian Power system. By attributing a water value acting as marginal cost for the water stored and opportunity cost for water releasing (the model considers future inflows by using stochastic dynamic programming) the authors estimated a reduction of up to 32% in hydropower generation under the worst scenario (strongly driven by meeting the irrigation demands during the irrigation season). A considerable reduction in hydropower generation is likely to hinder climate change mitigation efforts by increasing CO2 emissions and by limiting hydropower’s ability to complement intermittent renewable energy sources like wind and solar power. A significant portion of the power demand shifting from winter to summer is also highlighted by the authors, keeping the annual average. Pumped storage was not included in the hydropower parcel due to the low representation in the generation mix for the control period (2007-

2011) due to the study having some years already. Nowadays pump storage plays a significant role in hydropower generation.

These are most in line with regional studies. Solaun et al. (2017) analyzed the impacts of climate change on hydropower by focusing on three distinct hydroelectric power plants in Southern Spain combining climatological, technical, and economic data and projections. The results predict a 10 to 49% drop in production by the end of the century, depending on the plant and scenario. The authors also found that the decrease in production is higher in hydropower plants with greater storage capacity. The plants that, in their current configuration, least efficiently utilize water and are forced to spill excess flow are the least affected. However, the authors believe this is not so much related to having a reservoir or not, but rather to the ratio between production and installed capacity. Plants with additional operation capacity and reservoirs have market advantages that were not explored. This decrease in production would significantly affect the operating margins of the facilities and, in certain scenarios, could reach an economically unsustainable level by the end of the century. An investment analysis has been carried out as well, showing that climate change may jeopardize future investments in similar facilities.

Teotónio et al. (2017) assessed the impacts of climate change on hydropower generation and the power sector in Portugal by using the TIMES model up to 2050. The results confirm hydropower vulnerability to climate change, given that any decrease in water availability induces an immediate decrease in electrical hydropower generation (between 17% and 41% depending on the scenario). These predictions are considerably higher when compared to studies conducted by Cleto J. (2008) and Alves M. (2013) who predicted a hydropower generation decrease of only 7% by 2050 for Portugal. The different magnitude of results provided by Teotónio et al. (2017) can be explained by improved calculations, the most recent climate change scenarios and updated projections concerning technology costs, energy services demand and primary energy prices. The results also have shown that the stronger the climate change impacts, the higher the GHG emissions, since natural gas increases its share in the electrical mix cause there’s no renewable potential to offset the hydropower generation reduction.

Indirect impacts, such as increased competition among sectors and across countries, must also be addressed and integrated into research. Teotónio et al. (2017) emphasizes that the climate change consequences, such as reduced runoff and increased irrigation needs, will likely diminish water availability for hydropower generation when compared to competing end-users – namely agriculture, industry, and domestic consumption. Pereira-Cardenal et al. (2014) show that lower inflows and higher irrigation demands will lead to an increase in water values and may reduce hydropower generation. Therefore, increased competition for water use in a situation of water stress will likely become more frequent and intense. These are in line with the analysis recently conducted by Fortes et al. (2022) addressing competing water uses between agriculture and energy in Portugal. Results show that, by 2050, climate change can lead to an increase in annual irrigation water needs by up to 84%, mainly in spring and summer. Combining this with the expected reduction in river runoff can lead to a decline in summer and spring hydropower capacity factors from half to three times below current values.

Regarding competition across countries, Teotónio et al. (2017) stated that it is expected that climate change will exacerbate the existing complexity of transboundary water management. In Portugal, the main river basins are transboundary and, hence, competition is likely to intensify in the context of greater water scarcity induced by climate change.

3.4 Implications for the Iberian Market

The impacts of climate change extend beyond hydropower generation and have implications for the broader electricity market. Understanding how climate change affects hydropower and its subsequent influence on the electricity market is crucial for effective energy planning, policy development, and market operation.

Golombek et al. (2012) uses an economic equilibrium model to study the individual impact of temperature and precipitation changes on electricity demand, hydropower supply, and thermal power efficiency in Western Europe for the period 2070–2100. The authors suggest that an increase in summer electricity demand due to cooling needs combined with the summer reduced inflow and the lower thermal efficiency effect put upward pressure on summer electricity prices. On the opposite, the reduction in winter heating needs combined with higher inflows during winter time should decrease electricity prices during this period. They conclude that net effects include a 1 % increase in electricity prices and a 4 % reduction in supply, mostly due to reduced winter demand. This is specifically true for Nordic countries where cooling needs are not very representative since there are few days with an average temperature above 22°C. In Southern Europe, the scenario is different due to more extreme temperatures. For Portugal, a residual reduction in demand of about 1% while in Spain, a 4.7% increase. An increase of around 2% in electricity prices was estimated for both countries, being one of the most affected in Europe.

Teotónio et al. (2017) also conclude that hydropower vulnerability to climate change implies additional investments in generation capacity, mainly in solar PV and natural gas. This will crowd out some other investments in the Portuguese economy. Accordingly, there will be a loss of economic efficiency in the energy system as long as more capacity (investments and fixed costs) is needed to satisfy electricity demand. Also, an increase in the price of electricity supplied to the Portuguese economy (between 3% - 17%, depending on the scenario) is projected.

4 Hydropower and its role in the context of climate change

4.1 Climate change impacts on water resources and hydropower in the Iberian Peninsula

Water resources stand out as a crucial factor to be considered when dealing with the effects of climate change. This significance arises from the direct impact of climate change on the availability, timing, and consistency of water supply and demand (Lehner et al. 2005). Given that water is essential for consumption, industry, agriculture, energy production, transportation, recreation, and waste management, these implications affect a wide range of sectors. These sectors, which are essential to the foundation of our society, can be profoundly impacted by shortages and extreme events like floods and droughts (Santos et al. 2007). Global climate change affects various hydrological factors, including (Estrela et al. 2012; Veiga et al. 2005):

- **Temperature**: Climate change's most apparent impact is on temperature, a key driver of other hydrological variables.
- **Precipitation**: Alongside temperature, precipitation is a core hydrological variable to express the impact of global climate changes.
- **Evapotranspiration**: Increased temperatures generally lead to greater potential evapotranspiration, affecting water availability.
- **Soil Moisture**: Temperature, precipitation, and evapotranspiration affect soil moisture, impacting crop growth and irrigation needs.
- **Runoff**: All the aforementioned hydrological factors have a clear impact on runoff. It is challenging to anticipate future runoff due to a number of additional climatic variables and human impacts, such as streamflow management, regulation of surface-groundwater interactions, and streamflow diversions.
- **Groundwater**: Changes in precipitation patterns affect aquifer recharge, groundwater levels, flow, and quality.
- **Floods and Droughts**: Climate change intensifies climate variability. With warmer temperatures, the water-holding capacity of the atmosphere increases which could result in increased precipitation intensity and longer dry periods, potentially increasing both floods and droughts.
- **Aquatic Ecosystems**: Aquatic ecosystems, reliant on temperature, water quantity, quality, and availability time, may face significant alterations.
- **Water Quality**: Changes in runoff patterns and pollutant transport may affect water quality.
- **Water Demand**: Temperature-related changes influence water demand, especially in agriculture.
- **Sea Level Rise**: Rising temperatures will cause a rise in sea level (the consequence of the thermal expansion of the ocean waters and melting of glaciers), impacting coastal aquifers and ecosystems (saline intrusion).

The Iberian Peninsula (IP) experiences a Mediterranean climate, which is typical of Southern Europe and the Mediterranean region, which is known as a "hot spot." This highlights the high vulnerability of IP to the impacts of climate change (Andrade et al. 2021; Rasilla et al. 2013).

A combination of geographical and climatic factors contributes to this designation. Its lower latitude results in greater exposure to solar radiation, which intensifies with global warming. The contrast between the Mediterranean Sea and surrounding landmasses, coupled with the region's mountainous terrain, contributes to heat retention and temperature inversions. Climate change-induced feedback mechanisms, such as glacial melt and reduced albedo, further amplify warming. Additionally, the region's dry summers and altered ocean currents play roles in elevating temperatures (Tuel et al. 2020).

Studies have projected several severe consequences for this region due to climate change, including higher temperatures, increased evaporation, reduced annual precipitation (with uneven seasonal and spatial patterns), more frequent and severe droughts, a gradual decrease in average streamflow, and alterations in river behaviour resulting in reduced runoff. Numerical projections for the Iberian Peninsula estimated a reduction of approximately 10% in mean annual precipitation and 19% in runoff, varying depending on the specific scenario (Ceballos-Barbancho et al. 2008; Mourato, Moreira et al. 2014; Solaun et al. 2017). The southern regions, in proximity to the Mediterranean basin, are expected to experience more pronounced declines. The impacts of global warming on precipitation patterns lead to a contrasting seasonality, characterized by longer dry periods and intensified winter rainfall. Alongside severe droughts, increased concerns regarding floods, particularly in the northern regions during the wetter months, should be addressed (Fernandez et al. 2017; Pereira-Cardenal et al. 2014; Rasilla et al. 2013). Furthermore, temperature anomalies of up to 3.0°C are anticipated, amplifying potential evapotranspiration and water requirements in the region. For further analysis see section 3.2.

Considering hydropower's unconditional reliance on water resources, the correlation between water availability and electricity generation is significant. Water availability primarily depends on precipitation, which affects hydropower generation through various mechanisms. It can change the flow of rivers and the water stored upstream, which affects the energy produced downstream. It also influences river flow, which depends on both current and past rainfall. Additionally, climate variations also have an impact on water availability. Therefore, the levels and consistency of precipitation strongly define electrical generation, making hydropower one of the most climate-sensitive Renewable Energy Sources (RES) (Andrade et al. 2021; Lehner et al. 2005; Teotónio et al. 2017).

Climate change's effects on hydropower can be categorized into two main types (Berga 2016; Teotónio et al. 2017): i) direct impacts induced by climate-related changes in hydro-meteorological variables, which directly influence water availability for power generation; and ii) indirect impacts, characterized by increased competition for water resources resulting from the exacerbated scarcity of this vital natural asset.

4.1.1 Direct Impacts

Climate change can directly impact hydropower generation in several ways, including changes in precipitation, alterations in river flows, shifts in evaporation rates, glacier melting, sedimentation and dam safety. The increasing frequency of extreme weather events, such as heavy rainfall causing floods and prolonged dry periods leading to droughts, can also harm hydropower systems and increase operational risks (Hamududu et al. 2012; Lehner et al. 2005; Teotónio et al. 2017).

The effects of climate change on hydropower generation vary based on the type of infrastructure. Hydropower plants with reservoirs are generally less vulnerable to short-term fluctuations compared to run-of-river power plants because reservoirs provide better control over sudden changes in river flow and variability. Additionally, smaller dams with reduced surface areas are expected to be less impacted by climate change due to lower evaporation rates compared to larger dams with extensive surface areas (IHA 2022; Kumar et al. 2011; Lu et al. 2020).

In the Iberian Peninsula (IP), shifts in precipitation patterns leading to seasonal and spatial variations in river flows, along with reduced runoff, are anticipated to decrease hydropower production. A reduction of over 30% in hydropower generation is projected, making IP one of the most affected regions in Europe (Pereira-Cardenal et al. 2014; Solaun et al. 2017; Teotónio et al. 2017). This significant drop in hydropower output could hinder efforts to mitigate climate change by increasing CO2 emissions and limiting the ability of hydropower to complement intermittent renewable energy sources like wind and solar power. Furthermore, several studies highlight a notable shift in power demand from winter to summer, presenting new scheduling challenges (Pereira-Cardenal et al. 2014).

4.1.2 Indirect Impacts

Climate change can indirectly impact hydropower generation by intensifying competition among various economic sectors that depend on water resources, such as energy and agriculture. As a result of climate change, reduced runoff and higher irrigation needs due to increased evaporation rates may lead to reduced water availability for hydropower compared to other users like agriculture, industry, and households (Teotónio et al. 2017).

Additionally, climate change can pose challenges to the management of shared river basins between countries. Any change in the upstream country can affect the availability and quality of water resources downstream. In the context of climate change, if an upstream country increases its water usage, it might lead to water shortages downstream, affecting water-dependent economic activities like farming and energy production. In the Iberian Peninsula, several major river basins are shared between Portugal and Spain, increasing the likelihood of competition for water resources due to climate-induced water scarcity. Moreover, competitive energy companies, driven by their individual interests and profits, tend to prioritize their own strategies rather than considering broader sector optimization criteria (such as benefit from cascade effects). This situation is particularly concerning for the Portuguese hydropower system, as it heavily relies on rivers like the Douro, Tagus, and Guadiana, which are downstream from significant Spanish hydropower plants and irrigation systems (Pereira-Cardenal et al. 2014; Rasilla et al. 2013; Santos FD et al. 2007).

Furthermore, both countries have experienced significant population growth and are popular tourist destinations. This growth, along with increased tourist demands, places additional stress on water resources, increasing the risk of water scarcity(Teotónio et al. 2017).

4.2 Hydropower's role in climate change mitigation and future opportunities

Hydropower and climate change show a double relationship. On the one hand, hydropower is an important renewable energy resource that contributes significantly to avoiding GHG emissions and mitigating global warming. On the other hand, it is likely that climate change will alter river discharge, resulting in impacts on water availability, water regularity, and hydropower generation (Berga 2016).

The power sector is responsible for 40 per cent of global carbon emissions, making it the single largest contributor to global warming. To limit global temperature rises to 1.5°C, it will need to rapidly decarbonize. In parallel, the overall level of electricity generation is expected to more than double as economies grow, and electricity replaces other fuels in a wide range of sectors, including the transport sector (IHA 2022). Over the last century, electric power systems have relied on the stability provided by a fleet that is highly dispatchable (i.e., power plants that can control and adjust their power production to demand) such as coal, gas, nuclear and hydropower. But now this landscape is rapidly changing, and all the net zero projections for change rely heavily on a dramatic shift in the composition of the world's electricity-generating fleet, with variable renewable energy sources (mostly wind and solar) becoming dominant (IHA 2022; Kumar et al. 2011; Ramião et al. 2023). Low-carbon dispatchable technologies will have to step in and guarantee reliable, long-lasting, and affordable electricity generation for consumers. Hydropower is not only today's main source of low-carbon electricity but, due to its storage capacity, is also equipped to become the lead provider of grid flexibility – it will be the backbone of reliable, safe, and decarbonised power systems (IHA 2022; Teotónio et al. 2017). However, to fully harness the hydropower potential, it's important to know where the opportunities are.

The integration of pump hydro storage (PHS) into hydropower facilities with reservoirs represents an opportunity that amplifies the importance of hydropower in the years to come. It serves as a crucial tool in the pursuit of sustainable objectives, enabling the storage of surplus renewable energy production (Berga 2016; IHA 2022; Kumar et al. 2011). The increasing demand for PHS is evident, exemplified by recent efforts in both Portugal and Spain to expand their installed capacity in this area (REE 2023b; REN 2022b). Furthermore, PHS facilitates improved water resource management, a vital aspect given the challenges posed by climate change and the potential for water scarcity in the Iberian Peninsula.

The modernization of ageing hydropower infrastructure not only offers a significant business opportunity for the sector but is also imperative for sustaining output and enhancing efficiency and flexibility (Berga 2016; IHA 2022). Moreover, the integration of innovative technologies, including advanced software solutions and technological upgrades such as hydraulic short circuits, battery hybridization, and variable speed turbines, can be leveraged to enhance control and efficiency (IHA 2022). These advancements are particularly vital in the context of climate change, as they enable more accurate predictions of critical water resource scarcity periods and the implementation of strategies to manage water reserves effectively.

Innovative solutions like hybrid floating photovoltaics (FPV) present a unique opportunity. Installing FPV on existing hydropower reservoirs offers the distinct advantage of leveraging the grid connections of hydropower and the simultaneous generation of solar and hydropower energy. Solar energy is harnessed during daylight hours, while hydropower continues to provide energy when the sun is not shining. The advantages extend beyond energy production. By installing FPV on existing hydropower reservoirs, land space is conserved, and the panels provide shade to the water body. This shading effect reduces water evaporation from the reservoirs, particularly beneficial in regions susceptible to droughts, helping to prevent water shortages (IHA 2022).

In navigating this transition towards a sustainable and decarbonized energy landscape, it's crucial to emphasize the role of government incentives. Government policies and mechanisms that reward flexibility in balancing the energy system, comprehensive planning, and financial frameworks are indispensable. Moreover, international collaboration and synergies between neighbouring countries, such as Spain and Portugal, hold immense importance. Implementing cascade strategies in shared water bodies and avoiding water retention in upstream regions are practical examples of such collaborative efforts. These measures not only optimize energy production but also enhance the resilience of the power systems in the face of climate change challenges (Berga 2016; Teotónio et al. 2017).

4.3 Bridge for the Iberian Electricity Market

Given that hydropower accounts for a sizeable component of the Iberian Peninsula's electrical supply, a decrease in its output has a direct impact on the total amount of electricity available. To compensate for the shortfall in hydropower generation, and due to the high variability of remaining renewables, the Iberian Peninsula will likely need to rely more on non-renewable sources or reinforce the storage capacity. This shift toward non-renewable sources, which often have higher marginal costs or Levelized Cost of Electricity (LCOE), will lead to an increase in the average market price of electricity. From an environmental perspective and in line with the decarbonization goals, the preferable approach is to expand renewable capacity and storage. However, this may require substantial investments and could also result in short-term increases in market prices (Golombek et al. 2012; Pereira da Silva et al. 2019; Teotónio et al. 2017).

Additionally, several authors suggest that rising electricity demand during summer for cooling purposes, coupled with decreased summer inflow and lower thermal efficiency, could drive an increase in summer electricity prices. On the opposite, reduced winter heating requirements alongside increased winter inflows may lead to decreased electricity prices during the winter season. As previously mentioned, the anticipated extension of dry periods compared to wet months may contribute to an overall rise in the average annual market price (Golombek et al. 2012).

From an economic perspective, research indicates that climate change scenarios will imply additional investments in generation capacity, particularly in solar PV (due to its low LCOE) and natural gas (to compensate for the intermittency of renewables when hydropower production decreases). This, in turn, could potentially displace other investments within the Iberian economy. Consequently, the energy system may experience a decrease in economic efficiency, given the requirement for more capacity (and the associated investments and fixed costs) to meet electricity demand. As a result, there is a projected increase in the price of electricity supplied to the Iberian economy, with estimates reaching up to 17% (Teotónio et al. 2017).

Higher electricity prices have the potential to elevate operational expenses for industries and result in increased utility bills for consumers, subsequently affecting both industrial competitiveness and household purchasing power. Furthermore, diminishing hydropower generation can have implications for energy security, as hydropower is frequently utilized for load stability due to its low intermittency and high reliability (Berga 2016; IHA 2022). Thus, diversifying the energy mix becomes imperative to ensure a dependable energy supply. It's noteworthy that both Spain and Portugal have already demonstrated their commitment to this diversification through ambitious renewable integration and storage plans outlined in their respective 2030 decarbonization strategies (APA 2023; MITECO 2021). This transition entails a focus on increasing energy storage solutions, reinforcing grid infrastructure to accommodate increased renewable capacity, and promoting the development of solar, wind, and energy storage projects.

Despite the clear environmental benefits and long-term economic gains, a significant shift toward renewable energy generation can exacerbate the "missing money problem. This issue arises as renewables, with their minimal marginal costs, can lower electricity market prices, creating a disconnect between the revenue generated by renewable generators and the expenses incurred by grid operators to maintain grid reliability and support the integration of intermittent renewables. To effectively address this evolving energy landscape, a multi-faceted approach that encompasses grid infrastructure enhancement, revised market designs, and properly valued grid services from conventional power sources is essential (Duan et al. 2020; Leal et al. 2023).

In this evolving energy ecosystem, effective energy storage solutions are essential in mitigating the challenges posed by the "missing money problem." Among these, hydropower stands as an advantageous choice when compared to batteries. Hydropower, in addition to its generation capacity, offers energy storage capabilities, particularly in the case of pumped storage facilities. This advantage arises from its ability to store significant amounts of energy for extended periods, something often challenging for batteries. The energy density of water, combined with the durability and long operational lifespan of hydropower infrastructure, makes it an attractive option for large-scale energy storage.

Despite the significant impact of climate change on hydropower, it remains a technology with a dual role in our evolving energy landscape. While environmental and climate-related constraints may limit the expansion of hydropower capacity, its critical importance in addressing the "missing money problem" and offering reliable storage properties cannot be overlooked. Pumped storage exemplifies this duality, as it not only supports grid stability but also presents an opportunity for intelligent water resources management in a changing climate. This adaptability underscores hydropower's continued relevance and its role in shaping the future of sustainable energy systems.

5 Methodology

In this chapter, a comprehensive overview is provided of the steps taken to assess the potential impacts of climate change on the future Iberian power system. The methodology diagram is depicted in Figure 9, providing a broader picture of the entire process.

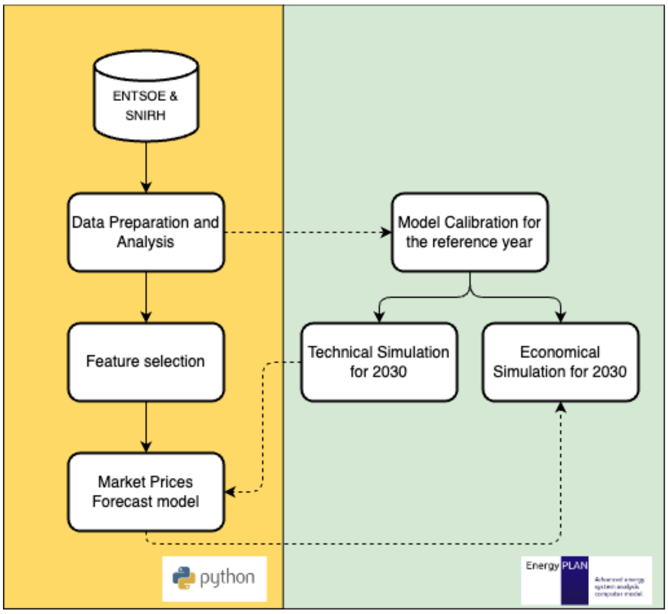


Figure 9. Flowchart with the schematic representation of the methodology applied and the interaction between Python (left) and EnergyPLAN (right)

The process initiates with the collection of essential data required to accurately characterize the Iberian power system, encompassing generation and load profiles, cross-border exchange balances, market prices, and installed capacities. The preparation of this data to align with the specifications of each problem was accomplished using Python software. Following this data preparation step, the modelling phase of the Iberian power system begins.

This phase involves calibration and validation using historical records to accurately represent system conditions and specifications. The modelling step assumes significant importance as it establishes the baseline scenario that will undergo perturbations through simulation. These perturbations align with predicted evolutions of various system variables. For future analysis, the year 2030 was chosen, aligning with the National energy and climate plans of both Spain and Portugal. These plans provide a framework for predicting the evolution of each power system. While it would have been possible to conduct this simulation using Python, the complexity and time-intensive nature of accounting for intricate technical specifications and interdependencies between technologies led to the selection of the EnergyPLAN simulation tool. EnergyPLAN offers two types of simulation: technical simulation, which primarily relies on technical parameters and seeks to reduce non-renewable generation, and market simulation, based on short-term marginal costs, with a focus on minimizing operational expenses. Given that market simulation requires additional inputs, including external market prices, priority was given to conducting the technical simulation for 2030. The results obtained from this technical simulation serve as inputs for a market price forecast model, developed using Python, to project market prices in 2030. Subsequently, an economic simulation becomes feasible. The impacts of climate change are considered by changing the hydropower capability index, resulting in three distinct scenarios based on hydrological regimes: the average, wet, and dry scenarios. According to the previous chapter, it is more likely that the current dry scenario will become the most common in the future, so special emphasis will be given to this perspective.

