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

Diogo Henrique Esteves Couceiro[1]
diogocouceiro@tecnico.ulisboa.pt
[1]*Instituto Superior Técnico, Universidade de Lisboa, Portugal*
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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.

Keywords: energy; renewables; hydropower; energy transition; pump-storage

1 Introduction

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 [1]. 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 1.8 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 [2]. 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 [3]. What sets hydropower apart is its dispatchable capacity in facilities equipped with reservoirs, commonly known as dammed hydropower, which allows the integration of the most effective technology for energy storage – Pumped Hydro storage [4]. In a future perspective of a substantial increase in the penetration of variable renewable sources, such as solar and wind energy, pumped hydro storage presents a unique opportunity to store surplus generation and allocate it to critical periods of consumption. Therefore, it stands as an essential element in this landscape of transition and decarbonization of the Iberian power system.

However, hydropower exhibits a dual relationship with climate change. It plays a crucial role in achieving sustainability goals and reducing greenhouse gas emissions. Yet, it is uniquely vulnerable to climate change impacts [5]. Climate change is expected to bring significant shifts in global water resources, affecting hydropower generation. These changes involve variations in precipitation timing, magnitude, and distribution, as well as runoff pattern adjustments [6]–[8]. These effects vary depending on geographical locations, influenced by natural factors [9]. The Iberian Peninsula is forecasted to experience a substantial up to 40% decline in hydropower generation by 2070, particularly in the southern region [8]–[11]. This significant impact is closely tied to the prevailing Mediterranean climatic conditions in the region. The Mediterranean Basin is considered a climate change "hot spot" due to its vulnerability to rising temperatures, prolonged droughts, and alterations in precipitation patterns, intensifying the challenges posed by climate change [12], [13].

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

2 Objectives

This work addresses hydropower's evolving role in managing renewable energy fluctuations amid climate change. It focuses on the Iberian power system's resilience, specifically hydropower's generation and pump consumption patterns. The study uses multidisciplinary methods, including data collection, modelling, scenario simulation, and market price forecasting. The objectives encompass analysing historical hydropower patterns in the Iberian power system, predicting the 2030 energy mix, projecting the use of storage capacity, assessing future CO2 emissions and renewable energy source (RES) utilization, and exploring unique hydropower generation and pump consumption trends.

3 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 1, providing a broader picture of the entire process. The process starts with collecting essential data to characterize the Iberian power system. This data encompasses generation and load profiles, cross-border exchange balances, market prices, and installed capacities. Python software is used for data preparation to align it with specific problem requirements. Following this, the modelling phase begins, involving calibration and validation with historical records. The modelling phase establishes a baseline scenario that undergoes perturbations in line with anticipated system variable changes. The year 2030 is chosen for analysis, aligning with Spain and Portugal's National energy and climate plans 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. Two simulation types are offered by EnergyPLAN: technical and market simulation. Given the need for additional inputs in market simulation, priority is given to technical simulation for 2030. The results from technical simulation serve as inputs for a Python-based market price forecast model to project 2030 market prices. 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.

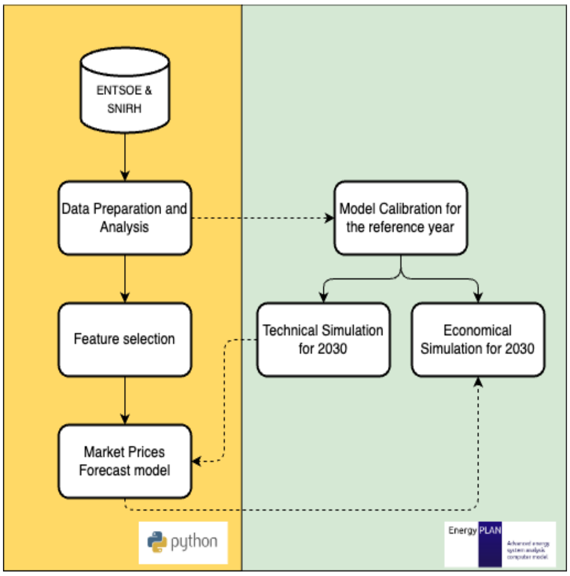

Figure 1. Flowchart with the schematic representation of the methodology applied and the interaction between Python (left) and EnergyPLAN (right)

3.1 Data acquisition and preparation

3.1.1 Iberian power System data

Data essential for a comprehensive Iberian power system analysis was accessed via ENTSO-E, an organization coordinating Europe's electricity transmission [14]. ENTSO-E's Transparency Platform offers extensive European electricity data, including generation, capacity, trade balances, load profiles, consumption, and market prices [15]. An API key from ENTSO-E provided access to country-specific data. Python was used for thorough data preprocessing to prepare it for the market price forecasting model. Data from ENTSO-E is available from 2015 onwards, reported hourly. Discrepancies between ENTSO-E data and national transmission system operators' data should be noted, with REN [16] using net generation and ENTSO-E using gross generation. Similar disparities with REE [17] arise from ENTSO-E's aggregation of hydro water reservoir and pump-storage generation until 2022, unlike REE's separate reporting. Despite these variations, ENTSO-E values were used for consistency and comparability in this analysis.