5.1 Data Collection and Analysis

5.1.1 Iberian Power System Data

To comprehensively analyze and define the Iberian power system, essential data was accessed through the European Network of Transmission System Operators for Electricity (ENTSO-E). ENTSO-E is an organization responsible for coordinating and optimizing the operation of electricity transmission systems across multiple European nations. It plays a central role in ensuring the reliability, efficiency, and security of Europe's interconnected electricity grid. ENTSO-E achieves this through grid coordination, market integration, grid planning, data exchange, and policy advocacy. Its efforts are instrumental in promoting cross-border electricity trading, enhancing grid resilience, and fostering the development of a sustainable energy system in line with European energy and climate goals (ENTSO-E 2023b).

ENTSO-E’s Transparency Platform serves as a rich repository of European electricity-related data, offering a comprehensive collection and publication of information regarding electricity generation, transportation, and consumption across the pan-European market (ENTSO-E 2023a). This platform was instrumental in retrieving the specific data needed for this research. An API key provided by ENTSO-E granted access to essential data for each country, including information on generation categorized by technology, installed capacity figures, export/import balances, load profiles, consumption patterns and market prices.

Nevertheless, the raw data obtained from these sources often requires substantial preparation to ensure accuracy and consistency. To address this, a thorough data preprocessing and cleaning phase was conducted using Python. This process was essential to refine the data and render it suitable for utilization as input for the market price forecasting model.

It's important to note several considerations for post-data processing. Firstly, the data provided by ENTSO-E is available from 2015 onwards, meaning that analyses are limited to this timeframe. Additionally, all the data is on an hourly basis, providing a detailed view of electricity generation, consumption, and market dynamics. Hydropower generation data is further categorized into three distinct technologies: hydrowater reservoir, run-of-river, and pump storage. It's also worth noting that the load distribution data doesn't account for pump-storage consumption. Nevertheless, this specific information is available within the consumption per technology data, allowing for a comprehensive assessment of hydropower dynamics in the Iberian power system.

It's essential to acknowledge certain disparities between the data provided by ENTSO-E and data from national transmission system operators (TSOs). Notably, there's a discrepancy between ENTSO-E data and the data hub reports from REN, the Portuguese TSO (REN 2023). This variance arises from the differing methodologies used in calculating electricity generation. REN accounts for net generation, which discounts receptions for auxiliary services, while ENTSO-E values represent the gross value delivered to the grid. Similarly, a similar mismatch exists between ENTSO-E data and reports from REE, the Spanish TSO (REE 2023a). This discrepancy is related to how ENTSO-E aggregates hydro water reservoir and pump-storage generation until 2022 into a single category, whereas REE reports these values separately. However, these differences are minimal in nature, and for the purposes of this analysis, ENTSO-E values were used to maintain consistency and comparability.

5.1.2 Hydrometeorological data

In the context of assessing the impacts of climate change on hydropower and its implications for the Iberian electricity market, it is crucial to consider additional variables related to water resources. These variables not only help define hydrological behaviour but also provide insights into forthcoming changes and trends.

For the hydrometeorological data used in this analysis, a focus was placed on Portuguese river basins due to data availability constraints, as Spanish data was not accessible. Given that four river basins (Minho, Douro, Tejo, and Guadiana) are transboundary, with over 55% of reservoir capacity in Spain concentrated within them, it was considered a reasonable approximation that the hydrological behaviour downstream in Portugal would reasonably represent conditions in Spain. The data was sourced from SNIRH (National Information System for Water Resources), a comprehensive database and information system in Portugal dedicated to the management and monitoring of water resources (SNIRH 2023b). SNIRH gathers and maintains a wide range of data related to hydrological and meteorological conditions, water quality, water use, and other critical aspects of water resources.

The data includes the mean daily inflow and monthly volume stored for 26 hydrometric stations, aligning with the hydropower installed capacity reported in the REN national grid characterization report for 2022 (REN 2022a). Additionally, mean daily temperature and precipitation data were collected from over 40 meteorological stations. To harmonize this data with the ENTSO-E hourly data, which forms the basis of our analysis, mean daily inflow and precipitation were divided by 24 hours, while monthly stored volume and daily temperature were assumed to remain constant throughout each hour. After collecting, cleaning, and preparing the data to ensure a uniform hourly basis for analysis, the average values from the selected stations were used to represent overall Iberian conditions. In cases where data points were missing, interpolation techniques were applied to estimate and fill in these gaps.

The inclusion of these hydrological and meteorological variables in the dataset serves a twofold purpose. Firstly, it aims to enhance the representation of water-resource factors, offering a more nuanced understanding of how hydropower generation is intrinsically linked to inflow rates and the availability of water stored in reservoirs. Secondly, these variables provide insights into the broader impacts of climate change on water resources, including increased evaporation rates and potential shifts in precipitation patterns, which directly affect runoff and subsequently, hydropower generation.

By incorporating these additional layers of data, the forecasting model gains sensitivity to external factors such as rising temperatures, enabling better calibration of predictions to account for shifts in water availability, potential increases in evaporation, and evolving irrigation needs.

5.1.3 Correlation analysis

Correlation analysis is a fundamental statistical technique used to assess the degree of association or relationship between two or more variables. In the context of this study, correlation analysis plays a pivotal role in understanding how various factors influence electricity prices in the Iberian Peninsula. The strength and direction of these relationships are essential for developing accurate price forecasting models. Two common methods for measuring correlation are the Spearman correlation coefficient and the Pearson correlation coefficient. These methods differ in their suitability for different types of data (Hauke et al. 2011).

- **Pearson Correlation:** Pearson correlation is appropriate for assessing the linear relationship between two continuous variables. It measures the strength and direction of a linear association. However, it assumes that the data follows a normal distribution, and it may not perform well when data is not normally distributed or when there are outliers.
- **Spearman Correlation:** Spearman correlation, on the other hand, is a non-parametric measure of correlation. It is used when the variables being studied are not normally distributed or when the relationship between variables is not necessarily linear. Spearman's rank correlation assesses the monotonic relationship, which means it can capture relationships that may be increasing or decreasing but not necessarily linear.

In the context of modelling electricity prices in the Iberian Peninsula, several variables involved in the analysis may not follow a normal distribution due to their complex nature and interactions. Additionally, the relationships between these variables and electricity prices may not strictly adhere to linearity.

Given these considerations, the Spearman correlation is more suitable for this study. It allows us to assess the monotonic relationships between the variables (Xi) and electricity prices (Yi) without relying on assumptions of normality or linearity. This is especially valuable when dealing with real-world data that often exhibit non-standard distributions and complex interactions (Leal et al. 2023). Spearman's correlation operates by independently ranking the values of the Xi and Yi variables in ascending or descending order, followed by the calculation of their differences (Di). With this information, Spearman's correlation between the variables is computed using the formula:

$$r_S = 1 - \frac{6\sum_{i=1}^{n} D_i^2}{n^3 - n}\ , D_i = X_i - Y_i$$

5.2 Modelling the Iberian Power System

The context of modelling in the energy domain is multi-faceted and is essential for understanding, analyzing, and developing real-world energy systems. Its primary objective is to construct a representation of an energy system that allows for in-depth analysis and improvements. These models can encompass entire energy systems or focus on specific aspects, such as demand response (Lund et al. 2014).

Models in the energy field are broadly categorized into two main types: macro-models and micro-models (Lund and Thellufsen 2021; Østergaard 2015a). Macro-models are designed for large-scale analysis, frequently covering regional, national, or even global scales. They offer a high-level overview of the entire energy system, focusing on energy supply and demand at a broad scale. Typically, these models employ a lower temporal resolution (this coarser resolution effectively manages computational complexity), making them well-suited for long-term analyses using annual or multi-year time steps. These models provide insights into the overall energy mix, energy security, and trends in energy markets. However, they may not capture intricate local variations or specific technology interactions. In contrast, micro-models narrow their focus on smaller, localized areas or specific components of an energy system. They offer a more detailed and fine-grained representation of the system, often drilling down to individual technologies or specific geographic regions. Micro-models, driven by their attention to local dynamics, operate with a higher temporal resolution, using hourly or sub-hourly time steps to meticulously capture fluctuations in energy generation and consumption. These are ideal for understanding the behaviour of specific energy system components and are typically used to evaluate the integration of renewable energy sources, optimize microgrids, and assess local energy management strategies. However, it's worth noting that micro-models are inherently more complex and data-intensive, requiring comprehensive data on individual technologies, geographic locations, and operational characteristics, which can result in higher computational demands.

In the context of simulating future annual energy production and assessing the impacts of climate change on the Iberian Power system, the choice of modelling approach is crucial. Given the goal of evaluating how climate change affects energy production and system behaviour, a micro-model, such as EnergyPLAN, is more suitable. This fine-grained approach allows for the perturbation of inputs to observe the effects of climate change on future simulations, making it a valuable tool for addressing the intricacies of the Iberian Power system in the context of changing environmental conditions (Lund et al. 2014; Lund et al. 2021).

Since 1999, Aalborg University in Denmark has been developing EnergyPLAN, a powerful tool that tackles the challenging field of Generation Expansion Planning (GEP) modelling. Its purpose is to determine how many and what type of energy conversion units should be installed within a defined planning horizon based on a predefined energy demand function (Ferrão et al. 2022). EnergyPLAN addresses this challenge through a bottom-up approach, establishing relationships between the evolution of demand for various forms of energy and the penetration and efficiency of different conversion technologies. The solution is found through simulation, adjusting the model's parameters to test different scenarios and comparing the results of different simulations (Østergaard 2015). The model is designed for hourly energy balance and allows the optimization of objective functions, such as maximizing the penetration of renewable energies or minimizing generation costs. With hourly resolution and annual values, EnergyPLAN assesses critical indicators, including the balance between imports and exports, the fraction of generation from renewable sources, and CO2 emissions, among others (Lund and Thellufsen 2021).

EnergyPLAN, was selected for several compelling reasons. It's open-source and widely used worldwide, including in Portugal. The simulation tool specifically focuses on future energy systems, which aligns with the core objective of this thesis. EnergyPLAN simulates energy systems in hourly time steps for an entire year, crucial for assessing climate change effects and capturing the full spectrum of fluctuations in energy supply and consumption. Additionally, it offers valuable online resources, such as up-to-date technology cost data, enriching the modelling experience and providing a versatile tool for understanding the intricacies of the Iberian Power system in a changing environment (Lund and Thellufsen 2021).

To ensure the creation of effective models, a well-defined methodology is essential, providing a structured approach to the modelling process. The typical workflow in energy modelling involves four fundamental steps (Lund et al. 2021):

1. **Define Reference Energy Demands**: At the outset of modelling an energy system, it is critical to determine the amount and types of energy that need to be supplied to meet the identified demands.
2. **Define a Reference Energy Supply System**: To evaluate the impact of new models, a baseline is needed. This step involves modelling the existing supply system to assess how proposed changes affect the current setup.
3. **Define the Regulation of the Energy Supply System**: Models can be optimized by adjusting various parameters that give priority to different technologies or regulation strategies.
4. **Define Alternatives**: Given the inherent uncertainties about the future, creating multiple scenarios is crucial. This approach allows for an exploration of various potential developments. By creating different models, researchers gain insights into technology interactions and their impact on the overall system. This helps prevent issues where the actual trajectory of technology development differs from what was initially anticipated.

5.2.1 Model overview: input/output and technical/market simulation

The EnergyPLAN model relies on multiple input parameters to facilitate an accurate simulation. It conducts an hourly annual energy assessment across various sectors, encompassing electricity, heating, cooling, industry, and transportation. However, since this study primarily concentrates on the electrical system, only this sector and its corresponding generation and demand components will be considered.

Inputs are essentially demands, installed capacities, hourly profiles of resource availability and strategies to handle the excess of energy produced by fluctuating renewables. The electrical demand is defined through two essential inputs: the total energy demand over a year (TWh) and distribution data consisting of 8784 values (the simulation tool only works for a leap year) that represent hourly demand throughout the entire year (MWh). Furthermore, non-dispatchable technologies, including fluctuating renewable energy sources, require similar distribution data to properly represent generation patterns. The model also requires information regarding the capacities of each generation technology, with additional efficiency values for dispatchable generation technologies (Lund and Thellufsen 2021).

Additionally, it requires the specification of transmission line capacity, as well as a strategy to manage Critical Excess Electricity Production (CEEP), representing surplus electricity that cannot be exported due to transmission capacity limitations. Furthermore, it's important to note that services with sub-hourly time scales, such as 'frequency regulation' or 'spinning reserve,' are not explicitly considered. However, EnergyPLAN implicitly allows for a portion of the generation systems to be allocated to these grid services. This is achieved by defining a percentage of the installed generation capacity available for stabilization purposes (Lund and Thellufsen 2021).

The simulation outputs include annual, monthly, and hourly data regarding electricity production per generation technology, electricity imports/exports, excess electricity production, fuel usage, fuel costs, CO2 emissions, and the proportion of renewable energy. Users can select from two simulation strategies: technical or economic (Lund and Thellufsen 2021; Østergaard 2015).

Technical simulation focuses on the demand/supply side and optimal technical performance. It optimizes the power output from various renewable energy sources, prioritizing the reduction of fossil fuel consumption and CEEP. This strategy considers only technical parameters, neglecting any external or internal cost influence.

In contrast, the market-economic simulation aims to minimize the operational costs of the system, dispatching units based on short-term marginal costs. It optimizes the operation of each technology in accordance with business-economic profits, including any taxes, technology costs and market prices. For this reason, an additional cost data input for the energy system should be provided, along with a distribution file containing market prices for each hour. Figure 10 provides a comprehensive visualization of the necessary input and output data.

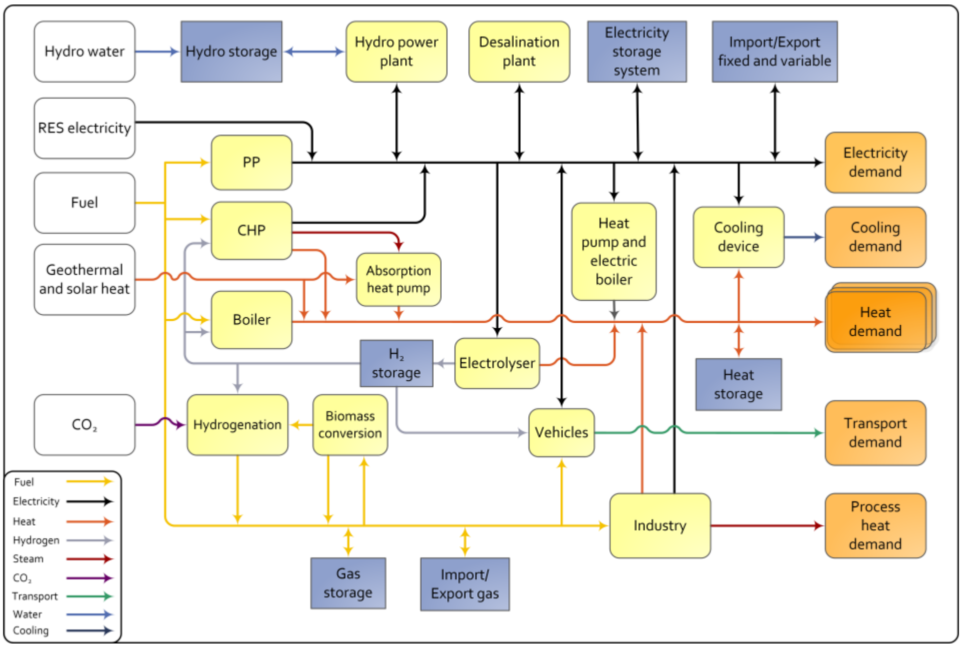


Figure 10. Schematic representation of EnergyPLAN model (Lund and Thellufsen 2021)

5.2.2 Merit Order and limitations

Within the EnergyPLAN model, the merit order is a method for ranking the different generation technologies that are available at any given time. This order's specifics vary based on the simulation strategy employed (Lund et al. 2014; Lund and Thellufsen 2021; Østergaard 2015).

Non-dispatchable renewable sources, in both technical and market simulations, are given priority in electricity production. Marginal production costs are defined as zero from the market perspective. For hydropower, the approach slightly differs in technical and market simulations (Lund and Thellufsen 2021).

In the technical simulation, two main steps guide the process: first, the system calculates the optimal utilization of all available water inputs within capacity limitations and uses this as input. Second, hydropower is strategically allocated to minimize excess electricity production. If reversible hydropower is considered, the pump is used to avoid excess electricity production. Turbine generation aims to avoid reliance on power plants.

For market-economic simulation, the focus is on identifying the maximum achievable production based on available water input, turbine capacity, and water storage capacity. The aim is to sell this maximum production at the highest possible market prices to maximize income. The hydropower pump and turbine play key roles in optimizing profitability, considering marginal costs and energy conversion losses.

As for power plants, their role also varies depending on the simulation type. In a technical simulation, power plants are given priority only after all other electricity production units if demand still exceeds supply, or when production is required for grid stability. In the market simulation, power plants generate electricity whenever the electricity price surpasses their variable operational costs. The same principles apply to nuclear and waste facilities. In the technical simulation, they are afforded priority in electricity production. Nuclear power plants, for instance, can operate in part-load as part of a CEEP regulation strategy. In the market simulation, both technologies produce electricity whenever the electricity price exceeds their variable operational costs.

A significant limitation of EnergyPLAN is its inability to offer spatial resolution. This means that the model cannot simulate demand and generation within specific geographical regions or account for energy transmission constraints between different areas. This limitation is especially evident when dealing with hydropower and hydro pump storage. In EnergyPLAN, these components are often treated as a collective unit, resembling a large-scale dam. This simplified approach fails to account for the intricate technical variations and geographical distinctions that may exist among individual hydro plants. Moreover, another limitation arises when using the technical simulation in EnergyPLAN, as it prioritizes exports over pumped hydro, a scenario that leads to the assumption that the external market will consistently absorb or supply energy and neglects the importance of water resources management and water value.

5.2.3 Reference Year

To ensure the accurate simulation of the energy system using EnergyPLAN, it's essential to conduct a simulation of a reference year and subsequently compare the results with real energy statistics for the same time frame. The model's validity is confirmed if the output values match the available historical data. If this correspondence is not attained, a calibration procedure should be performed to approximate these values (Lund et al. 2014). The importance of a well-calibrated reference model cannot be overstated, as it serves as the foundational basis for all forthcoming scenarios. Moreover, the creation of a reference year allows users to understand the energy composition and unique aspects of a specific country, develop an intuitive sense of the model, and recognize its limitations.

The reference year selected for this study is 2021. This choice is attributed to several key factors. Firstly, 2021 provides recent and comprehensive data for both countries involved in the analysis. Additionally, the energy consumption patterns for this year were notably stable in the aftermath of the COVID-19 pandemic. Furthermore, the hydro capability index was close to 1, making it an ideal choice to represent an average year and allow for future comparisons (similarly, the capability indexes for wind and solar energy were also very close to 1, but these indexes have minimal fluctuations). Lastly, the year 2021 was not influenced by external events such as the conflict between Russia and Ukraine, which had implications for energy systems in 2022.

The primary data sources for creating the model included comprehensive reports from REN and REE for the specific year (REE 2023a; REN 2021), along with data obtained from ENTSOE (see section 5.1.1). In the EnergyPlan software, which was used for both technical and economic simulations, the following fields related to electricity were taken into consideration: Electricity (in the Demand section), Heat and Electricity, Central Power Production, Variable Renewable Electricity, and Fuel Distribution (in the Supply section), as well as Electricity (in the Balancing and Storage section). To ensure a well-rounded representation, various sections such as General, Investment, Fixed Operations and Maintenance (OM), Fuel, and Variable OM were also considered in the Cost section. The calibration process was consistent for both Portugal and Spain, as described in the following sub-sections.

It is important to note that, in this analysis, only the peninsular system was considered, including the respective generation/load profiles. Both the modelling and calibration were conducted separately for Portugal and Spain to maintain model accuracy and facilitate comparisons of technology contributions in both countries' scenarios.

5.2.3.1 Portugal Calibration

In 2021, Portugal's electricity demand amounted to 49.6 TWh. This demand must be met by the energy supply side plus the import/ export balance. Pump storage consumption should also be deducted from this equation since it's not considered in the global demand.

5.2.3.1.1 Variable renewable energy

In 2021, fluctuating renewable sources, which include solar, wind, and run-of-river technologies, made up 59% of the total electricity generation. To model their variable and non-dispatchable nature, we need data on their installed capacity and an hourly distribution for each technology, as previously mentioned, in relative terms. This distribution was calculated by dividing the hourly generation by the total installed capacity.

As for biomass power plants, despite the EnergyPlan simulation tool having a specific tab for defining their generation as dispatchable, the approach was to treat them as a variable renewable energy source. This decision simplified the process and was driven by some difficulties during the calibration process and data constraints. It's important to note that this choice aligns with the fact that biomass power plants aren't completely dispatchable. The assumed values are detailed in Table 1.

Table 1. Portuguese installed capacity for variable renewable energy sources in 2021

Technology	Installed Capacity [MW]
Wind Onshore	5183
Wind Offshore	25
Solar	890
River Hydro	2857
Biomass	684

5.2.3.1.2 Central Power Production

2021 Portuguese dispatchable sources are mainly comprised of two categories: Natural Gas and Coal Power Plants and Dammed Hydropower. When dealing with Power Plants, the software further divides them into two subcategories: Cogeneration and non-cogeneration plants. For each of these, the installed capacity, fuel distribution, and efficiency value must be defined. In 2021, there was a gradual phase-out of coal power plants in Portugal, culminating in the closure of the country's last coal plant in November (Pego Power Plant) (José Mendes 2021). As a result, coal played a minimal role, accounting for only 1.4% of the generation mix. In contrast, natural gas was a significant contributor, representing 30% of the total generation. Due to this shift and to simplify the analysis, only natural gas was considered. The installed capacity for each subcategory and respective efficiencies and fuel distribution are presented in Table 2.

Table 2. Installed capacity for Power Plants in Portugal

Technology	Installed Capacity [MW]	Efficiency [%]	NGas [TWh/year]
Cogeneration	756	55	3.524
Non-Cogeneration	4044	40	11.016

Dammed hydropower, despite being a renewable energy source, is modelled as a dispatchable source due to its storage capacity. To accurately model this, the defined generation installed capacity should encompass both the hydropower reservoir generation capacity and the reversible hydro generation capacity (sometimes these values are combined). ENTSOE data was especially valuable in this regard, providing detailed information on the installed capacity for different technologies (ENTSO-E 2023a). Furthermore, hydropower with storage capacity requires specific hourly distribution data files containing information on the water supply to the water reservoir in GWh throughout the year. This data was generously provided by REN after establishing contact. The sum of this daily water supply constitutes the annual water supply, another input for the model.

To effectively model the storage component, two essential inputs are required: the reservoir storage capacity and the pump capacity. The storage capacity value was estimated based on REN's data for the daily water regime, considering the daily percentage variations, and it's estimated to be around 3200 GWh (REN 2023). The pump capacity proved to be a bit more challenging due to discrepancies in the published values and a 32% increase between 2021 and 2022. Nonetheless, all the published values were close to 3000 MW, so this value was assumed (ENTSO-E 2023a; REN 2021, 2022a). Moreover, the model also allows for defining the beginning and ending shares of the reservoir's capacity to provide a more accurate description of water resource management. This value was derived from REN's daily water regime reports (REN 2023). All the parameters are summarized in Table 3.

Table 3. Dammed hydro inputs for Portugal

Dammed Hydro Capacity	5000 MW
Dammed Hydro Efficiency	90%
Annual production	4.34 TWh
Reservoir Storage Capacity	3200 GWh
Pump Capacity	3000 MW
Pump Back Efficiency	80 %
Begin/ End share of capacity	60%/30%

The first limitation of the model becomes apparent when dealing with hydropower pump consumption in market simulations. This limitation arises because the market strategy leverages the pump operation to optimize profits according to market prices, causing the pump to operate significantly under market influence, resulting in exceedingly high pump values (see section 5.2.2). To address this limitation, the pump capacity was constrained to the equivalent of the 80th percentile of its usage in 2021. In 2021, the installed pumping capacity was 3000 MW; however, the average usage of this mechanism was only 234 MW, and the 80th percentile was 400 MW as can be seen in Figure 11. This discrepancy in usage is a result of hydrological conditions and commercial factors that don't strongly favor electricity storage to make it competitive. To ensure consistency, this assumption was maintained for future scenarios.

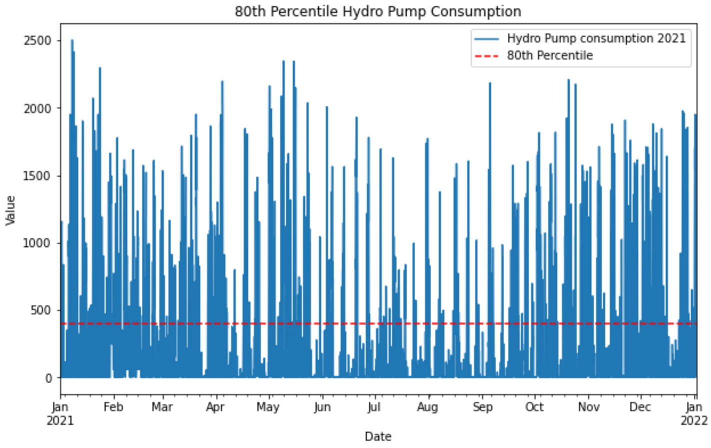


Figure 11. 80th Percentile of Portuguese Hydro pumped consumption

5.2.3.1.3 Interconnection and regulation

The transmission line capacity was set at 3500 MW, as it provided the most accurate results during calibration. Additionally, this value closely aligns with the average import and export capacity outlined in REN's grid characterization for 2021 (REN 2022a). However, it's important to note that this capacity setting was exclusively used for market simulations. EnergyPLAN's inherent prioritization of exports over-pumping, which can't be adjusted, often results in residual values for pump storage, particularly in technical simulations that don't consider economic factors. Therefore, in technical simulations, the transmission line capacity was deliberately set to zero, allowing for an increase in pumping. It's important to note that without transmission line capacity, the model lacks the ability to import/export, which will be covered by the central power plant.

Grid stabilization requirements are crucial for maintaining a reliable and stable electrical grid, which is essential for the functioning of modern society. Dispatchable power sources can be controlled and adjusted based on demand, making them ideal candidates for regulation purposes. EnergyPLAN allows users to define electric grid stabilization requirements, and it considers dispatchable hydro and thermal power plants as the technologies that can provide these services. For this thesis, specific minimum stabilization shares were defined: 10% for the market simulation and 30% for the technical simulation. The higher percentage for the technical simulation accounts for the absence of direct consideration of transmission line capacity exchange, which also plays a role in grid stabilization. These values were determined based on the 15th percentile proportion of these technologies (plus import/export balance for technical simulation) in relation to the total load.

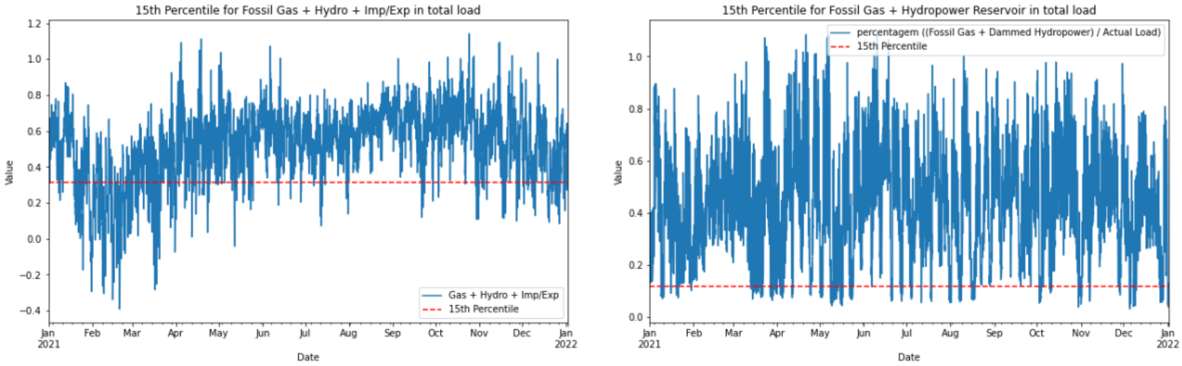


Figure 12. Minimum stabilization share for technical simulation (left) and market simulation (right)

5.2.3.2 Model Simulation and Validation

The model validation process involved error analysis by assessing the relative deviation between the model's outputs and actual data, as defined by the formula:

$$Error\ (\%) = \frac{(real\ data - model\ data)}{real\ data} * 100\%$$

Despite the calibration and various assumptions made, aligning EnergyPLAN's output with historical data can be challenging, as actual operations might not always conform to short-term least-cost combinations of production units or simple merit order rules. For this reason, a 10% confidence interval was considered an acceptable margin of error. It provided a reasonable degree of flexibility to account for such discrepancies. Additionally, the calibration for both dammed hydropower and imports/exports exchanges was carried out by considering the global balance. The resulting data and outcomes are presented in the table below.

Table 4. Portuguese Model Validation

Technology	Real Values [TWh]	Market Simulation [TWh]	Error (%)	Technical Simulation [TWh]	Error (%)
Biomass	3,45	3,45	0,000	3,45	0,000
Wind Offshore	0,05	0,05	0,000	0,05	0,000
Wind Onshore	12,92	12,91	0,077	12,83	0,697
River Hydro	7,066	7,06	0,085	7,07	-0,057
Hydro Balance	4,15	4,02	3,133	4,11	0,964
Pump-Storage Consumption	2,06	1,84	10,680	2,03	1,456
Reservoir Hydro	6,21	5,86	5,636	6,14	1,127
Solar	1,73	1,73	0,000	1,73	0,000
Fossil Gas + Coal	15	15,44	-2,933	20,07	-1,210
Imp-Exp Balance	4,83	4,69	2,899		
Import	8,13	11,97	-47,232		
Export	3,3	7,28	-120,606		
Total = Demand	49,446	49,6	-0,311	49,56	-0,231

5.2.3.3 Spain Calibration

In 2021, Spain's peninsular electricity demand amounted to 244 TWh. This demand must be met by the energy supply side plus the import/ export balance. Pump storage consumption should also be deducted from this equation since it's not considered in the global demand.

5.2.3.3.1 Variable renewable energy

In 2021, the Spanish peninsular region reached a historic high in renewable energy generation, accounting for 48.4% of the total electricity generation mix. This surge was primarily attributed to significant increases in wind and solar power production (REE 2023b, 2023a). The calibration process for Spain closely followed the procedure applied in Portugal. However, it's essential to note some distinctions. Firstly, the installed capacity data for River Hydro didn't align with ENTSOE figures, which could be attributed to potential errors as hourly generation values occasionally exceeded the officially reported capacity. To address this, the installed capacity for River Hydro was adjusted to match the annual generation values, closely resembling data from the Spanish grid operator, REE (REE 2023b). Moreover, the Solar installed capacity in Spain comprises both Photovoltaic (PV) and Solar Thermal technologies, while in Portugal, Solar Thermal isn't prevalent (ENTSO-E 2023a). Additionally, Spain includes a category for 'Other Renewables' encompassing biogas, marine energy, and geothermal sources, which aren't accounted for in Portugal's model. The assumed values are presented in the following table.

Table 5. Spanish installed capacity for variable renewable energy sources in 2021

Technology	Installed Capacity [MW]
Wind Onshore	26664
Wind Offshore	0
Solar	11390
River Hydro	1994
Biomass	704
Other renewables	269

5.2.3.3.2 Central Power Production

In 2021, the power plants in operation in Spain were primarily fueled by three sources: natural gas, coal, and fuel oil. Much like the Portuguese scenario, natural gas played a predominant role in the generation mix. Despite a significant 35.9% reduction in coal-fired power capacity due to the permanent closure of multiple thermal units throughout this year, Spain still retained a noteworthy portion of coal installed capacity and generation (REE 2023a). Although fuel oil accounted for a smaller share, it still contributed approximately 1 TWh to the generation. Therefore, these three fuels were taken into consideration. However, due to a lack of detailed information on the cogeneration status of these power plants, all these fuels were aggregated within the same power plant, as detailed in the table Table 7.

Table 6. Installed capacity for Power Plants in Spain

Technology	Installed Capacity [MW]	Efficiency [%]
Power Plant	36625	49

Table 7. Fuel distrbution within Spanish Power plants

	NGas	Coal	Fuel oil
Distribution [TWh/year]	61.7	5.16	1.32

For Dammed Hydropower, the installed capacity aligned with both REE and ENTSOE records. Unfortunately, detailed hourly distribution data, specifying water supply to the reservoirs in GWh over the year, wasn't attainable. Therefore, similar to the approach adopted for hydrological data in section 5.1.2, the distribution pattern from Portugal was assumed. The yearly water supply was carefully adjusted to match the annual generation. Storage capacity was extracted from the REE daily energy balance reports, in congruence with hyperannual regime hydroelectric reserves (REE 2021). As for pump capacity, its value was not clear due to variations in data reports and the presence of both pure and reservable pump capacities. For this reason, the chosen value corresponded to the maximum capacity observed throughout the reference year. Lastly, the beginning and end shares of capacity were also derived from the REE daily reports. The established parameters are defined in Table 8.

Table 8. Dammed hydro inputs for Spain

Dammed Hydro Capacity	19816 MW
Dammed Hydro Efficiency	90%
Annual production	20,5 TWh
Reservoir Storage Capacity	9400 GWh
Pump Capacity	4000 MW
Pump Back Efficiency	80 %
Begin/ End share of capacity	50%/30%

Similar to the limitation encountered in the Portuguese scenario related to overpumping during market simulation, the pump capacity for this strategy in the Spanish context was also restricted. It was constrained to the 80th percentile value, which matched 971 MW (see Figure 13).

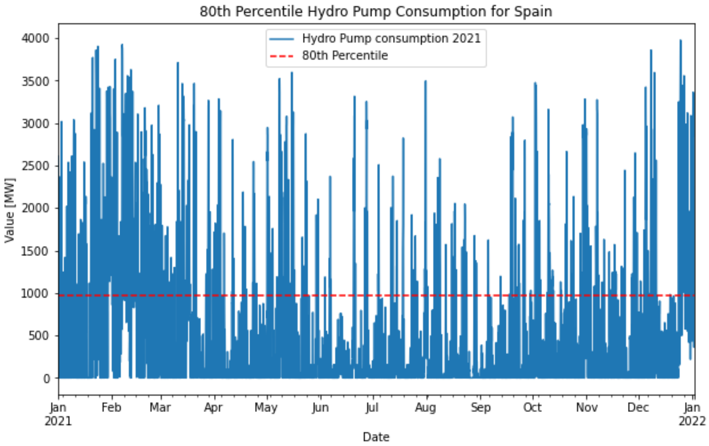


Figure 13. 80th Percentile of Spanish Hydro pumped consumption

Unlike Portugal, Spain has additional components in its energy mix, namely Nuclear and Waste generation. Nuclear power holds significant importance in Spain's electrical mix, contributing to 23% of the total generation in 2021. Waste generation, although more residual, still accounted for 2.5 TWh during the same year. Consequently, both these technologies were incorporated during the modelling phase. For Nuclear power, this involved defining the installed capacity, overall efficiency, and a hourly distribution. For Waste-to-energy involved defining the yearly waste input, efficiency, and an hourly distribution. The inputs are presented in Table 9 and Table 10. By default, both units are considered to be operating as base load by the EnergyPLAN model.

Table 9. Nuclear inputs for Spain

	Capacity [MW]	Efficiency [%]
Nuclear	7117	33

Table 10. Waste input for Spain

	Waste input [TWh]	Efficiency [%]
Waste	7.1	35

5.2.3.3.3 Interconnection and regulation

The transmission line capacity was set to 6000MW, encompassing the average utilisation rate of commercial exchange capacity for both the France and Portuguese cross-border connection presented on REE reports for 2021. For the same reasons encountered during the Portuguese calibration, this value was only used for the market calibration and the technical transmission capacity was set to 0MW.

Regarding the regulation strategy, the same 10% was used for the market simulation but a lower value of 15% compared to the Portuguese scenario was used for the technical simulation due to a smaller expression of the exchange balance (the difference between imports and exports was residual during 2021).

5.2.3.3.4 Model Simulation and Validation

Both the error analysis and the calibration for dammed hydropower and imports/exports exchanges were conducted the same way as in section 5.2.3.2. The resulting data and outcomes are presented in the table below.

Table 11. Spanish Model Validation

Technology	**Real Values [TWh]**	**Market Simulation [TWh]**	**Error (%)**	**Technical Simulation [TWh]**	**Error (%)**
Biomass	4,17	4,17	0,000	4,17	0,000
Wind Onshore	59,15	59,15	0,000	59,1	0,085
River Hydro	8,55	8,55	0,000	8,55	0,000
Hydro Balance	19,55	19,76	-1,074	19,54	0,051
Pump-Storage Consumption	4,63	8,31	-79,482	0,62	86,609
Reservoir Hydro	24,18	28,07	-16,088	20,16	16,625
Solar	25,41	25,26	0,590	25,26	0,590
Waste	2,48	2,48	0,000	2,48	0,000
Nuclear	54,3	54,29	0,018	54,29	0,018
Other renewables	0,89	0,89	0,000	0,89	0,000
Power Plant	68,2	70,97	-4,067	70,19	-1,715
Imp-Exp Balance	0,81	0,86	-6,173		
Import	14,87	25,4	-70,814		
Export	14,06	24,54	-74,538		
Total = Demand	243,50	246,38	-1,180	244,47	-0,396

5.3 2030 Simulation Scenarios

In order to comprehensively evaluate the potential changes in the future Iberian power system compared to the reference year and analyze their impact on hydropower generation and pumping patterns, it is imperative to define and accurately model various scenarios. The analysis is set for the year 2030, primarily due to the wealth of available data in the respective countries' climate and energy strategy plans, and its temporal proximity, which helps mitigate uncertainty in the analysis.

To conduct simulations for the year 2030, critical input data is required. This includes projections for electricity demand, capacities of various technologies, distribution profiles, and transmission line capacity. For Portugal, this data is primarily sourced from the Plano Nacional de Energia e Clima (PNEC) (APA 2023) and Roteiro para a Neutralidade Carbónica 2050 (RNC2050) (APA 2019). It’s noteworthy that the development of RNC2050 was closely aligned with the preparations for the Plano Nacional de Energia e Clima (PNEC). The PNEC, being the more recent of the two (published in 2021 and revised in 2023, while RNC was published in 2019), takes precedence, and particular emphasis will be placed on the information provided in the PNEC. For Spain, the data is derived from the Plano Nacional Integrado de Energia y Clima (PNIEC), also published in 2021 (MITECO 2021).

The projections for electricity demand and installed capacities in these scenarios do not incorporate hydrogen considerations. This simplification is deliberate, as a significant portion of the additional installed capacity is expected to be exclusively dedicated to hydrogen production, which would, in turn, generate additional demand.

Additionally, it's worth noting that the analysis of climate change impacts is approached with certain simplifications due to data limitations. To address the inherent uncertainties, the hydro capability index will be varied to represent three historical years, encompassing dry, average, and wet scenarios. Consequently, the distribution profiles for river hydro and dammed hydro will be adjusted to match the respective scenario, introducing a level of sensitivity into the model. However, it's essential to highlight that the remaining distribution profiles remain consistent with the reference year. This approach is justified, as the hydro capability index is the most volatile variable, and the other distribution profiles maintain relative stability across these scenarios.

The costs for the different technologies, fuels and CO_2 emissions can be consulted in 7.1.

5.3.1 Portugal 2030

Portugal has strong motivations to remain at the forefront of the energy transition and aims for a carbon-neutral economy. To achieve this, Portugal has advocated for increased ambition at both national and European levels for the year 2030. These ambitions are focused on reducing greenhouse gas emissions, incorporating renewable energy sources across various sectors, enhancing energy efficiency, and promoting interconnections. These goals include (APA 2023):

1. Achieving a 55% reduction in CO2 emissions compared to 2005, with a more pronounced decarbonization process in electricity production, targeting a 70% reduction and a maximum of 10 Mt CO2 eq for this sector.
2. Ensuring that renewable energy sources make up 49% of the gross final energy consumption by 2030. For the electricity sector, these must represent 85%.
3. Increasing energy efficiency, resulting in a 35% reduction in primary energy consumption.

4. Establishing a target of 15% of total installed capacity for electricity interconnections.

In the 2030 projections, it's important to highlight the substantial growth of wind and solar technologies, which will exhibit the most substantial growth in the coming decade. As anticipated, there's a 23% decrease in the installed capacity of non-renewable sources like natural gas. The expected evolution of installed capacities for 2030 is presented in Table 12. In addition to the increase in pump capacity, the storage capacity was further enhanced with 1 GW of batteries, following PNEC recommendations. The transmission line capacity was assumed to be 4200 MW, considering the projected developments in the grid as outlined by PNEC. The total electricity demand for these projections was set at 65 TWh.

Table 12. Expected evolution of installed capacities for Portugal in 2030

Technology	Installed capacity [MW]
Wind Onshore	6760
Wind Offshore	2000
Solar PV	11000
Biomass	1400
River Hydro	2857
Dammed Hydro	5000
Pumped Storage	3900
Power Plant (Natural Gas)	4200
Batteries	1000

5.3.2 Spain 2030

In alignment with European energy and climate policies, the Spanish Government has made significant efforts in recent years with the development of the Strategic Framework for Energy and Climate. This framework encompasses a range of strategic and legislative components, all aimed at defining the key action points on the journey to climate neutrality and capitalizing on the societal, economic, and environmental opportunities that this transition presents. A key aspect of this framework is the Plano Nacional Integrado de Energia y Clima (PNIEC). It represents a substantial strategic planning exercise and represents the full maturity of Spain's energy and climate planning process. This commitment is firmly rooted in the fight against climate change, with the overarching goal of attaining climate neutrality by 2050. The primary objectives outlined in this framework include (MITECO 2021):

1. A 55% reduction in greenhouse gas emissions compared to 2005, setting a maximum threshold of 50 Mt Co2 eq for the electricity sector.
2. Achieving 48% renewables in final energy use, imposing generating 81% of electricity from renewable sources.
3. Improving energy efficiency by 44%.
4. Establishing 19 GW of own consumption and 22 GW of storage capacity.
5. Establishing a target of 15% of total installed capacity for electricity interconnections.

The expected evolution of installed capacities for 2030 is presented in Table 13. In addition to the increase in pump capacity, the storage capacity was further enhanced with 2.5 GW of batteries, following PNIEC recommendations. The transmission line capacity was assumed to be 12200 MW (excluding the exchange capacity with Morocco), considering the projected developments in the grid as outlined by PNIEC. The total electricity demand for these projections was set at 248 TWh.

Table 13. Expected evolution of installed capacities for Spain in 2030

Technology	Installed capacity [MW]
Wind	50333
Solar PV	46484
Biomass	1408
River Hydro	1994
Oher Renewables	321
Dammed Hydro	17000
Pumped Storage	9524
Nuclear	3181
Waste	341
Power Plant (Natural Gas)	29000
Batteries	2500

5.3.3 Variation of the Hydro Capability Index

To assess the potential impacts of climate change on the future Iberian power system, variations in the hydro capability index (the deviation between the total hydropower produced over the amount produced in an average year) were considered. This was done by extending the analysis beyond the reference year, which had a hydro capability index close to 1, to include simulations for both wet years (with a hydro capability index greater than 1) and dry years (with a hydro capability index lower than 1).

This approach allows us to uncover patterns and gain insights into how the energy system will perform under more extreme conditions, with a particular focus on hydropower generation and pumping. As mentioned earlier, climate change is expected to lead to a significant reduction in annual precipitation, subsequently impacting runoff and hydropower generation. Thus, dry years are likely to become more common in the future. However, it's also important to note that climate change is set to intensify the variability of precipitation throughout the year. This means that dry periods will be extended while wet periods will become more concentrated, leading to heavy rain and potential floods. Therefore, analyzing wet years is equally valuable in understanding the system's response to these changing conditions.

The selection of wet and dry years was based on historical data from the last decade (REN 2021). In addition to the reference year of 2021, 2016 was identified as the wettest year, while 2017 was the driest (see Figure 14). In the simulations for these varying climate scenarios, a series of critical parameters related to hydropower had to be adjusted. This includes modifying the hourly distribution for river hydro and the hourly water supply for dammed hydro reservoirs to align with the specific year being simulated. In contrast, the hourly distributions related to the other variable sources, wind and solar, were kept fixed to simplify. Nonetheless, this decision is reasonable since these sources exhibit remarkable stability in their capability indexes (see Figure 14), and any anticipated climate change impacts are expected to be minimal compared to the significant fluctuations in water resources.

Figure 14. Capability indexes for the different renewable sources (2013-2022) (REN 2021)

5.4 Market Prices Forecast Model

To assess the impacts of climate change on the future Iberian electricity market, the development of a forecast model is essential. Accurate electricity price predictions require detailed information regarding the composition of the technologies within the Iberian power system, as their generation profiles significantly influence the evolution of electricity prices (Bhatia et al. 2021; Fragkioudaki et al. 2015; Leal et al. 2023). Following the creation of technical scenarios for both Portugal and Spain in 2030, the output distributions serve as inputs for the forecast model. It's important to note that the Iberian electricity market operates as a unified entity, and therefore, a global model for the entire region was formulated, mirroring its real-world operation. These forecasted prices will also serve a valuable purpose by enabling the execution of a market simulation for 2030. This market simulation offers a unique perspective, allowing us to understand how patterns could evolve when considering short-term least-cost perspectives, especially given that technology dispatchability doesn't always adhere strictly to technical parameters. However, since the input required by EnergyPLAN is the external market prices, the results of this simulation will be focused on the Portuguese power system.

5.4.1 Machine learning models for forecasting

This chapter encompasses the assessment of the three distinct algorithms for this purpose: a decision tree, gradient boosting, and a basic artificial neural network (ANN).