3.1.2 Hydrometeorological data

Assessing climate change's impact on hydropower and the Iberian electricity market requires considering key water resource variables. These variables define hydrological behaviour and indicate future trends. A focus was placed on Portuguese river basins due to data constraints, assuming they reasonably represent conditions in Spain. Data was obtained from SNIRH [18], a comprehensive water resource database in Portugal, including inflow, stored volume, pumped flow, temperature, and precipitation data. To harmonize this data with ENTSO-E's hourly data, adjustments were made, and missing data gaps were interpolated. These additional variables enhance the understanding of hydropower generation's connection to water availability and provide insights into climate change's broader water resource impacts.

3.2 Modelling the Iberian Power System

In the energy domain, modelling is vital for understanding and improving real-world energy systems. It constructs representations for in-depth analysis, focusing on various aspects like demand response. For simulating future annual energy production and assessing climate change impacts on the Iberian Power system, EnergyPLAN is a suitable choice. It enables the perturbation of inputs to observe climate change effects, making it valuable for addressing the system's intricacies [19]. EnergyPLAN was chosen for several reasons. It's open source, widely used, and focuses on future energy systems, simulating them hourly for a full year, capturing supply and demand fluctuations. It also provides up-to-date technology cost data.

3.2.1 Model Overview

EnergyPLAN has been developed since 1999 by Aalborg University. It is a powerful tool that tackles the challenging field of Generation Expansion Planning (GEP) modelling [20]. It determines optimal energy conversion units based on predefined demand, using hourly data. The model relies on input parameters encompassing demands, capacities, and strategies to manage excess energy. It considers transmission capacity and implicitly handles services with sub-hourly time scales. Simulation outputs include data on electricity production, imports/exports, excess electricity, fuel use, costs, CO_2 emissions, and renewable energy proportions. Users can choose between technical and economic simulation strategies, addressing different priorities [19], [21].

To ensure accurate EnergyPLAN simulation, a reference year like 2021 is chosen and compared with real energy data. Calibration is crucial if values don't match historical data [21]. This year offers stability post-pandemic and minimal fluctuations in capability indexes. Data sources include REN [22], REE [23], and ENTSOE reports [15]. Sections in the software, including Demand, Supply, Balancing, Storage, and Cost, are considered for well-rounded representation. Calibration processes are consistent for both Portugal and Spain. Only the peninsular system is analyzed, with separate modelling and calibration for each country to enable technology contribution comparisons.

3.2.2 Portugal and Spain calibration

In 2021, Portugal's electricity demand was 49.6 TWh. Fluctuating renewables, including solar, wind, and run-of-river technologies, accounted for 59% of the total generation. Biomass plants were treated as variable renewables. Natural gas contributed 30% to the generation mix, replacing coal.

Dammed hydropower, categorized as dispatchable due to storage capacity, relies on detailed ENTSOE data and hourly water supply distribution from REN [16]. Modelling the storage component requires two inputs: reservoir storage (about 3200 GWh) and pump capacity (approx. 3000 MW). Market simulations saw the pump operation heavily influenced by market prices, leading to excessively high pump values. To maintain consistency, pump capacity was restricted to the 80th percentile of its 2021 usage (400 MW) across scenarios.

The transmission line capacity, initially set at 3500 MW, provided accurate calibration results. In technical simulations, which exclude economic factors, the transmission line capacity was adjusted to zero, enabling increased pumping. This adjustment affected import/export capabilities, which were managed by the power plant due to the inherent limitations of EnergyPLAN's prioritization of exports over pumping in technical simulations. Grid stabilization relies on dispatchable power sources, like hydro and thermal plants. Specific stabilization shares are defined: 10% for market simulation and 30% for technical simulation, accounting for the absence of direct transmission line capacity exchange. These values align with the 15th percentile proportion of these technologies, including import/export balance concerning total load.

The calibration process included error analysis, with a 10% confidence interval to account for operational variations, and the results are depicted in Table 1. The same methodology was applied to Spain, with the consideration of nuclear and waste, which doesn't exist in Portugal.