Decision Tree: A decision tree is a supervised machine learning algorithm that's highly interpretable and suitable for both classification and regression tasks. It works by recursively partitioning the data into subsets based on the most significant features, making it an excellent choice for modelling complex relationships. Decision trees are advantageous for their transparency and ease of understanding (Fragkioudaki et al. 2015).

Gradient Boosting: Gradient boosting is an ensemble machine learning technique used for regression and classification. It operates by combining the predictions of multiple weak learners (usually decision trees) to create a strong predictive model. It sequentially corrects the errors of its predecessors, making it highly accurate and robust. Gradient boosting is particularly adept at capturing intricate patterns in the data (Bhatia et al. 2021). In this context, a Gradient Boosting Regressor model was utilized with 1600 estimators (trees).

Artificial Neural Network (ANN): ANNs are a class of deep learning models inspired by the structure of the human brain. They consist of interconnected layers of artificial neurons that process and transform input data. ANNs are highly flexible and can model complex, nonlinear relationships within the data. They are commonly used for various tasks, including regression. For this case, a multi-layer perceptron regressor (MLP) was utilized, featuring four hidden layers, each comprising 100 neurons. This neural network model belongs to the category of feed-forward neural networks, known for their simplicity and direct flow of information through the network layers (Leal et al. 2023). Training was conducted for a maximum of 1000 iterations, and early stopping was implemented to improve convergence and overall performance during the training process.

5.4.2 Training and Validation Stage

In the training phase of the models, it's essential to provide them with specific data referred to as training data. This dataset includes predictors (inputs) along with corresponding solutions (targets), enabling the models to learn, adapt, and minimize errors during their construction (Bhatia et al. 2021; Fragkioudaki et al. 2015; Leal et al. 2023). For this case, the inputs comprise generation profiles for each technology present in the Iberian power system, imports and exports balance, the combined load profile, and the hydrometeorological variables. The target variable is the market prices. Subsequently, it's imperative to evaluate the models' ability to generalize to new, unseen cases. This evaluation process is known as model validation. To perform model validation effectively, a distinct dataset, composed of predictors/inputs and targets/solutions, is essential. This dataset should contain data that the models have not encountered during training, ensuring a fair assessment of their performance.

To accomplish this, a data-splitting approach was employed. 70% of the available data was allocated for model training, while the remaining 30% was set aside for validation. Additionally, a data shuffling step was applied during training. The purpose of data shuffling is to prevent the models from detecting and memorizing patterns based on the order of the data, thereby enhancing their ability to generalize to new data (Lago et al. 2021).

All input variables were scaled up during preprocessing. Scaling is a critical step for ensuring the accuracy and stability of predictive models, as it helps bring variables to a common scale, facilitating efficient training and robust predictions. It is also essential for boosting the models' sensitivity, convergence, and general forecast accuracy. This procedure holds particular importance for the ANNs since they are more sensitive to feature scaling compared to decision trees and gradient boosting due to their use of activation functions, gradient-based optimization, and the potential for large-scale features to dominate weight updates, which can hinder effective learning (Lago et al. 2021).

Grid search, a widely applied technique in machine learning, was employed to systematically identify the optimal hyperparameters for each model. By exploring a predefined grid of hyperparameter values, this approach automated the process of hyperparameter tuning, ensuring that the models were configured with the most effective set of parameters. This technique eliminated the need for time-consuming manual experimentation, ultimately enhancing the predictive accuracy and overall performance of the models (Lago et al. 2021; Leal et al. 2023).

For this analysis, data spanning the years 2015 to 2020 was utilized, encompassing valuable information regarding electricity generation, demand, import/export balances, and corresponding market prices. The year 2021 was intentionally omitted from consideration. This decision was driven by the exceptional nature of 2021, marked by historically high gas prices due to the conflict between Russia and Ukraine (see Figure 15). Including 2021 data in the training dataset could lead to the models conserving these exceptional price levels and projecting them into future forecasts, which would not accurately represent typical market conditions.

5.4.3 Performance metrics

The performance of the forecasting models was evaluated using two crucial error metrics: Mean Absolute Error (MAE) and Mean Squared Error (MSE) (Shcherbakov et al. 2013). These metrics are instrumental in assessing the accuracy of the model's predictions. MAE quantifies the average absolute difference between the predicted and actual values, providing a straightforward measure of prediction error:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \widehat{y_i}|$$

where n is the number of samples, y_i is the actual value, and $\widehat{y_i}$ is the predicted value.

In contrast, MSE goes a step further by measuring the average squared difference, amplifying the impact of larger errors:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \widehat{y_i}|^2$$

Both MAE and MSE allow us to assess how well the models approximate the actual electricity prices, with lower values signifying more accurate predictions. The results obtained for the Iberian Peninsula data are presented in Table 14

Table 14. Errors quantification for the different models

	MAE [EUR/MWh]	MSE [EUR/MWh]
Decision Tree	2.71	18.45
Artificial Neural Network	2.28	9.01
Gradient Boosting	2.5	10.54

Overall, the ANN model stands out as the most accurate among the three, delivering the lowest MAE and MSE. However, further investigation, fine-tuning, and possibly ensemble approaches might help refine these models to improve their forecasting capabilities.

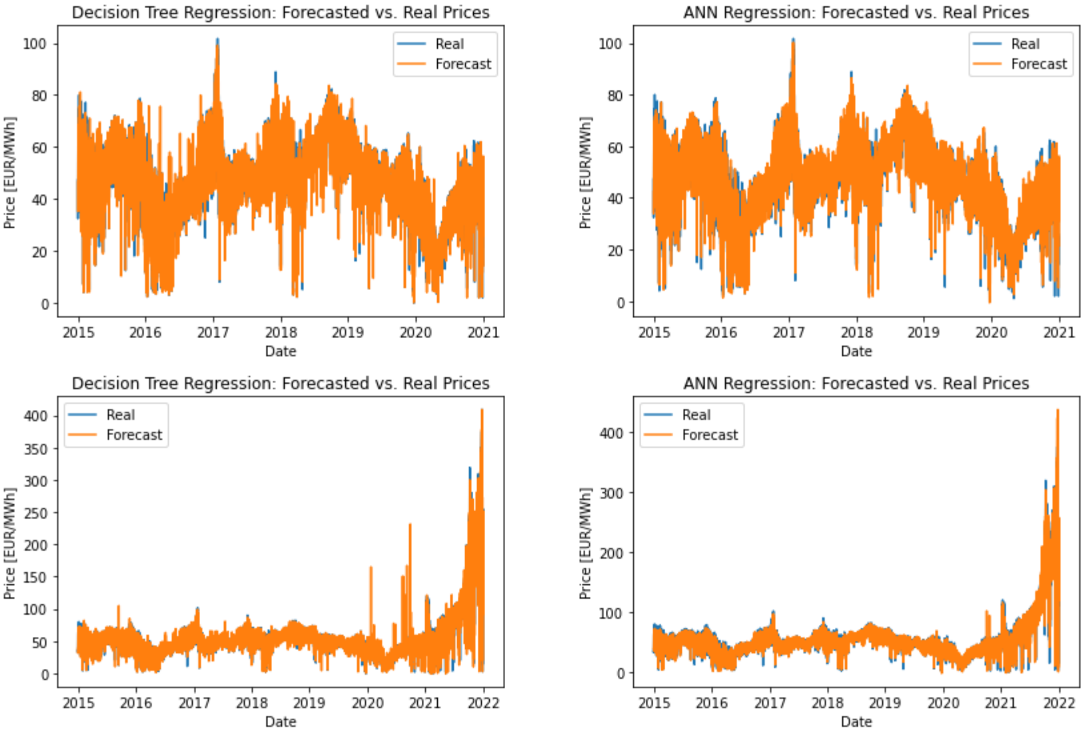


Figure 15. Forecasted vs Real Prices for the different models and the impact of considering 2021

6 Results

6.1 System overview and patterns

Some conclusions can be drawn right after the data acquisition and treatment. Figure 16 left plot presents the historical evolution of market prices from 2015 to 2020, alongside the mean inflow during this period. Notably, it showcases the pronounced influence of inflow on market prices, with periods of high flow rates driving prices down, while drier periods are marked by higher market prices. This underscores the significant impact of hydropower on the Iberian power system. In Figure 16 right plot, we observe the expected alignment between inflow patterns and hydropower generation.

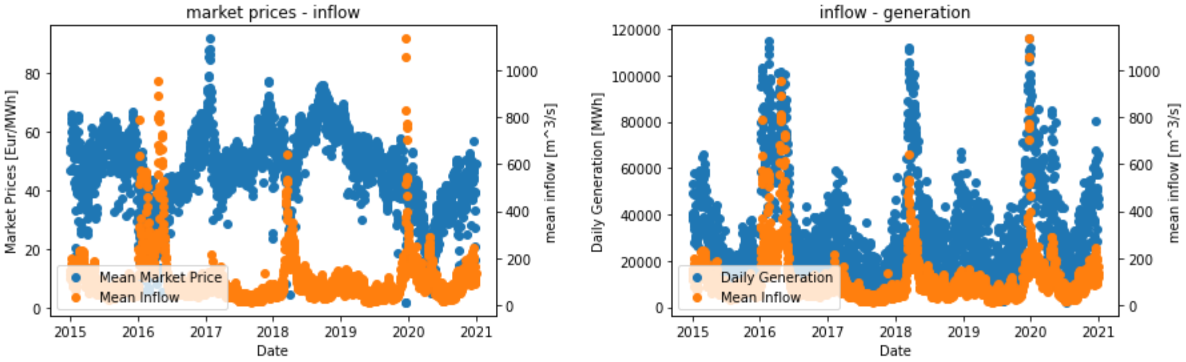


Figure 16. Market prices vs inflow (left plot) and Daily generation vs inflow (right plot)

It's also worth noting the intriguing differences when comparing key variables between a wet year, 2018, and a dry year, 2017, during the month in which the reservoir reached its minimum levels for the timeframe analyzed (December during the dry year). The variations are presented in Figure 17. One of the most notable distinctions lies in the inflow data. In the dry year, 2017, the inflow is significantly smaller and displays more pronounced oscillations compared to the wet year, 2018. This variation has a direct impact on the share of non-dispatchable renewables, as indicated by the blue color in the final plot. In the dry year, there's a marked decrease in the contribution of hydro-run-of-river power compared to the wet year, which is a primary driver for the decrease in non-dispatchable renewables. This change results in a more prominent role for fossil gas in the dry scenario, which also justifies the observed increase in market prices. Additionally, it's interesting to observe that both pump hydro power (light blue) and dammed hydropower (brown) exhibit similarities. The pump hydro power aligns with the peaks in renewables, leading to lower prices, while dammed hydropower acts as a reliable base load, meeting demand during times when renewable generation is lacking. However, it's important to highlight that during the dry year, the role of dammed hydropower as a buffer for fossil gas is significantly hampered by the low inflow. This low inflow is represented by the decreasing reservoir volume stored, which limits the available generation due to technical and resource management constraints.

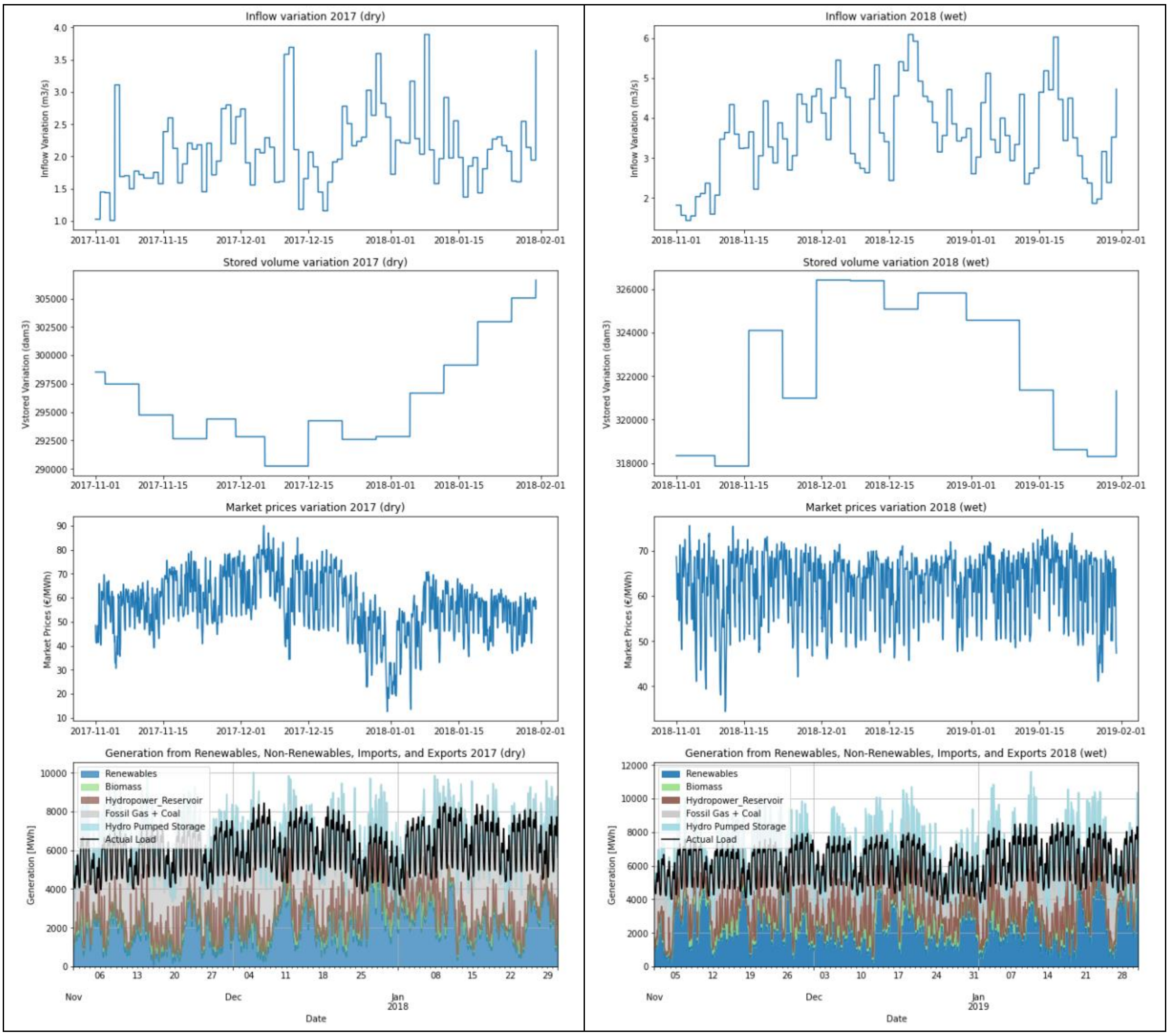


Figure 17. Inflow, stored volume, market prices and generation mix variation during December for 2017 (dry) and 2018 (wet)

The correlation analysis covered the period from 2015 to 2020, excluding 2021 due to unusual market conditions. The results are presented in Table 15 and Table 16. Several key conclusions emerged from this analysis. Days characterized by higher fossil fuel generation and/or increased electricity demand were positively correlated with higher market prices, both at hourly and daily intervals. Renewable energy generation, including solar, wind, and both types of hydropower, displayed daily negative correlations with market prices. This is largely due to the low marginal costs associated with renewable energy sources. As renewable energy generation increased, market prices tended to decrease, as these sources were able to supply electricity to the grid at minimal additional cost. Hydropower with reservoir capacity demonstrated positive hourly correlations. This suggests that it can be employed during peak demand periods when market prices are typically higher. Solar generation demonstrated a positive hourly correlation, reflecting its comparatively lower contribution when compared to other renewable sources. Furthermore, hydro-pumped storage also showed a negative correlation, indicating that water was pumped during periods of lower market prices, effectively harnessing excess renewable energy for later use. Hydrological variables revealed strong negative correlations, aligning with expectations. Increased mean flow rates were closely linked to increased hydro generation, primarily run-of-river, which subsequently contributed to lower market prices. The reservoir volume data indicated that diminishing reservoir levels were associated with higher market prices, suggesting both peak shaving capabilities and a propensity for operating as a base load source. Meteorological variables also exhibited correlations in line with expectations. Higher temperatures had a positive correlation with market prices, likely due to reduced hydropower generation. In contrast, increased mean precipitation had a negative correlation, as it increased hydropower generation and contributed to lower market prices.

In Spain, two significant technologies, waste-to-energy and nuclear, exhibit distinct correlations with electricity market prices. Nuclear power generation demonstrates a negative correlation, indicating that, despite being a non-renewable energy source, its high generation levels tend to have a dampening effect on electricity prices. This phenomenon can be attributed to nuclear power's inherent qualities as a stable and low-cost electricity source, which can help stabilize the grid and mitigate price volatility. Conversely, waste-to-energy generation is positively correlated with market prices in Spain. This is primarily due to the fact that around 75% of the waste utilized in waste-to-energy processes originates from non-renewable sources. While waste-to-energy facilities provide a stable and consistent electricity source, their contribution to Spain's electricity generation is relatively low compared to sources like nuclear. Consequently, during periods of high electricity demand, waste-to-energy often operates in combination with other non-renewable sources to meet the increased demand, potentially leading to higher market prices.

Table 15. Correlations obtained between several variables and market prices for Portugal

2015-2020 PT	**hourly correlation**	**daily correlation**
Biomass	-0,263	-0,297
Hydro Run-of-river	-0,038	-0,237
Solar	0,059	-0,200
Dammed Hydropower	0,161	-0,153
Fossil Gas + Coal	0,667	0,639
Wind	-0,277	-0,274
Load	0,405	0,318
Hydro Pumped Storage	-0,417	-0,271
Mean flow	-0,215	-0,242
Mean stored volume	-0,215	-0,242
Mean temperature	0,093	0,097
Mean precipitation	-0,076	-0,090

Table 16. Correlations obtained between several variables and market prices for Spain

2015-2020 ES	**hourly correlation**	**daily correlation**
Biomass	-0,029	-0,055
Hydro Run-of-river	-0,257	-0,356
Nuclear	-0,032	-0,044
Solar	0,044	-0,201
Waste	0,332	0,370
Dammed Hydropower	0,111	-0,141
Fossil Gas + Coal	0,753	0,761
Wind	-0,352	-0,378
Actual Load	0,493	0,404
Hydro Pumped Storage	-0,563	-0,471
Mean flow	-0,206	-0,234
Mean stored volume	-0,208	-0,234
Mean temperature	0,093	0,098
Mean precipitation	-0,077	-0,092

6.2 Portugal and Spain 2030

6.2.1 Technical output

The technical simulation projections were conducted as the initial phase of this study, primarily to provide essential input data for the Iberian market price forecast model. In these simulations, the outlook for the year 2030 was considered, focusing on three distinct hydro scenarios: wet, dry, and an average year. These scenarios are not only compared to each other but are also contrasted with the reference year of 2021. The choice of the year 2021 as a reference point is significant, given that it represents a time when the hydro capability index closely approximated 1. This makes it an ideal candidate for understanding how the energy system might evolve in response to changing conditions. A null transmission line capacity was assumed since EnergyPLAN prioritizes energy exportation over pumped hydro, which would induce very small pump consumption. For this reason, and due to the extreme penetration of renewables projected for the coming years, the system will be prone to critical excess electricity production (CEEP), which could be converted into exportations, and, conversely, periods of critical imports when renewable sources are insufficient to meet demand. However, this approach provides a valuable framework for assessing the energy self-sufficiency of both Portugal and Spain.

Portugal's energy mix in 2030, presented in Figure 18, is marked by a remarkable increase in the share of renewable energy sources. Almost all forms of renewables have witnessed an expansion in their contributions compared to 2021. Notably, solar photovoltaic (PV) experienced substantial growth, with an increase of at least 25%. This growth is attributed to a significant reinforcement of 10,000 MW in installed capacity, which is 13 times higher than the installed capacity in 2021. As a result, in 2030, solar PV will take the lead in shaping the energy landscape alongside wind power. The growth of wind energy's contribution, although positive, is less significant, at approximately 4% compared to 2021. This growth primarily results from the fact that the installed wind capacity was already substantial in 2021, surpassing other renewable sources, and the significant reinforcement in 2030 will be predominantly in offshore wind. Biomass energy also contributes to renewable energy growth, increasing in proportion to its installed capacity.

The hydro energy sector, however, presents a more complex picture. Run-of-river hydro, significantly influenced by the chosen hydro scenario, has seen a decrease in its contribution. This reduction can primarily be attributed to its installed capacity remaining relatively stable compared to 2021 and its lack of significant storage capacities. These facilities are strongly dependent on the prevailing hydrological regime, resulting in the lowest contribution during dry years and the highest during wet years. In contrast, hydropower equipped with a reservoir exhibits different dynamics. Despite its installed capacity (for electricity generation) remaining unchanged compared to 2021, it benefits from the increased capacity for pump storage. This enhancement of pump storage capacity is especially noticeable in both the average and wet scenarios, leveraging the excess of renewables and increasing the dammed hydro share in the generation mix compared to 2021. In the dry scenario, the impact of a dry hydrological year is more significant for run-of-river than for reservoirs, with a share only slightly smaller than in 2021, highlighting not only the critical role of reservoirs in managing water resources but also the importance of this hybrid relationship between pump and turbine.

Non-renewables, predominantly natural gas, experience a substantial decrease in their share for 2030 (33% under the best scenario - wet). It's worth noting that in the dry scenario, this decrease is notably lower (22.6%). This difference is primarily a response to the decrease in both hydropower types, with a more pronounced impact on run-of-river generation. This situation underscores the significant influence of climatic conditions on the electricity mix, accordingly, influencing the percentages of renewables in electricity generation and the CO_2 emissions as presented in Table 17.

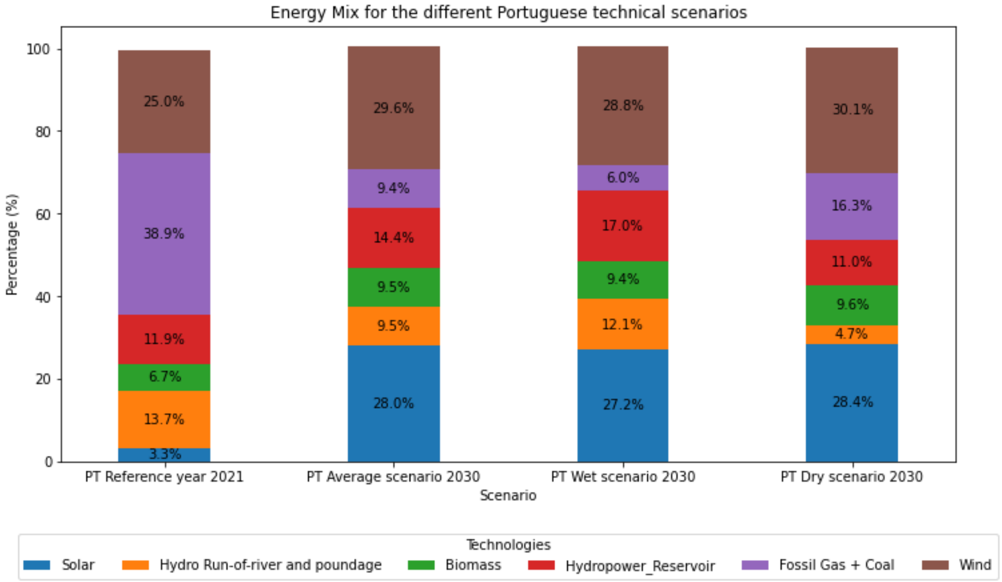


Figure 18. The energy mix for the different Portuguese 2030 technical scenario

Table 17. Percentage of renewables and CO2 emissions for Portugal 2030 scenarios

Scenarios Portugal	% of RES	CO_2 emissions [Mt]
2021	59.5	9.118
Average scenario 2030	88.3	3.174
Wet scenario 2030	92	2.051
Dry scenario 2030	80	5.556

In Figure 19, the variation in hydro-pumped storage consumption and battery charging is depicted. It underscores the important role hydro-pumped storage will play in the future Portuguese electricity system. This technology efficiently harnesses excess electricity generated by intermittent renewables, reducing dependence on non-renewable sources. In comparison to 2021, pump storage usage increased dramatically: by 467% in the average scenario, 632% under the wet scenario, and 421% in the dry scenario. This remarkable increase can be attributed mainly to the substantial growth in renewables, which permits more effective utilization of pump capacities. Additionally, it's noteworthy that while the hydrological regime significantly impacts the share of hydropower generation, the variations in pump consumption between scenarios are comparatively smoother, reflecting the reservoir's capacity to respond to fluctuations in water supply. Battery patterns remain stable across scenarios, with scenarios characterized by higher water supply displaying only modest increases in battery usage.

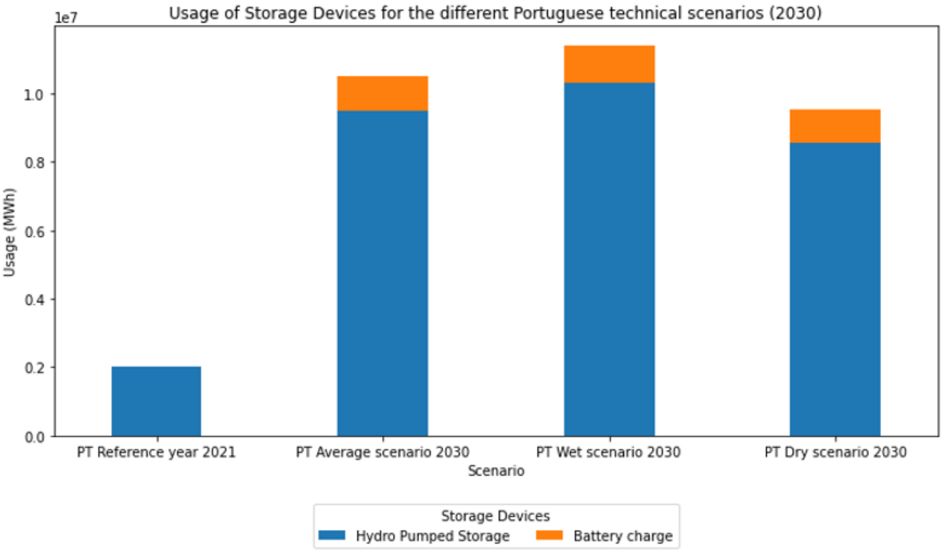


Figure 19. Storage devices consumption for Portuguese 2030 technical scenarios

The critical excess electricity production (CEEP) and the critical imports for each scenario, presented in Table 18, also give valuable information. The variation in excess electricity is mainly driven by the variation in non-dispatchable renewables, which shows variations according to the availability of run-of-river. For these reasons, the wetter scenario shows high losses in excess electricity. Even with critical excess, all the scenarios still resort to natural gas, reflecting that the storage capacity is still insufficient to leverage the full capacity of renewables. Critical imports align with these results, with both the wet and average scenarios presenting residual dependency, suggesting that by 2030 Portugal will be almost able to achieve electricity independence. In contrast, critical imports for the dry scenario are 5 times higher than the other two, reflecting the huge impact that a dry year can have in terms of generation dependency. Nonetheless, the transmission line capacity will be important and will help to reduce the critical excess and provide a response to the imports needed.

Table 18. Critical excess electricity production and critical imports for Portuguese 2030 technical scenarios

Scenarios Portugal	CEEP [TWh]	Critical imports [TWh]
Average scenario 2030	1.46	0.05
Wet scenario 2030	2.24	0.05
Dry scenario 2030	1.36	0.26

Spain's energy mix for 2030, presented in Figure 20, closely mirrors the results observed for Portugal. Notably, there is a substantial increase in renewables, particularly in solar and wind energy, driven by significant investments in these sources. However, an interesting distinction emerges regarding hydropower. Hydropower equipped with a reservoir increases its share in all scenarios. This indicates that the combination of pump capacity and increased renewable capacity allows for a proportionally higher use of turbines than in the reference scenario of 2021, even in the dry year scenario. Additionally, hydro run-of-river experiences a reduction in its share across all scenarios, as further developments in terms of installed capacity are not expected for these facilities. Their contribution in 2021 was already minimal, accounting for only 3.5% of the overall generation mix compared to 14% in Portugal. Nonetheless, its behaviour between scenarios mirrors that of Portugal.

Both nuclear and waste generation experience a decline in their shares within the electricity mix due to reduced installed capacity. As they are modelled as base load sources, they show no significant variations between scenarios. Fossil gas (labelled as Fossil gas and coal in the figure, although coal will be phased out by 2030), which played a significant role in 2021, experiences a substantial reduction, aligning with the primary goal of decarbonizing the electricity sector. Notably, in the dry scenario, this reduction is less pronounced, although not as much as in the Portuguese scenario due to the residual contribution of run-of-river hydro. Consequently, the differences between scenarios in terms of renewable energy percentages in electricity generation and CO2 emissions, while significant, are comparatively smaller (see Table 19).

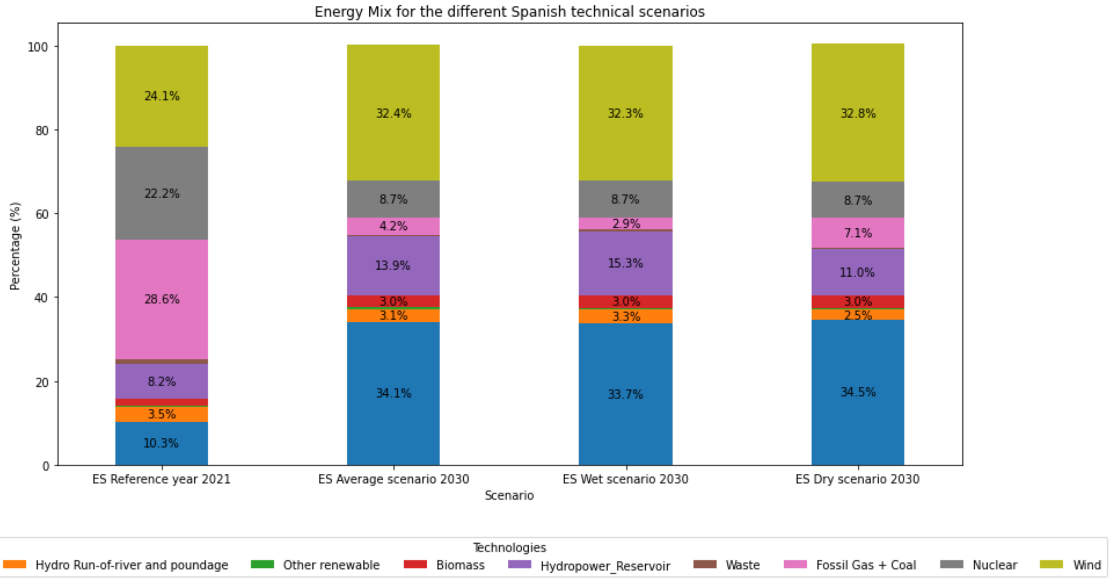


Figure 20. Energy mix for the different Spanish 2030 technical scenario

Table 19. Percentage of renewables and CO2 emissions for Spain 2030 technical scenarios

Scenarios Spain	% of RES	CO_2 emissions [Mt]
2021	49.1	30.906
Average scenario 2030	85.5	4.931
Wet scenario 2030	86.8	3.386
Dry scenario 2030	82.4	8.312

Figure 21 illustrates the variation in hydro-pumped storage consumption and battery charging for Spain. In contrast to Portugal, pump storage consumption remains nearly identical across scenarios. This highlights that the primary driver for differences in pump consumption is run-of-river generation, which constitutes a minor portion of Spain's energy mix compared to Portugal's. Batteries come into play in the dry scenario and are marginally needed in the average scenario. Energy Plan, by default, assumes that batteries start the year at full capacity. To charge the battery, it must first be discharged. Consequently, the drier the year, the more likely the battery is to be discharged and subsequently recharged.

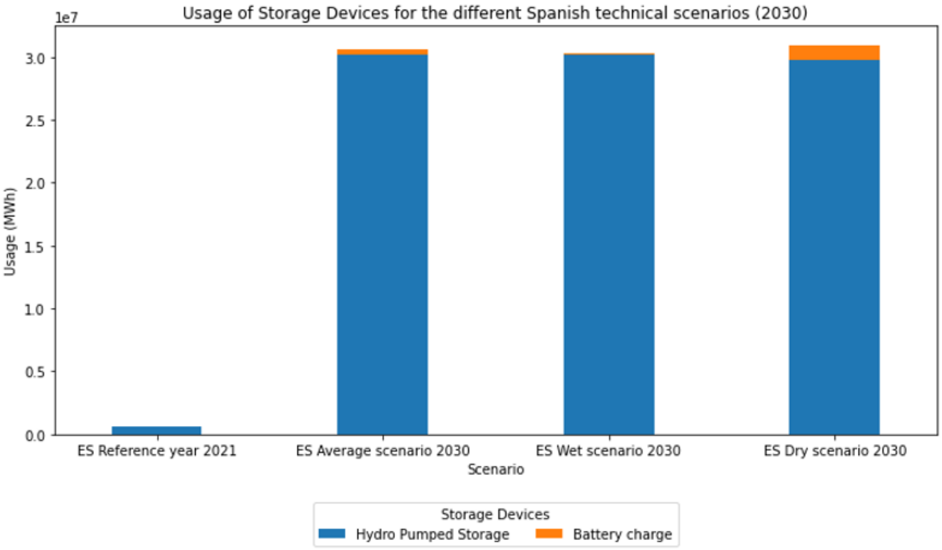


Figure 21. Storage devices consumption for Spanish 2030 technical scenarios

Regarding the critical excess electricity production (CEEP) and critical imports, the conclusions we can draw are very similar to the ones for Portugal. Critical excess is higher for the wet scenario and smaller for the dry scenario, as expected, due to the reduction in water inflow and consequently a reduction in run-of-river (non-dispatchable renewable). Nonetheless, the variations between scenarios are smaller in proportion. This has to do with what was already mentioned regarding the share of run-of-river being residual to the Spanish generation mix compared to a higher share in Portugal. For all the scenarios, there's no need to import, meaning that the installed capacity projected for the future Spanish system will, in principle, guarantee full electricity independence for the country.

Table 20. Critical excess electricity production and critical imports for Spanish 2030 technical scenarios

Scenarios Spain	CEEP [TWh]	Critical imports [TWh]
Average scenario 2030	29.7	0
Wet scenario 2030	31.12	0
Dry scenario 2030	27.78	0

6.2.2 Iberian Market Prices 2030

After running the technical simulation models on EnergyPlan for 2030, the hourly distributions were utilized as input for a forecast model trained and tested with hourly data. During this phase, two noteworthy limitations emerged. Firstly, the artificial neural network (ANN) model, despite initially demonstrating promising results in both training and testing phases, displayed significant signs of overfitting. The overfitting issue indicated that the model had excessively tailored itself to the training data, making it less capable of generalizing to unseen data. Addressing this challenge would require extensive and time-consuming parameter tuning and regularization. As a result, an alternative approach was considered, where gradient boosting, known for its robustness against overfitting, was explored as a potentially more efficient and effective modelling technique for the given context.

Secondly, a significant limitation arose in the forecast model when it was initially run on an hourly basis. The market prices displayed an unexpected behaviour, with price peaks occurring during periods of high renewable energy generation and vice versa. This counterintuitive pattern was primarily influenced by hydropower facilities with reservoirs. These facilities demonstrate a positive hourly correlation with market prices, often used for peak shaving. However, this positive correlation led the model to assume that hydropower generation increased costs, which did not align with reality, given that renewables have a marginal cost of zero. To rectify this issue, the forecast model was adjusted to operate on a daily basis by resampling the inputs to align with a daily timeline. On a daily basis, this correlation became negative, reflecting the real conditions more accurately, as the hourly timestep is not sufficient to adequately capture the reduction in prices due to dammed hydropower.

The results for the distinct scenarios are presented in Figure 22.

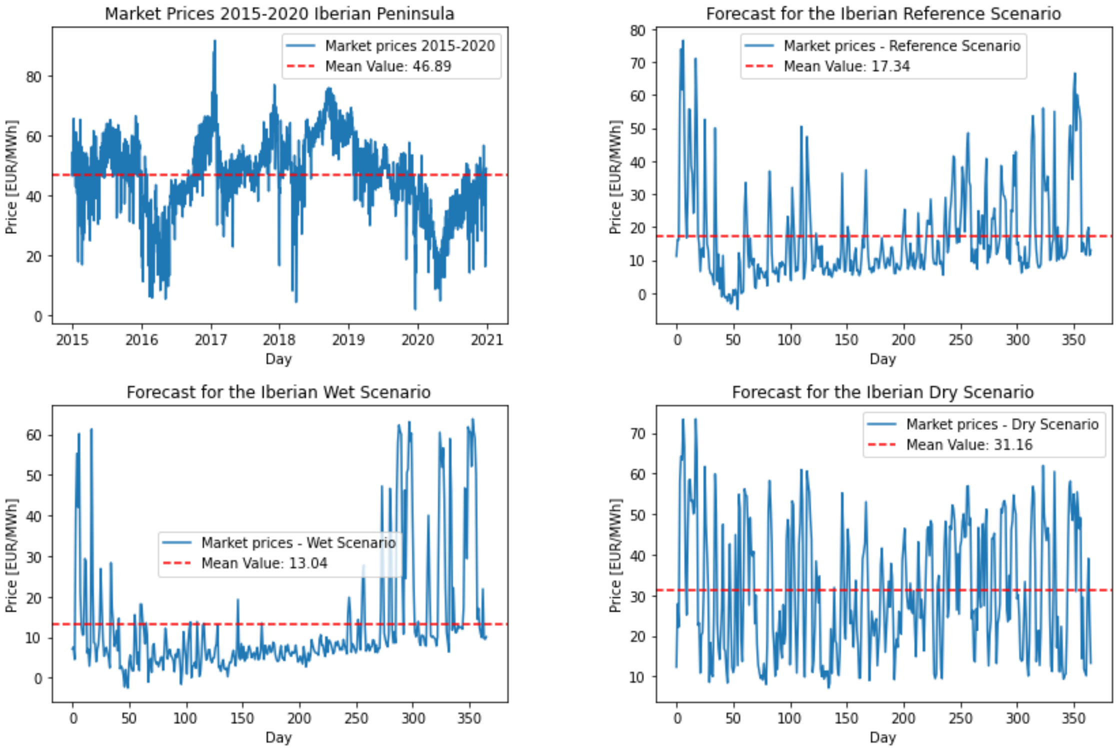


Figure 22. Market prices evolution up to 2020 (top-left plot) vs 2030 Market prices forecast for the different Iberian scenarios

The average forecasted market prices reveal substantial decreases when compared to the testing/training period (2015-2020), primarily driven by the increased installed capacity and share of renewable energy sources in the electricity generation mix. As expected, these reductions are more significant for both the average scenario (66% decrease) and the wet scenario (76% decrease). In contrast, the dry scenario experienced a more modest decrease of 48%. These values are directly linked to the percentage of available water resources, which are considerably more abundant in the wetter scenarios. The dry year stands out due to a reduced penetration of renewable energy, particularly during the summer months. This period is characterized by substantial fluctuations in market prices, resembling the availability of solar energy. Prices tend to decline during the day when solar generation is abundant, but they surge during the night when non-renewable sources are required to meet the demand (wind is also weaker during summer). In both the wet and reference scenarios, hydropower plays an essential role in peak shaving during these months, effectively stabilizing prices at lower levels. The beginning and end of the year are marked by extreme fluctuations in market prices for all three scenarios. These months match with the highest load requirements that cannot be fully met by the available renewable capacity. It's also noteworthy that the increasing penetration of renewable sources results in electricity prices closely replicating the patterns of renewable generation, indicating a more linear relationship compared to the present conditions (see Figure 23).

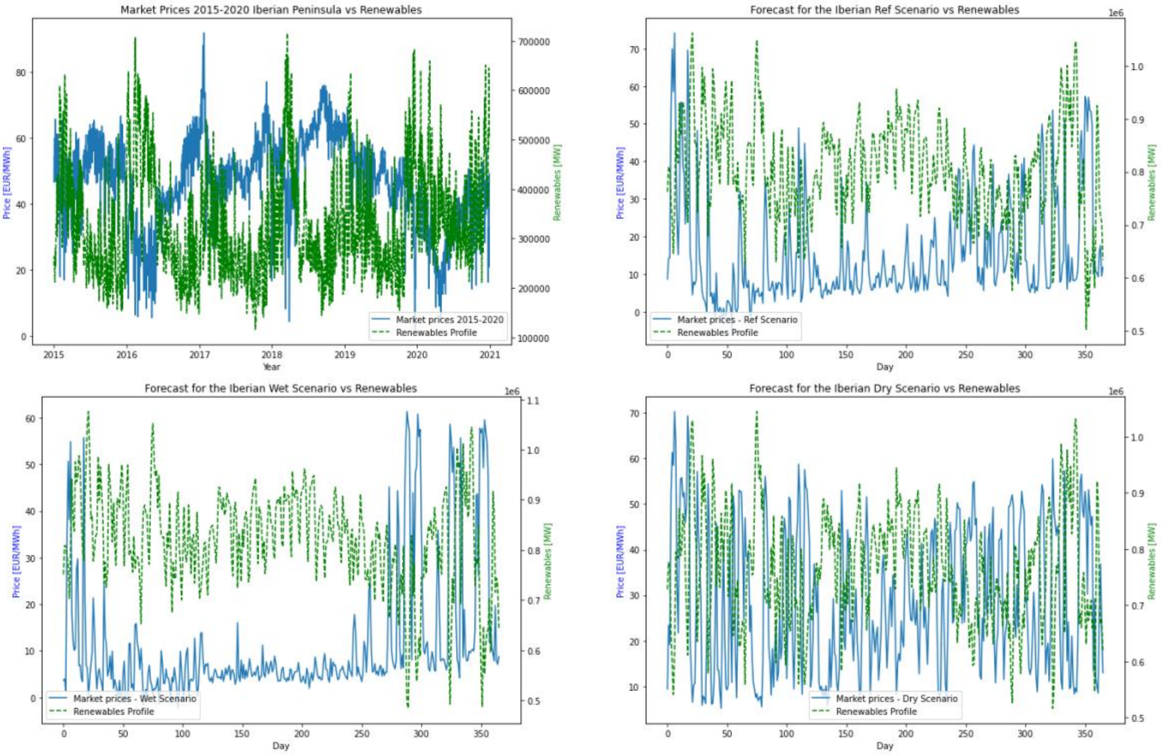


Figure 23. Iberian Market prices vs Renewables. Before and after

6.2.3 Economical simulation

The forecast of the Iberian model prices provided valuable input for conducting simulations using the market simulation approach. This allowed a deep understanding of how the Portuguese market would respond to external influences, particularly an external market characterized by high penetration of renewables and significantly lower average prices throughout the year. This strategy, driven by decisions based on short-term least-cost solutions, is notably influenced by market dynamics. Nonetheless, it provides valuable insides about how economic considerations, particularly cost optimization, are likely to reshape energy generation patterns. Furthermore, it highlights the competitiveness of each technology in relation to marginal costs. This simulation is essential for assessing the changes in import and export balances, which had to be neglected in the technical simulation due to the limitations of the EnergyPLAN model, as previously discussed. Nevertheless, for this type of simulation, certain assumptions made during the reference year, specifically those regarding pump installed capacity (operating at the 80th percentile of capacity), have been retained in proportion to the new installed capacity projected for 2030. It's worth noting that this analysis will be limited to Portugal, as the external market dynamics in Spain would also be influenced by neighbouring countries, such as France, for which relevant data was not accessible.

The distribution of each technology's share in the different scenarios is depicted in Figure 24. This distribution closely reflects the one obtained for the technical scenario, with two key deviations related to dispatchable sources. Hydropower reservoirs transfer a significant portion of their share to imports.

This shift can be attributed to the lower market prices resulting from increased renewable energy penetration. Consequently, it becomes more cost-effective to import electricity than to generate it from reservoirs. Recognizing this, the model employs turbine generation only when transmission lines operate at full capacity. In the dry scenario, hydropower reservoir share increases to compensate for the decrease in run-of-river (non-dispatchable) generation. The same happens for Fossil Gas, which in this case is exclusively utilized when both the transmission line capacity and hydropower generation are unable to meet the load requirements.

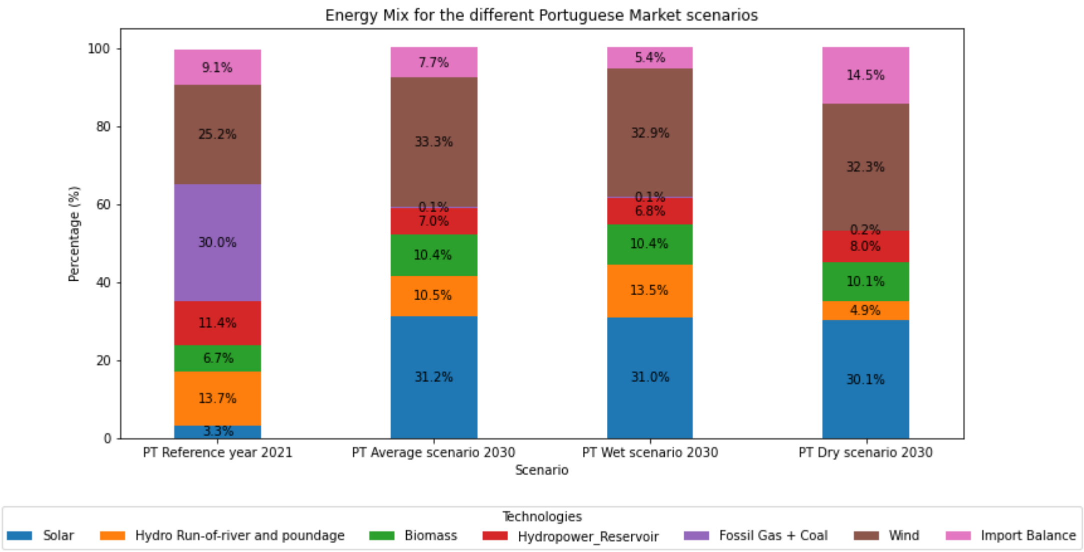


Figure 24. Energy mix for the different Portuguese 2030 economic scenarios

Table 21. Percentage of renewables and CO2 emissions for Portugal 2030 economic scenarios

Market Scenarios Portugal	% of RES	CO_2 emissions [Mt]
2021	59.4	9.131
Average scenario 2030	91.8	2.380
Wet scenario 2030	94.1	1.688
Dry scenario 2030	84	4.668

Another intriguing aspect to consider is the utilization of storage devices in each scenario. One notable observation is the substantial increase in pump consumption within the dry scenario. This trend becomes more understandable when we delve into the evolution of reservoir storage throughout the year and compare it with the external market prices.

At the start of the year, there are two initial market peaks closely tied to spikes in demand, a common pattern across all market price scenarios (see Figure 22). Both the average and wet scenarios can readily respond to this surge by relying on the reservoirs (see Figure 26). This response is smoother for the wet scenario, where the reservoirs discharge less due to the higher percentage of river hydro and water supply. Subsequently, in both scenarios, there's the ability to charge the reservoirs up to their maximum capacity, effectively anticipating the market peaks that will occur at the end of the year when it becomes more cost-efficient to rely on the reservoirs for peak shaving instead of resorting to natural gas. This transition occurs notably quickly due to the abundance of renewables, especially water supply, typically after the 50th day (see Figure 22). In contrast, the dry scenario paints a different picture. During the drier months, there's a shortage of hydropower, primarily run-of-river, leading to a decrease in the percentage of available renewables and resulting in higher market prices. Consequently, the interplay between turbine generation (for peak shaving) and pump consumption (to effectively regulate the storage capacity so the reservoir can respond to end-of-year market price surges) becomes more cyclical. This delays the attainment of the maximum storage capacity and leads to increased turbine generation and pump consumption.

Overall, the values of pump storage consumption are notably lower than those observed in the technical scenario, where the maximum market scenario (dry) reached 5 TWh, while the maximum technical scenario (wet) achieved 10 TWh. This variance can be attributed to the inclusion of imports and exports in the market simulation. In the technical scenario, with null transmission capacity, all excess was directed towards pumping, and any deficit (critical imports) was managed through reservoir generation. The usage of batteries remains consistent across all scenarios, suggesting that the storage capacity of batteries is limited due to the continued presence of critical excess electricity production (CEEP).

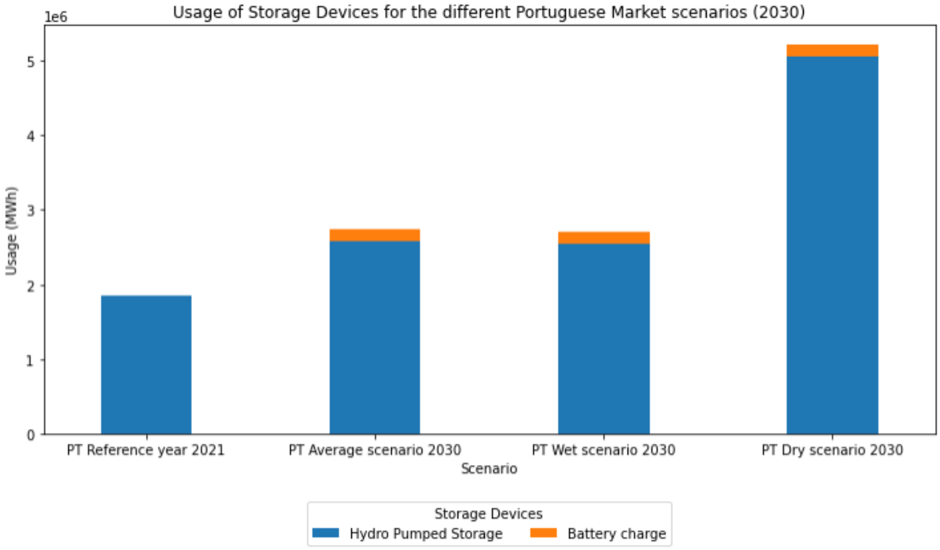
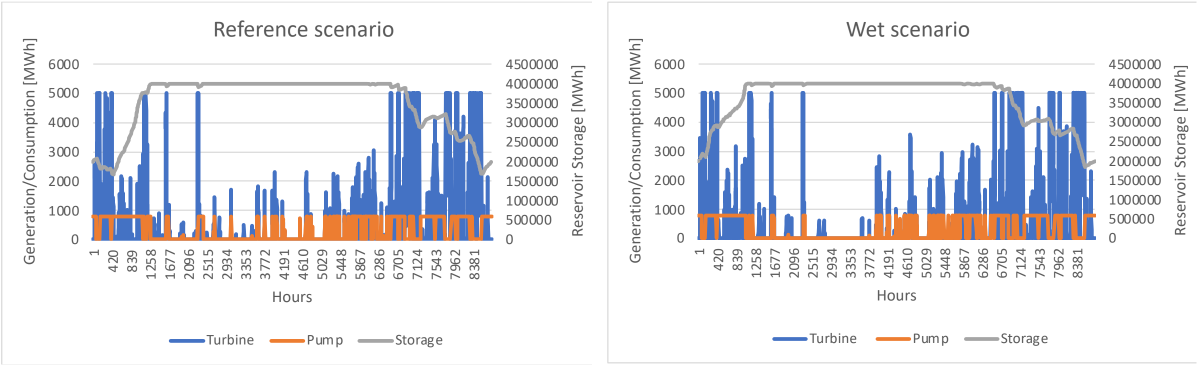


Figure 25. Storage devices consumption for Portuguese 2030 economic scenarios



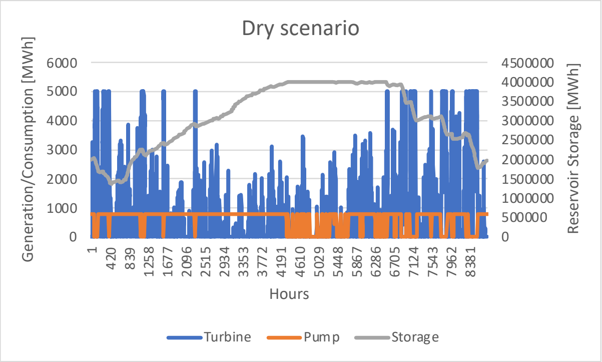


Figure 26. Reservoir Storage variation for each economic scenario

The imports and exports balance aligns with the previously discussed insights. Notably, in the dry scenario, there is a higher dependence on external imports. The lower penetration of renewables in this scenario results in less excess renewable generation, directly impacting the export dynamics. Conversely, for the wet and average scenarios, the values exhibit some similarity, with the wet scenario being residually less dependent on imports and with a higher level of exports due to the increased inflow of renewables. It's worth emphasizing that the model is designed to optimize overall profits. This implies a strategic control of dispatchable sources to maximize profit. From an economic standpoint, the model often prefers to import during hours with low market prices, even when it has water available in the reservoir and generates excess electricity to be sold during hours with higher market prices. The results are presented in Figure 27.

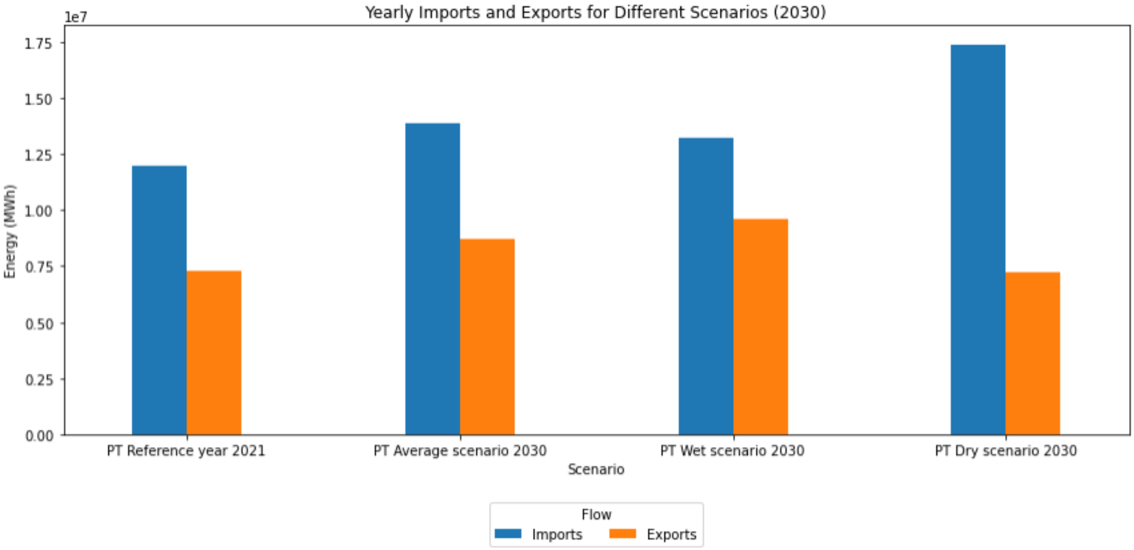


Figure 27. Yearly Imports and Exports for the different economic scenarios

Some conclusions can be drawn from the critical excess electricity production (CEEP) and the imports and exports balance. Regarding the CEEP, when compared with the technical simulation, and since this market simulation already considers the transmission line capacity, if it still results in CEEP, we can conclude that not only the storage capacity but also the transmission lines will be insufficient to respond to excess electricity. The imports are greater than the exports for all scenarios, reflecting that it is generally more cost-effective to import. This aligns with the expectations for a future marked by a significant increase in renewables, which will decrease Iberian market prices when both Portugal and Spain have excess renewable energy. Given Spain's significantly higher installed capacity of renewables and its primary role in driving down market prices, Portugal can capitalize on these conditions, making it likely that imports will increase.

Table 22. CEEP and Exchange balance for the different economic scenarios

Market Scenarios Portugal	CEEP [TWh]	Imports [TWh]	Exports [TWh]	∆ Imp/Exp
Average scenario 2030	0.82	13.89	8.71	5.18
Wet scenario 2030	1.22	13.26	9.59	3.67
Dry scenario 2030	0.65	17.40	7.22	10.18

6.2.4 Verification of values against the objectives of the PNIEC+PNEC

A comprehensive assessment of the obtained values is essential to ensure that the Iberian Peninsula is progressing toward a sustainable and environmentally responsible future. It is imperative to verify how these results align with the energy and climate objectives outlined in the national plans of both countries, ensuring that the region's evolution is in harmony with these sustainable development goals. In comparison to the targets established in the energy and climate plans, all the scenarios exhibit substantially lower levels of CO2 emissions. Portugal, with a target of 10 Mton, consistently falls below this threshold across all scenarios. Similarly, Spain, aiming for 50 Mton, successfully maintains emissions at lower levels in all technical scenarios. For Portugal, a key objective is to achieve a renewable energy share of 85% in the electricity generation mix. This target is met in all scenarios except the dry one, where the market simulation nearly reaches the goal with an 84% renewable share. The incorporation of transmission line capacity in the market simulation significantly reduces natural gas consumption, bringing Portugal closer to its renewable energy target for the dry year. In the case of Spain, the target is set at 81% renewable energy in the electricity generation mix. This benchmark is attained in all the technical scenarios evaluated.

Cost implications are particularly evident during dry years, where costs tend to escalate, sometimes surpassing those of the reference year, especially in Portugal. This increase is largely attributable to the higher costs associated with CO2 emissions. However, the market simulation, incorporating exchange capacity, stabilizes these cost fluctuations and keeps expenses in check. It efficiently leverages renewable energy sources and market dynamics to mitigate cost spikes. In contrast, the results for Spain are notably more stable than those for Portugal in the technical simulation. This stability suggests that Spain is better positioned to withstand the impacts of climate change, primarily due to the minimal contribution of non-dispatchable hydropower in Spain. Nevertheless, price fluctuations in response to water resource scarcity are also apparent.

Table 23. Total Costs for 2030 Portuguese Scenarios

Scenarios Portugal	Total Costs (M€)
Reference Technical Scenario	8774
Average Technical Scenario 2030	8168
Wet Technical Scenario 2030	7879
Dry Technical Scenario 2030	8794
Reference Market Scenario	8822
Average Market Scenario 2030	5639
Wet Market Scenario 2030	5569
Dry Market Scenario 2030	5707

Table 24. Total Costs for 2030 Spanish Scenarios

Scenarios Spain	Total Costs (M€)
Reference Technical Scenario	27872
Average Technical Scenario 2030	21793
Wet Technical Scenario 2030	21422
Dry Technical Scenario 2030	22698

6.3 Analyzing Climate Change Impacts on Hydropower Generation and Pumping Patterns in Portugal and Spain

Given the primary focus of this thesis on understanding the impacts of climate change on hydropower, it is intriguing to examine how the analysis has influenced both generation and pumping patterns. In the case of run-of-river generation, as previously discussed, its non-dispatchable nature and the absence of significant developments in the coming years imply that variations will primarily align with hydrological regimes. Consequently, further analysis in this regard is out of scope. Conversely, for hydropower facilities equipped with reservoirs, the situation is different. These facilities, characterized by their dispatchable sources and the symbiotic relationship between pumping and generation, are expected to exhibit substantial variations compared to historical data. This is particularly relevant in the context of a future marked by higher renewable energy penetration and the effects of climate change. It's important to note that the following values are presented for Portugal, but similar conclusions can be drawn for Spain. Detailed plots for Spain can be found in the appendices for reference.

6.3.1 Historically hydropower consumption and generation patterns

Historically, a noteworthy disparity exists between hydropower generation and pumping as depicted in Figure 28. This contrast arises not only from variations in installed capacity but primarily because pump storage is typically employed during periods of renewable energy excess, which, until now, has not been substantial enough to fully harness the technology's complete capacity. Regarding the yearly distribution, it's common to observe that wet months are linked to increased values for both pumping and generation. However, it's crucial to note that the magnitude of these values is significantly shaped by the availability of runoff, as anticipated (see Figure 29).

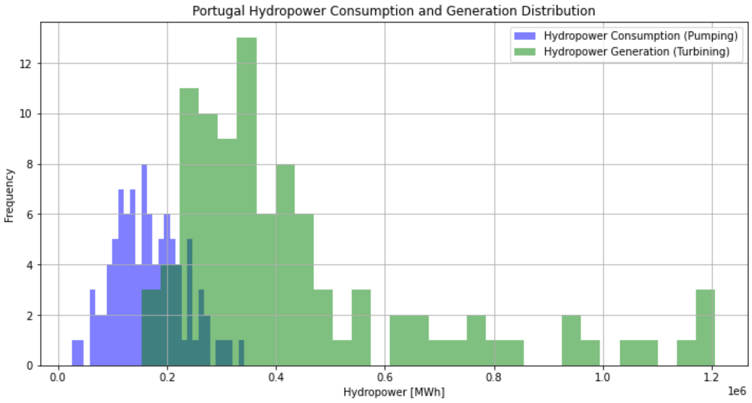


Figure 28. Monthly hydropower consumption and generation distribution for the period 2015-2022

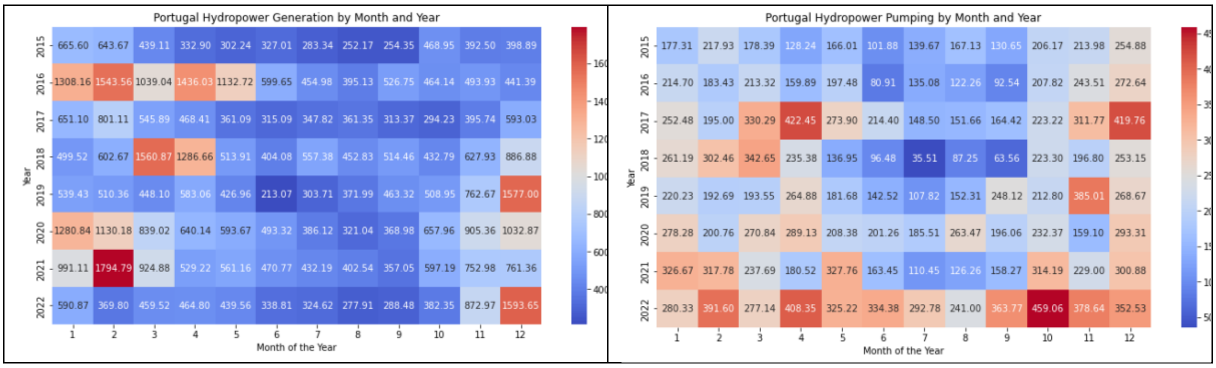


Figure 29. Monthly distribution for hydropower generation [MWh] and pump consumption [MWh]. Average year (2015-2022)

A noteworthy observation arises when examining the distribution of these variables across each hour for every day of the week, spanning the period from 2015 to 2023 (representative of an average week throughout the year). A notable shift is evident in the patterns of hydropower generation and pumping when comparing 2018 (reflective of the period between 2015 and 2020) with 2021 and 2022 (see Figure 30, Figure 31 and Figure 32). Before 2020, generation was predominantly concentrated during the daytime when market prices were elevated due to increased demand. Conversely, pump consumption was primarily concentrated during nighttime hours when, for contrasting reasons, market prices were lower, primarily owing to an excess of renewables, particularly wind generation. However, post-2020, a distinct shift in these patterns becomes evident. The generation now occurs extensively during the night, while pump consumption has shifted to the daytime. This transformation is primarily attributable to the substantial increase in installed solar PV capacity, with the 2022 installed capacity nearly three times larger than that of 2020, with 2021 marking the transitional year. The substantial growth in solar capacity, which achieves its maximum capacity factor during daylight hours, has contributed to a decrease in daytime electricity prices compared to nighttime, reflecting the higher proportion of excess renewable generation during the day. This shift in hydropower operations is a direct outcome of these evolving dynamics.

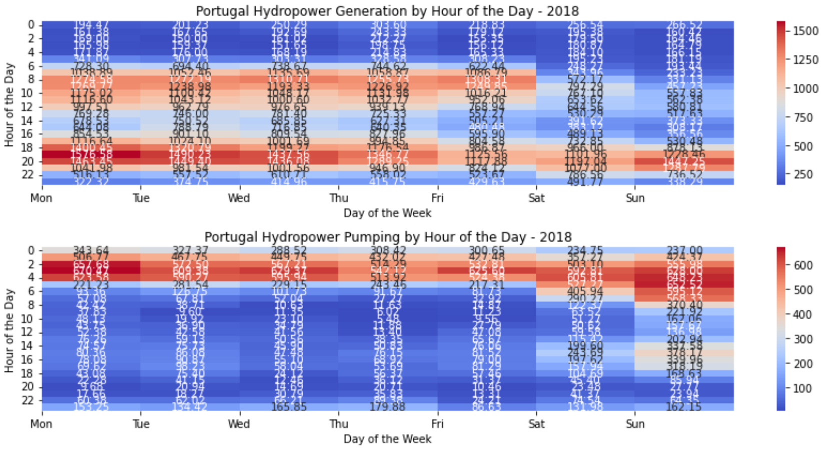


Figure 30. Portugal Hydropower generation [MWh] vs Pump consumption [MWh] in 2018 (Average week)

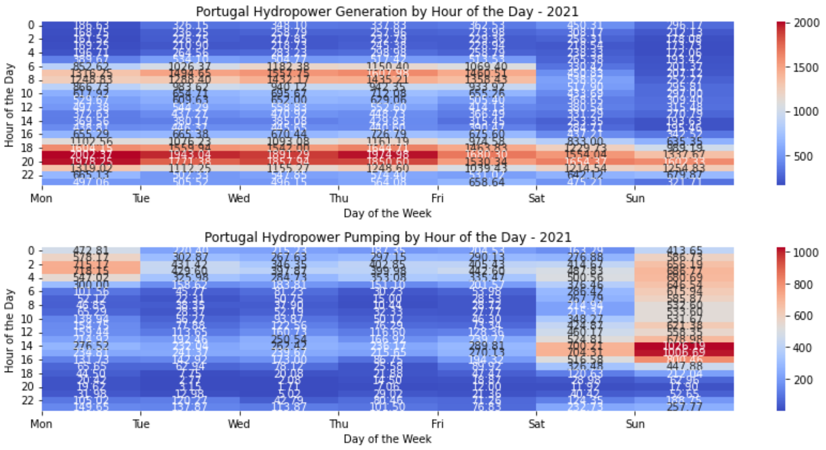


Figure 31. Portugal Hydropower generation [MWh] vs Pump consumption [MWh] in 2021 (Average week)

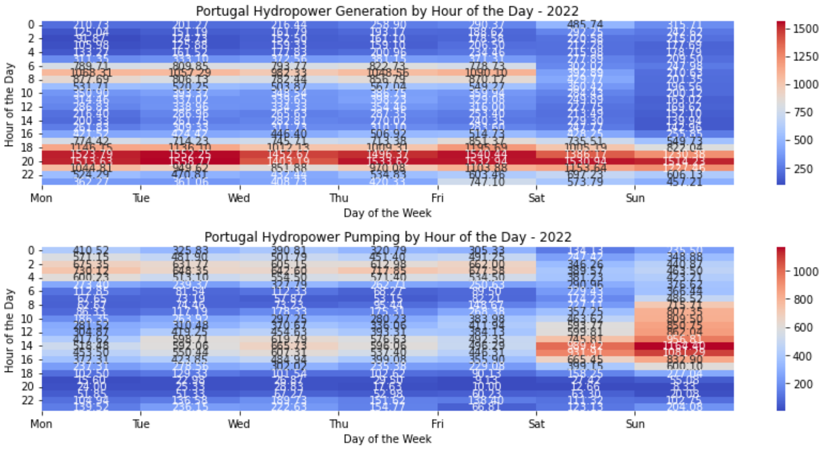


Figure 32. Portugal Hydropower generation [MWh] vs Pump consumption [MWh] in 2022 (Average week)

6.3.2 Hydropower consumption and generation patterns for 2030

The same analysis was conducted for the results obtained in technical and economic simulations for 2030.

6.3.2.1 Technical

Technical results exhibit the same trend, with pump consumption predominantly occurring during the day and turbine generation predominantly at night to reduce reliance on non-renewable sources (see Figure 33). These results align with the previously presented conclusions, with the wet scenario displaying the highest magnitude for both variables due to the abundant water resources available. It's important to emphasize that the primary objective of this simulation is to minimize the use of non-renewable sources. Additionally, it's worth noting that the disparity in generation between scenarios is more pronounced than that of pump consumption. This underscores the vital role of pumping during dry years in minimizing the reliance on natural gas generation. Pumping serves as an essential tool for achieving more consistent generation patterns, as is evident from the color-map, highlighting the symbiotic relationship between pump and turbine.

The results for Spain follow a similar pattern, on a larger scale (plots displayed in 7.2). However, two notable differences emerge. First, the turbine generation in Spain exhibits two distinct peaks, one in the early morning and another at the end of the day. This is primarily because demand increases earlier in Spain than in Portugal, during hours when solar generation remains low. Second, the order of magnitude for pump consumption is relatively consistent across all scenarios. This can be attributed to the lower proportion of run-of-river hydro in Spain.

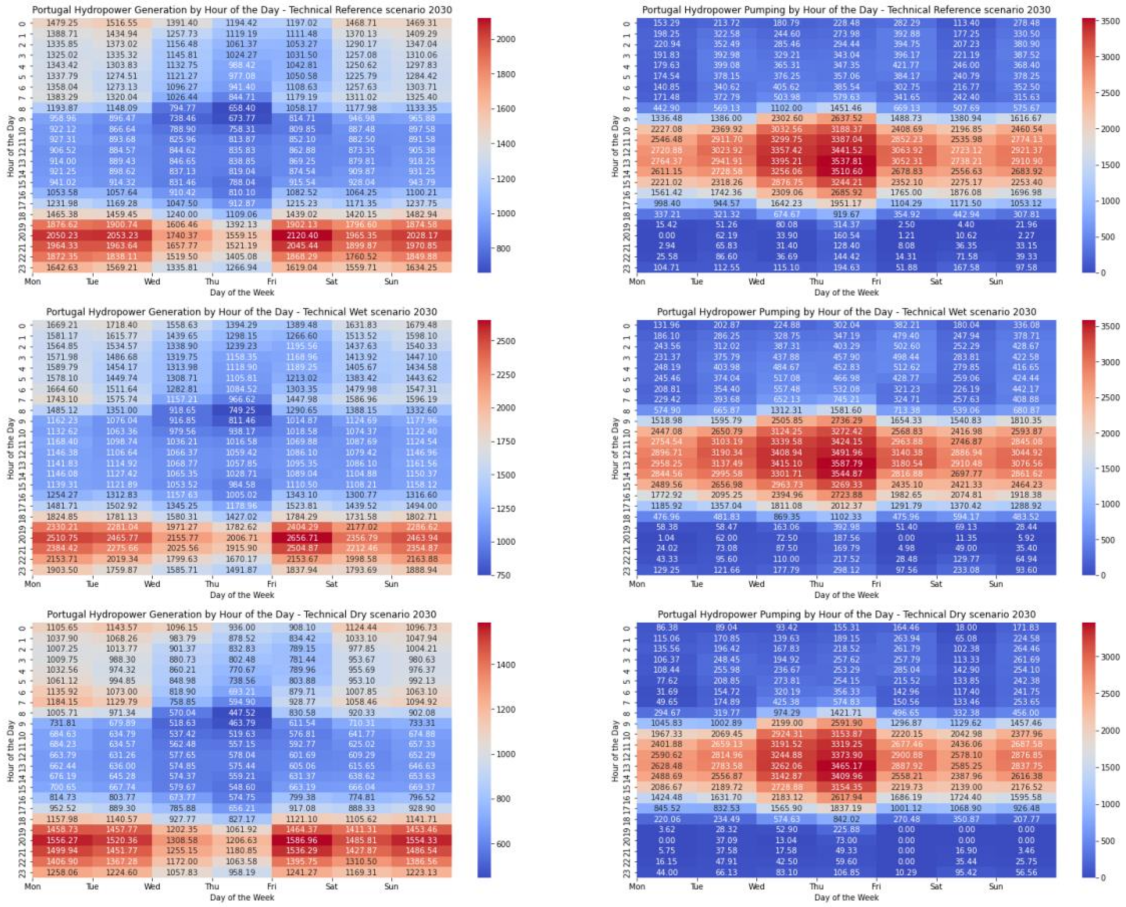
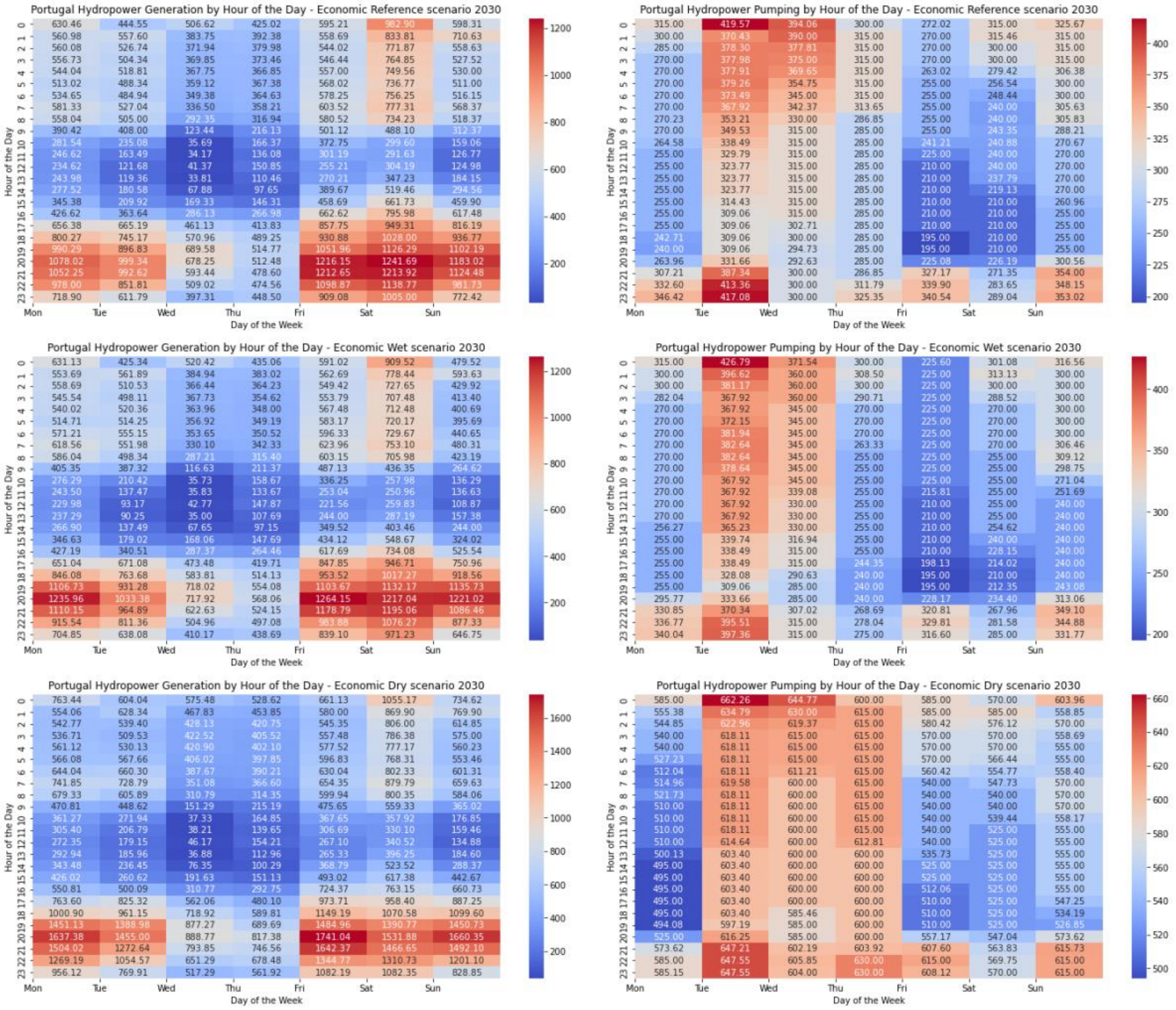


Figure 33. Portugal Hydropower generation [MWh] vs Pump consumption [MWh] for the different 2030 technical scenarios

6.3.2.2 Economic

Economic results align with the conclusions outlined in section 5.2.3.2. The results also exhibit the same patterns as those identified in the technical simulation, with the limitation on the order of magnitude of pump capacity to prevent the simulation tool from excessively increasing pump consumption in an effort to maximize profits. Generation is notably higher during the night in all scenarios, with a residual increase observed in the dry scenario to compensate for the reduction in run-of-river generation. In contrast, the usage of pump capacity is more dispersed, and fewer definitive conclusions can be drawn as the model initiates pumping whenever electricity prices are low. Nonetheless, it can be concluded that from a cost perspective, pump storage will be notably required in the future. In contrast to the technical simulation, the market simulation presents a more stable pump consumption profile throughout the day, where pumping primarily occurs when market prices are low. This pattern is largely influenced by market variations and exhibits more year-round fluctuations as opposed to a daily cycle. It underscores the occasional and strategic nature of importing energy for pump storage, reflecting real-world situations when such a practice is both economically and strategically advantageous.



Portugal Hydropower Generation by Hour of the Day - Economic Reference scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	630.46	444.55	506.62	425.02	595.21	982.90	598.31
1	560.98	557.60	383.75	392.38	558.69	833.81	710.63
2	560.08	526.74	371.94	379.98	544.02	771.87	558.63
3	556.73	504.34	369.85	373.46	546.44	764.85	527.52
4	544.04	518.81	367.75	366.85	557.00	749.56	530.00
5	513.02	488.34	359.12	367.38	568.02	736.77	511.00
6	534.65	484.94	349.38	364.63	578.25	756.25	516.15
7	581.33	527.04	336.50	358.21	603.52	777.31	568.37
8	558.04	505.00	292.35	316.94	580.52	734.23	518.37
9	390.42	408.00	123.44	216.13	501.12	488.10	312.37
10	281.54	235.08	35.69	166.37	372.75	299.60	159.06
11	246.62	163.49	34.17	136.08	301.19	291.63	126.77
12	234.62	121.68	41.37	150.85	255.21	304.19	124.98
13	243.98	119.36	33.81	110.46	270.21	347.23	184.15
14	277.52	180.58	67.88	97.65	389.67	519.46	294.56
15	345.38	209.92	169.33	146.31	458.69	661.73	459.90
16	426.62	363.64	286.13	266.98	662.62	795.98	617.48
17	656.38	665.19	461.13	413.83	857.75	949.31	816.19
18	800.27	745.17	570.96	489.25	930.88	1028.00	936.77
19	990.29	896.83	689.58	514.77	1051.96	1126.29	1102.19
20	1078.02	999.34	678.25	512.48	1216.15	1241.69	1183.02
21	1052.25	992.62	593.44	478.60	1212.65	1213.92	1124.48
22	978.00	851.81	509.02	474.56	1098.87	1138.77	981.73
23	718.90	611.79	397.31	448.50	909.08	1005.00	772.42

Portugal Hydropower Pumping by Hour of the Day - Economic Reference scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	315.00	419.57	394.06	300.00	272.02	315.00	325.67
1	300.00	370.43	390.00	315.00	270.00	315.46	315.00
2	285.00	378.30	377.81	315.00	270.00	300.00	315.00
3	270.00	377.98	375.00	315.00	270.00	300.00	315.00
4	270.00	377.91	369.65	315.00	263.02	279.42	306.38
5	270.00	379.26	354.75	315.00	255.00	256.54	300.00
6	270.00	373.49	345.00	315.00	255.00	248.44	300.00
7	270.00	367.92	342.37	313.65	255.00	240.00	305.63
8	270.23	353.21	330.00	286.85	255.00	240.00	305.83
9	270.00	349.53	315.00	285.00	255.00	243.35	288.21
10	264.58	338.49	315.00	285.00	241.21	240.88	270.67
11	255.00	329.79	315.00	285.00	225.00	240.00	270.00
12	255.00	323.77	315.00	285.00	210.00	240.00	270.00
13	255.00	323.77	315.00	285.00	210.00	237.79	270.00
14	255.00	323.77	315.00	285.00	210.00	219.13	270.00
15	255.00	314.43	315.00	285.00	210.00	210.00	260.96
16	255.00	309.06	315.00	285.00	210.00	210.00	255.00
17	255.00	309.06	302.71	285.00	210.00	210.00	255.00
18	242.71	309.06	300.00	285.00	195.00	210.00	255.00
19	240.00	309.06	294.73	285.00	195.00	210.00	255.00
20	263.96	331.66	292.63	285.00	225.08	226.19	300.56
21	307.21	387.34	300.00	286.85	327.17	271.35	354.00
22	332.60	413.36	300.00	311.79	339.90	283.65	348.15
23	346.42	417.08	300.00	325.35	340.54	289.04	353.02

Portugal Hydropower Generation by Hour of the Day - Economic Wet scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	631.13	425.34	520.42	435.06	591.02	909.52	479.52
1	553.69	561.89	384.94	383.02	562.69	778.44	593.63
2	558.69	510.53	366.44	364.23	549.42	727.65	429.92
3	545.54	498.11	367.73	354.62	553.79	707.48	413.40
4	540.02	520.36	363.96	348.00	567.48	712.48	400.69
5	514.71	514.25	356.92	349.19	583.17	720.17	395.69
6	571.21	555.15	353.65	350.52	596.33	729.67	440.65
7	618.56	551.98	330.10	342.33	623.96	753.10	480.31
8	586.04	498.34	287.21	315.40	603.15	705.98	423.19
9	405.35	387.32	116.63	211.37	487.13	436.35	264.62
10	276.29	210.42	35.73	158.67	336.25	257.98	136.29
11	243.50	137.47	35.83	133.67	253.04	250.96	136.63
12	229.98	93.17	42.77	147.87	221.56	259.83	108.87
13	237.29	90.25	35.00	107.69	244.00	287.19	157.38
14	266.90	137.49	67.65	97.15	349.52	403.46	244.00
15	346.63	179.02	168.06	147.69	434.12	548.67	324.02
16	427.19	340.51	287.37	264.46	617.69	734.08	525.54
17	651.04	671.08	473.48	419.71	847.85	946.71	750.96
18	846.08	763.68	583.81	514.13	953.52	1017.27	918.56
19	1106.73	931.28	718.02	554.08	1103.67	1132.17	1135.73
20	1235.96	1033.38	717.92	568.06	1264.15	1217.04	1221.02
21	1110.15	964.89	622.63	524.15	1178.79	1195.06	1086.46
22	915.54	811.36	504.96	497.08	983.88	1076.27	877.33
23	704.85	638.08	410.17	438.69	839.10	971.23	646.75

Portugal Hydropower Pumping by Hour of the Day - Economic Wet scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	315.00	426.79	371.54	300.00	225.60	301.08	316.56
1	300.00	396.62	360.00	308.50	225.00	313.13	300.00
2	300.00	381.17	360.00	300.00	225.00	300.00	300.00
3	282.04	367.92	360.00	290.71	225.00	288.52	300.00
4	270.00	367.92	345.00	270.00	225.00	270.00	300.00
5	270.00	372.15	345.00	270.00	225.00	270.00	300.00
6	270.00	381.94	345.00	270.00	225.00	270.00	300.00
7	270.00	382.64	345.00	263.33	225.00	270.00	306.46
8	270.00	382.64	345.00	255.00	225.00	255.00	309.12
9	270.00	378.64	345.00	255.00	225.00	255.00	298.75
10	270.00	367.92	345.00	255.00	225.00	255.00	271.04
11	270.00	367.92	339.08	255.00	215.81	255.00	251.69
12	270.00	367.92	330.00	255.00	210.00	255.00	240.00
13	270.00	367.92	330.00	255.00	210.00	255.00	240.00
14	256.27	365.23	330.00	255.00	210.00	254.62	240.00
15	255.00	339.74	316.94	255.00	210.00	240.00	240.00
16	255.00	338.49	315.00	255.00	210.00	228.15	240.00
17	255.00	338.49	315.00	244.35	198.13	214.02	240.00
18	255.00	328.08	290.63	240.00	195.00	210.00	240.00
19	255.00	309.06	285.00	240.00	195.00	212.35	243.08
20	295.77	333.66	285.00	240.00	228.17	234.40	313.06
21	330.85	370.34	307.02	268.69	320.81	267.96	349.10
22	336.77	395.51	315.00	278.04	329.81	281.58	344.88
23	340.04	397.36	315.00	275.00	316.60	285.00	331.77

Portugal Hydropower Generation by Hour of the Day - Economic Dry scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	763.44	604.04	575.48	528.62	661.13	1055.17	734.62
1	554.06	628.34	467.83	453.85	580.00	869.90	769.90
2	542.77	539.40	428.13	420.75	545.35	806.00	614.85
3	536.71	509.53	422.52	405.52	557.48	786.38	575.00
4	561.12	530.13	420.90	402.10	577.52	777.17	560.23
5	566.08	567.66	406.02	397.85	596.83	768.31	553.46
6	644.04	660.30	387.67	390.21	630.04	802.33	601.31
7	741.85	728.79	351.08	366.60	654.35	879.79	659.63
8	679.33	605.89	310.79	314.35	599.94	800.35	584.06
9	470.81	448.62	151.29	215.19	475.65	559.33	365.02
10	361.27	271.94	37.33	164.85	367.65	357.92	176.85
11	305.40	206.79	38.21	139.65	306.69	330.10	159.46
12	272.35	179.15	46.17	154.21	267.10	340.52	134.88
13	292.94	185.96	36.88	112.96	265.33	396.25	184.60
14	343.48	236.45	76.35	100.29	368.79	523.52	288.37
15	426.02	260.62	191.63	151.13	493.02	617.38	442.67
16	550.81	500.09	310.77	292.75	724.37	763.15	660.73
17	763.60	825.32	562.06	480.10	973.71	958.40	887.25
18	1000.90	961.15	718.92	589.81	1149.19	1070.58	1099.60
19	1451.13	1388.98	877.27	689.69	1484.96	1390.77	1450.73
20	1637.38	1455.00	888.77	817.38	1741.04	1531.88	1660.35
21	1504.02	1272.64	793.85	746.56	1642.37	1466.65	1492.10
22	1269.19	1054.57	651.29	678.48	1344.77	1310.73	1201.10
23	956.12	769.91	517.29	561.92	1082.19	1082.35	828.85

Portugal Hydropower Pumping by Hour of the Day - Economic Dry scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	585.00	662.26	644.77	600.00	585.00	570.00	603.96
1	555.38	634.79	630.00	615.00	585.00	585.00	558.85
2	544.85	622.96	619.37	615.00	580.42	576.12	570.00
3	540.00	618.11	615.00	615.00	570.00	570.00	558.69
4	540.00	618.11	615.00	615.00	570.00	570.00	555.00
5	527.23	618.11	615.00	615.00	570.00	566.44	555.00
6	512.04	618.11	611.21	615.00	560.42	554.77	558.40
7	514.96	619.58	600.00	615.00	540.00	547.73	570.00
8	521.73	618.11	600.00	615.00	540.00	540.00	570.00
9	510.00	618.11	600.00	615.00	540.00	540.00	570.00
10	510.00	618.11	600.00	615.00	540.00	539.44	558.17
11	510.00	618.11	600.00	615.00	540.00	525.00	555.00
12	510.00	614.64	600.00	612.81	540.00	525.00	555.00
13	500.13	603.40	600.00	600.00	535.73	525.00	555.00
14	495.00	603.40	600.00	600.00	525.00	525.00	555.00
15	495.00	603.40	600.00	600.00	525.00	525.00	555.00
16	495.00	603.40	600.00	600.00	512.06	525.00	555.00
17	495.00	603.40	600.00	600.00	510.00	525.00	547.25
18	495.00	603.40	585.46	600.00	510.00	525.00	534.19
19	494.08	597.19	585.00	600.00	510.00	525.00	526.85
20	525.00	616.25	585.00	600.00	557.17	547.04	573.62
21	573.62	647.21	602.19	603.92	607.60	563.83	615.73
22	585.00	647.55	605.85	630.00	615.00	569.75	615.00
23	585.15	647.55	604.00	630.00	608.12	570.00	615.00

Figure 34. Portugal Hydropower generation [MWh] vs Pump consumption [MWh] for the different 2030 economic scenarios

7 Conclusion

The main objective of this thesis was to assess how climate change will shape hydropower's role in the Iberian power system. Two significant factors must be taken into account when discussing the future of this region: the substantial increase in installed renewable energy capacity and the expected impacts of global warming on water resources. These environmental changes are likely to lead to the persistence of what we currently term a 'dry year.' As such, it is imperative to interpret the results with these factors in mind.

The EnergyPLAN simulations have yielded interesting insights. For the 2030 technical simulations, both Portugal and Spain were simulated as isolated 'islands' in terms of energy generation, as no transmission capacity was considered. This approach allowed for an assessment of their self-sustainability. In both countries, is anticipated a significant rise in the share of renewable energy sources, which presents a positive outlook in terms of reducing CO2 emissions and increasing renewable energy contributions. However, the influence of drier years becomes evident, with more pronounced effects on the Portuguese power system. Portugal's reliance on run-of-river power plants, a non-dispatchable renewable source known for its substantial variation across scenarios, intensifies the impact. Technical simulations for a dry year in Portugal reveal an 8.2% reduction in hydropower contribution compared to an average year. This results in a 75% increase in CO2 emissions and an additional cost of 626 million euros, exceeding the annual cost recorded in the reference year of 2021. The primary cost driver here is the higher cost of CO2 emissions.

For Spain, a similar set of conditions leads to significant but proportionally smaller impacts. There's a 3.5% reduction in hydropower contribution, a 68% increase in CO2 emissions, and a cost increase of 905 million euros, still smaller than the reference scenario.

Notably, pump storage consumption plays a critical role, with Portugal experiencing a more than 400% increase, while Spain observes even more substantial growth. This underscores the significance of pump storage in achieving sustainability goals and propelling dammed hydropower into the spotlight as the primary dispatchable energy source of the future.

The economic simulation yields more favourable outcomes for Portugal as it permits the integration of imports instead of relying on natural gas. This simulation, however, is exclusively conducted for Portugal due to the necessity for Spain to account for external influences from France. Anticipations indicate that imports will increase in a scenario where renewable energy generation dominates in Spain. As a result, Iberian prices are expected to decrease, and Portugal stands to benefit significantly from this shift. Market prices for the dry year, while still lower than the average market prices currently practised, exhibit substantial oscillations when compared to the reference and wet scenarios. In light of this trend, the role of pump storage becomes even more significant. Pump storage plays a pivotal role in the strategic management of water resources, mitigating the impact of market price fluctuations. The operation of pump storage involves filling the reservoirs during periods of low market prices with excess renewables and imports. Subsequently, this stored energy can be used into when electricity demand is at its peak, accompanied by higher market prices. This mechanism ensures a more stable variation in terms of costs and CO2 emissions while contributing to the reliability and flexibility of the Iberian power system.

Globally, the comprehensive analysis reveals that hydropower, particularly when equipped with reservoirs, will transition into a more regulatory role, departing from its current role as a contributor to the power system. This transformation is supported by the significant role of pump storage, which plays a significant part in capitalizing on the increasing surplus of renewables while diminishing the reliance on non-renewable energy sources. Pump storage assumes a more periodic function, aligning its operations with the rhythm of reservoir generation. The substantial increase in hydro-pumped storage across all scenarios signifies a shift towards dammed hydropower becoming the primary dispatchable source for the future of the Iberian power system. Consequently, the dependence on natural gas is reduced, marking a positive step toward sustainable and renewable energy generation. A noteworthy shift arises in the patterns of hydropower pumping and generation. Pumping operations are notably more prevalent during the daytime, coinciding with the hours of peak solar generation, while hydropower generation predominantly occurs during the night when renewable generation is scarcer and electricity prices are typically higher. Some differences emerge between the pump consumption profiles in technical and market simulations. The technical simulations are in alignment with expectations, showcasing a substantial increase in pump consumption during daylight hours, owing to the substantial expansion of solar PV installed capacity across all scenarios. In contrast, the market simulation presents a more stable pump consumption profile throughout the day, where pumping primarily occurs when market prices are low. This pattern is largely influenced by market variations and exhibits more year-round fluctuations as opposed to a daily cycle. It underscores the occasional and strategic nature of importing energy for pump storage, reflecting real-world situations when such a practice is both economically and strategically advantageous.

Nonetheless, it's essential to acknowledge several limitations in this analysis that may affect the results. Firstly, a major limitation lies in the assumption that a dry year accurately represents the impacts of climatic changes. While the prevailing trend points towards years becoming drier with reduced average annual runoff, there remains substantial geographical variability and seasonal disparities. Projections indicate that the northern region of the Iberian Peninsula may experience increased runoff due to higher precipitation levels, while the southern region could face more severe drought periods with a significant reduction in runoff. Alterations in precipitation patterns, characterized by condensed wet periods and extended dry periods, are expected. Load patterns are also projected to shift peak demands when compared to current conditions, particularly due to increased cooling needs brought about by rising average temperatures.

Another limitation arises due to the scarcity of comprehensive hydrological data. While the assumption was made that the hydrological regime in Portugal could represent the broader Iberian context, this may not be entirely accurate, even knowing that 55% of basins are transboundary.

EnergyPLAN itself has its own limitations. One significant constraint is its inability to offer spatial resolution. The model cannot simulate demand and generation within specific geographical regions or account for energy transmission constraints between different areas. This limitation becomes particularly evident when dealing with hydropower and hydro pump storage, as these components are often treated as a collective unit, resembling a large-scale dam in the model. This simplified approach does not consider the intricate technical variations and geographical distinctions that exist among individual hydro plants. Moreover, the value of water is not incorporated into EnergyPLAN's modelling. In reality, reservoirs often serve multiple purposes and minimum water volumes must be maintained. This will become especially crucial in a future marked by water resource scarcity.

Additionally, each simulation strategy has its own limitations. The technical scenario, for instance, does not consider the degree of freedom enabled by imports and exports. On the other hand, the economic scenario focuses solely on optimizing prices and assumes that export/import is solely limited by transmission capacity. In reality, given the geographic similarities between Spain and Portugal, if there is excess renewable energy in Portugal, the same condition may likely exist in Spain, making energy import less likely. Therefore, a hybrid scenario that falls between the two simulations may better approximate the real-world scenario.

In future developments, these limitations must be addressed. When forecasting electricity prices, the integration of CO2 emissions costs should be taken into account. While EnergyPLAN provides a valuable high-level view of future Iberian power systems and generation patterns with a relatively simple and less time-intensive modelling approach, alternative methodologies are available. These methods, such as Global Circulation Models (GCMs) and regional circulation models (RCMs) for meteorological variables, followed by hydrological models to capture runoff variations specific to each facility, and, lastly, power system models incorporating these projections, can offer more detailed and comprehensive analyses despite being considerably more complex and time-consuming.

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APPENDICES

7.1 Costs for 2021 and 2030

Table 25. Technology costs for 2021 and 2030

	2021			2030		
Technology	Investment (M€/unit)	Lifetime (years)	Fixed O&M (% of inv.)	Investment (M€/unit)	Lifetime (years)	Fixed O&M (% of inv.)
Large Power Plants	1.32	25	2.43	1.26	26	2.45
Nuclear Plants	4.5	60	2	4.12	60	1.9
Interconnection	1.26	25	2.45	1.26	25	2.45
Wind	1.2	26	3.2	0.91	30	3.97
Wind Offshore	2.19	26	3	1.75	30	1.94
Solar PV	1.1	33	1	0.85	40	0.6
Biomass	4	25	4.5	3.5	25	4.11
River Hydro	5.62	60	1.5	5.62	60	1.5
Dammed Hydro	2.55	60	1.5	2.55	60	1.5
Hydro Storage	7.5	50	1.5	7.5	50	1.5
Hydro Pump	0.6	50	1.5	0.6	50	1.5

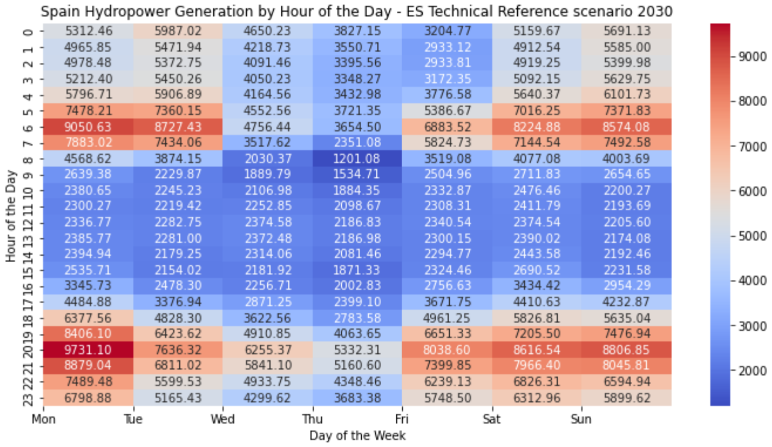
Table 26. Fuel costs for 2021 and 2030

	2021	2030
Fuel	Cost (€/GJ)	Cost (€/GJ)
Coal	3.2	4
Fuel oil	10	19.7
Natural Gas	11	12
Biomass	6	8

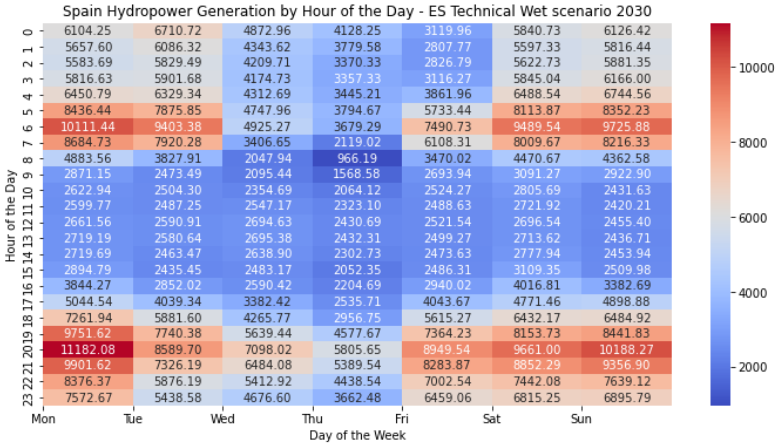
Table 27. CO2 emissions cost for 2021 and 2030

	2021	2030
	Cost (€/tonCO2)	Cost (€/tonCO2)
CO2 emissions	26.8	50

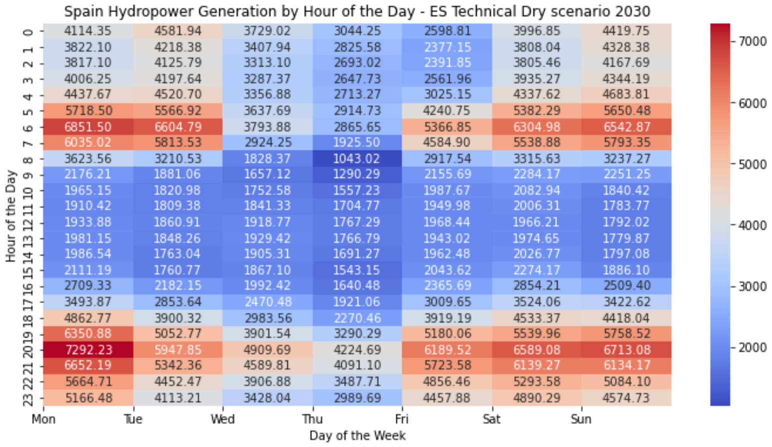
7.2 Spain Hydropower generation in 2030 Reference Technical scenario (Average week)



Hour	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	5312.46	5987.02	4650.23	3827.15	3204.77	5159.67	5691.13
1	4965.85	5471.94	4218.73	3550.71	2933.12	4912.54	5585.00
2	4978.48	5372.75	4091.46	3395.56	2933.81	4919.25	5399.98
3	5212.40	5450.26	4050.23	3348.27	3172.35	5092.15	5629.75
4	5796.71	5906.89	4164.56	3432.98	3776.58	5640.37	6101.73
5	7478.21	7360.15	4552.56	3721.35	5386.67	7016.25	7371.83
6	9050.63	8727.43	4756.44	3654.50	6883.52	8224.88	8574.08
7	7883.02	7434.06	3517.62	2351.08	5824.73	7144.54	7492.58
8	4568.62	3874.15	2030.37	1201.08	3519.08	4077.08	4003.69
9	2639.38	2229.87	1889.79	1534.71	2504.96	2711.83	2654.65
10	2380.65	2245.23	2106.98	1884.35	2332.87	2476.46	2200.27
11	2300.27	2219.42	2252.85	2098.67	2308.31	2411.79	2193.69
12	2336.77	2282.75	2374.58	2186.83	2340.54	2374.54	2205.60
13	2385.77	2281.00	2372.48	2186.98	2300.15	2390.02	2174.08
14	2394.94	2179.25	2314.06	2081.46	2294.77	2443.58	2192.46
15	2535.71	2154.02	2181.92	1871.33	2324.46	2690.52	2231.58
16	3345.73	2478.30	2256.71	2002.83	2756.63	3434.42	2954.29
17	4484.88	3376.94	2871.25	2399.10	3671.75	4410.63	4232.87
18	6377.56	4828.30	3622.56	2783.58	4961.25	5826.81	5635.04
19	8406.10	6423.62	4910.85	4063.65	6651.33	7205.50	7476.94
20	9731.10	7636.32	6255.37	5332.31	8038.60	8616.54	8806.85
21	8879.04	6811.02	5841.10	5160.60	7399.85	7966.40	8045.81
22	7489.48	5599.53	4933.75	4348.46	6239.13	6826.31	6594.94
23	6798.88	5165.43	4299.62	3683.38	5748.50	6312.96	5899.62

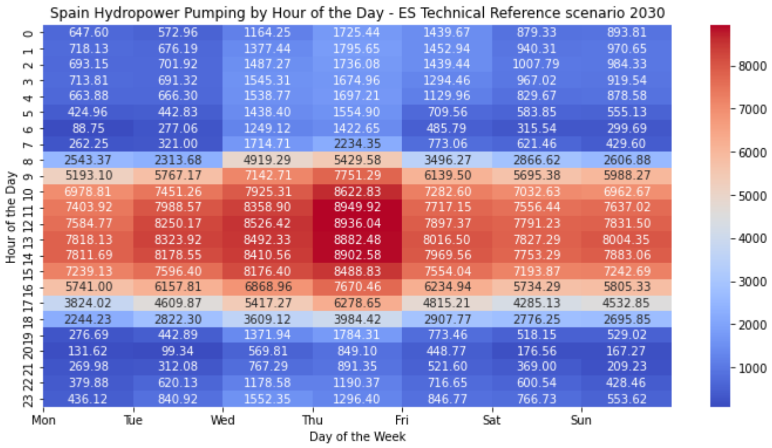


Hour	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	6104.25	6710.72	4872.96	4128.25	3119.96	5840.73	6126.42
1	5657.60	6086.32	4343.62	3779.58	2807.77	5597.33	5816.44
2	5583.69	5829.49	4209.71	3370.33	2826.79	5622.73	5881.35
3	5816.63	5901.68	4174.73	3357.33	3116.27	5845.04	6166.00
4	6450.79	6329.34	4312.69	3445.21	3861.96	6488.54	6744.56
5	8436.44	7875.85	4747.96	3794.67	5733.44	8113.87	8352.23
6	10111.44	9403.38	4925.27	3679.29	7490.73	9489.54	9725.88
7	8684.73	7920.28	3406.65	2119.02	6108.31	8009.67	8216.33
8	4883.56	3827.91	2047.94	966.19	3470.02	4470.67	4362.58
9	2871.15	2473.49	2095.44	1568.58	2693.94	3091.27	2922.90
10	2622.94	2504.30	2354.69	2064.12	2524.27	2805.69	2431.63
11	2599.77	2487.25	2547.17	2323.10	2488.63	2721.92	2420.21
12	2661.56	2590.91	2694.63	2430.69	2521.54	2696.54	2455.40
13	2719.19	2580.64	2695.38	2432.31	2499.27	2713.62	2436.71
14	2719.69	2463.47	2638.90	2302.73	2473.63	2777.94	2453.94
15	2894.79	2435.45	2483.17	2052.35	2486.31	3109.35	2509.98
16	3844.27	2852.02	2590.42	2204.69	2940.02	4016.81	3382.69
17	5044.54	4039.34	3382.42	2535.71	4043.67	4771.46	4898.88
18	7261.94	5881.60	4265.77	2956.75	5615.27	6432.17	6484.92
19	9751.62	7740.38	5639.44	4577.67	7364.23	8153.73	8441.83
20	11182.08	8589.70	7098.02	5805.65	8949.54	9661.00	10188.27
21	9901.62	7326.19	6484.08	5389.54	8283.87	8852.29	9356.90
22	8376.37	5876.19	5412.92	4438.54	7002.54	7442.08	7639.12
23	7572.67	5438.58	4676.60	3662.48	6459.06	6815.25	6895.79

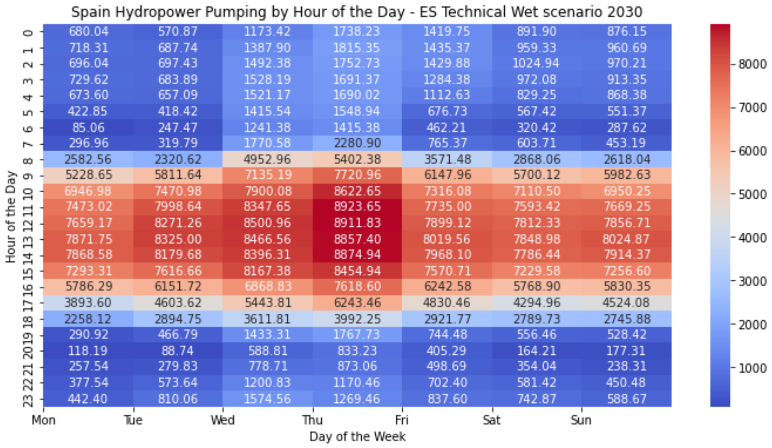


Hour	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	4114.35	4581.94	3729.02	3044.25	2598.81	3996.85	4419.75
1	3822.10	4218.38	3407.94	2825.58	2377.15	3808.04	4328.38
2	3817.10	4125.79	3313.10	2693.02	2391.85	3805.46	4167.69
3	4006.25	4197.64	3287.37	2647.73	2561.96	3935.27	4344.19
4	4437.67	4520.70	3356.88	2713.27	3025.15	4337.62	4683.81
5	5718.50	5566.92	3637.69	2914.73	4240.75	5382.29	5650.48
6	6851.50	6604.79	3793.88	2865.65	5366.85	6304.98	6542.87
7	6035.02	5813.53	2924.25	1925.50	4584.90	5538.88	5793.35
8	3623.56	3210.53	1828.37	1043.02	2917.54	3315.63	3237.27
9	2176.21	1881.06	1657.12	1290.29	2155.69	2284.17	2251.25
10	1965.15	1820.98	1752.58	1557.23	1987.67	2082.94	1840.42
11	1910.42	1809.38	1841.33	1704.77	1949.98	2006.31	1783.77
12	1933.88	1860.91	1918.77	1767.29	1968.44	1966.21	1792.02
13	1981.15	1848.26	1929.42	1766.79	1943.02	1974.65	1779.87
14	1986.54	1763.04	1905.31	1691.27	1962.48	2026.77	1797.08
15	2111.19	1760.77	1867.10	1543.15	2043.62	2274.17	1886.10
16	2709.33	2182.15	1992.42	1640.48	2365.69	2854.21	2509.40
17	3493.87	2853.64	2470.48	1921.06	3009.65	3524.06	3422.62
18	4862.77	3900.32	2983.56	2270.46	3919.19	4533.37	4418.04
19	6350.88	5052.77	3901.54	3290.29	5180.06	5539.96	5758.52
20	7292.23	5947.85	4909.69	4224.69	6189.52	6589.08	6713.08
21	6652.19	5342.36	4589.81	4091.10	5723.58	6139.27	6134.17
22	5664.71	4452.47	3906.88	3487.71	4856.46	5293.58	5084.10
23	5166.48	4113.21	3428.04	2989.69	4457.88	4890.29	4574.73

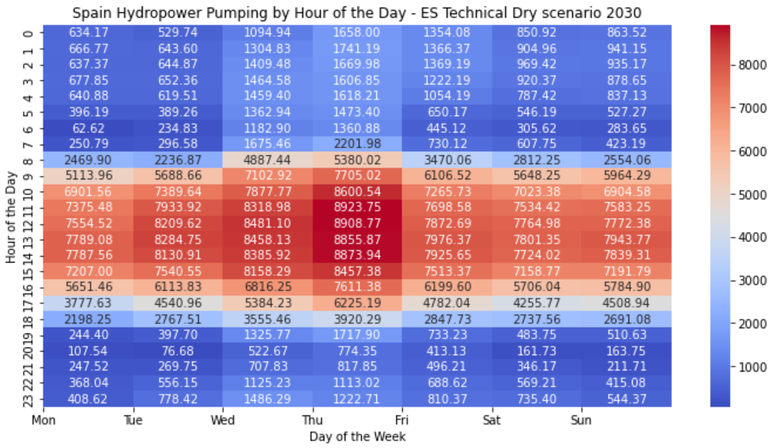
Figure 35. Spain Hydropower generation in 2030 Reference Technical scenario (Average week)


Spain Hydropower Pumping by Hour of the Day - ES Technical Reference scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	647.60	572.96	1164.25	1725.44	1439.67	879.33	893.81
1	718.13	676.19	1377.44	1795.65	1452.94	940.31	970.65
2	693.15	701.92	1487.27	1736.08	1439.44	1007.79	984.33
3	713.81	691.32	1545.31	1674.96	1294.46	967.02	919.54
4	663.88	666.30	1538.77	1697.21	1129.96	829.67	878.58
5	424.96	442.83	1438.40	1554.90	709.56	583.85	555.13
6	88.75	277.06	1249.12	1422.65	485.79	315.54	299.69
7	262.25	321.00	1714.71	2234.35	773.06	621.46	429.60
8	2543.37	2313.68	4919.29	5429.58	3496.27	2866.62	2606.88
9	5193.10	5767.17	7142.71	7751.29	6139.50	5695.38	5988.27
10	6978.81	7451.26	7925.31	8622.83	7282.60	7032.63	6962.67
11	7403.92	7988.57	8358.90	8949.92	7717.15	7556.44	7637.02
12	7584.77	8250.17	8526.42	8936.04	7897.37	7791.23	7831.50
13	7818.13	8323.92	8492.33	8882.48	8016.50	7827.29	8004.35
14	7811.69	8178.55	8410.56	8902.58	7969.56	7753.29	7883.06
15	7239.13	7596.40	8176.40	8488.83	7554.04	7193.87	7242.69
16	5741.00	6157.81	6868.96	7670.46	6234.94	5734.29	5805.33
17	3824.02	4609.87	5417.27	6278.65	4815.21	4285.13	4532.85
18	2244.23	2822.30	3609.12	3984.42	2907.77	2776.25	2695.85
19	276.69	442.89	1371.94	1784.31	773.46	518.15	529.02
20	131.62	99.34	569.81	849.10	448.77	176.56	167.27
21	269.98	312.08	767.29	891.35	521.60	369.00	209.23
22	379.88	620.13	1178.58	1190.37	716.65	600.54	428.46
23	436.12	840.92	1552.35	1296.40	846.77	766.73	553.62


Spain Hydropower Pumping by Hour of the Day - ES Technical Wet scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	680.04	570.87	1173.42	1738.23	1419.75	891.90	876.15
1	718.31	687.74	1387.90	1815.35	1435.37	959.33	960.69
2	696.04	697.43	1492.38	1752.73	1429.88	1024.94	970.21
3	729.62	683.89	1528.19	1691.37	1284.38	972.08	913.35
4	673.60	657.09	1521.17	1690.02	1112.63	829.25	868.38
5	422.85	418.42	1415.54	1548.94	676.73	567.42	551.37
6	85.06	247.47	1241.38	1415.38	462.21	320.42	287.62
7	296.96	319.79	1770.58	2280.90	765.37	603.71	453.19
8	2582.56	2320.62	4952.96	5402.38	3571.48	2868.06	2618.04
9	5228.65	5811.64	7135.19	7720.96	6147.96	5700.12	5982.63
10	6946.98	7470.98	7900.08	8622.65	7316.08	7110.50	6950.25
11	7473.02	7998.64	8347.65	8923.65	7735.00	7593.42	7669.25
12	7659.17	8271.26	8500.96	8911.83	7899.12	7812.33	7856.71
13	7871.75	8325.00	8466.56	8857.40	8019.56	7848.98	8024.87
14	7868.58	8179.68	8396.31	8874.94	7968.10	7786.44	7914.37
15	7293.31	7616.66	8167.38	8454.94	7570.71	7229.58	7256.60
16	5786.29	6151.72	6868.83	7618.60	6242.58	5768.90	5830.35
17	3893.60	4603.62	5443.81	6243.46	4830.46	4294.96	4524.08
18	2258.12	2894.75	3611.81	3992.25	2921.77	2789.73	2745.88
19	290.92	466.79	1433.31	1767.73	744.48	556.46	528.42
20	118.19	88.74	588.81	833.23	405.29	164.21	177.31
21	257.54	279.83	778.71	873.06	498.69	354.04	238.31
22	377.54	573.64	1200.83	1170.46	702.40	581.42	450.48
23	442.40	810.06	1574.56	1269.46	837.60	742.87	588.67


Spain Hydropower Pumping by Hour of the Day - ES Technical Dry scenario 2030

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0	634.17	529.74	1094.94	1658.00	1354.08	850.92	863.52
1	666.77	643.60	1304.83	1741.19	1366.37	904.96	941.15
2	637.37	644.87	1409.48	1669.98	1369.19	969.42	935.17
3	677.85	652.36	1464.58	1606.85	1222.19	920.37	878.65
4	640.88	619.51	1459.40	1618.21	1054.19	787.42	837.13
5	396.19	389.26	1362.94	1473.40	650.17	546.19	527.27
6	62.62	234.83	1182.90	1360.88	445.12	305.62	283.65
7	250.79	296.58	1675.46	2201.98	730.12	607.75	423.19
8	2469.90	2236.87	4887.44	5380.02	3470.06	2812.25	2554.06
9	5113.96	5688.66	7102.92	7705.02	6106.52	5648.25	5964.29
10	6901.56	7389.64	7877.77	8600.54	7265.73	7023.38	6904.58
11	7375.48	7933.92	8318.98	8923.75	7698.58	7534.42	7583.25
12	7554.52	8209.62	8481.10	8908.77	7872.69	7764.98	7772.38
13	7789.08	8284.75	8458.13	8855.87	7976.37	7801.35	7943.77
14	7787.56	8130.91	8385.92	8873.94	7925.65	7724.02	7839.31
15	7207.00	7540.55	8158.29	8457.38	7513.37	7158.77	7191.79
16	5651.46	6113.83	6816.25	7611.38	6199.60	5706.04	5784.90
17	3777.63	4540.96	5384.23	6225.19	4782.04	4255.77	4508.94
18	2198.25	2767.51	3555.46	3920.29	2847.73	2737.56	2691.08
19	244.40	397.70	1325.77	1717.90	733.23	483.75	510.63
20	107.54	76.68	522.67	774.35	413.13	161.73	163.75
21	247.52	269.75	707.83	817.85	496.21	346.17	211.71
22	368.04	556.15	1125.23	1113.02	688.62	569.21	415.08
23	408.62	778.42	1486.29	1222.71	810.37	735.40	544.37

Figure 36. Spain Pump consumption in 2030 Reference Technical scenario (Average week)