Table 1. 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

3.3 2030 Simulation Scenarios

To comprehensively evaluate potential future changes in the Iberian power system and their impact on hydropower generation and pumping patterns for the year 2030, we must define and model various scenarios. Data sources primarily include the Plano Nacional de Energia e Clima (PNEC) [24] and Roteiro para a Neutralidade Carbónica 2050 (RNC2050) [25] for Portugal, and the Plano Nacional Integrado de Energia y Clima (PNIEC) [26] for Spain. 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. Climate change impacts are addressed with hydro capability index variations, represented by dry, average, and wet years. This approach allows us to assess how the energy system will respond under varying conditions, focusing on hydropower. These hydrological scenarios were selected based on historical data from the last decade, with 2016 identified as the wettest and 2017 as the driest year [22], [27]. Critical parameters for hydropower, such as hourly distribution for river hydro and water supply for dammed hydro reservoirs, were adjusted accordingly for the simulations to align with the specific climate scenarios. 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.

3.4 Market prices forecast model

To evaluate the impacts of climate change on the future Iberian electricity market, a forecast model was developed. Accurate electricity price predictions depend on detailed information about the composition of the Iberian power system, as different technologies' generation profiles significantly affect electricity prices [28], [29]. Following the creation of technical scenarios for both Portugal and Spain in 2030, the output distributions are used as inputs for the forecast model. It's important to note that the Iberian electricity market operates as a unified entity, so a single model reflecting its real-world operation was formulated. The forecasted prices facilitate a market simulation, providing insights into how patterns could evolve, especially considering short-term least-cost perspectives.

To assess climate change's impacts on the Iberian electricity market, three distinct algorithms were evaluated: a decision tree, gradient boosting, and an artificial neural network (ANN). These models were trained using data from 2015 to 2020. The exclusion of 2021 and subsequent data was based on its exceptional market conditions, marked by historically high gas prices because of the Russia-Ukraine conflict. These conditions might lead models to conserve these unusual price levels in their forecasts, making them less representative of typical market conditions. Before training, data shuffling was employed to prevent models from learning patterns based on data order, enhancing their ability to generalize to new data [30]. All input variables were scaled to ensure model accuracy and stability, especially crucial for ANN due to sensitivity to feature scaling [30]. Hyperparameter tuning was systematically performed using grid search to identify optimal model configurations, saving time and enhancing predictive accuracy [28]. Among the models, the ANN demonstrated the highest accuracy, exhibiting the lowest Mean Absolute Error (MAE) and Mean Squared Error (MSE).

4 Results and discussion

4.1 2030 Technical simulation

This modelling approach, despite not considering imports/exports, offers a valuable framework for evaluating the energy self-sufficiency of both Portugal and Spain.

In 2030, Portugal's energy mix (Figure 2) will see a significant surge in renewable sources, with solar photovoltaic (PV) notably growing by at least 25%, thanks to a substantial 10,000 MW increase in installed capacity. Wind energy also grows, although less significantly at about 4%, with most reinforcement in offshore wind. The hydropower sector displays a nuanced picture. Run-of-river hydro decreases due to its steady installed capacity and lack of storage. It's highly influenced by hydrological conditions, contributing less during dry years and more during wet ones. In contrast, hydropower with a reservoir benefits from increased pump storage capacity in all scenarios, elevating its contribution. Non-renewables, mainly natural gas, see a significant drop in their share for 2030, with the extent varying based on the hydropower scenario. Dry conditions have a milder impact on this decrease, underscoring the influence of climate on the energy mix. Hydro-pumped storage plays a crucial role in the Portuguese energy system, efficiently utilizing excess renewable energy and reducing reliance on non-renewables. Pump storage usage substantially increases compared to 2021, especially in wet scenarios, aligning with renewables' growth. Critical excess electricity production (CEEP) and critical imports depend on renewable variations, with wet scenarios experiencing higher excesses. However, even with critical excess, natural gas is used, indicating insufficient storage for full renewables utilization. Critical imports are 5 times more significant in dry scenarios, revealing the impact of climate conditions.

In Spain's 2030 energy landscape, a significant surge in renewable sources, particularly solar and wind energy, is evident, driven by substantial investments. Unlike Portugal, Spain sees an increase in hydropower with reservoirs in all scenarios, supported by expanded pump capacity and renewables, even in dry conditions. Nevertheless, run-of-river hydro's contribution decreases across scenarios due to no capacity growth. Both nuclear and waste generation witness a decline in their shares due to reduced installed capacity, with minimal variations between scenarios. Fossil gas, while significantly decreasing overall, experiences a less pronounced reduction in dry scenarios, partly due to the remaining influence of run-of-river hydro. 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 production, which constitutes a minor portion of Spain's energy mix compared to Portugal's. The trends in critical excess electricity production (CEEP) and critical imports align with the results for Portugal but with smaller variations in CEEP between wet and dry scenarios. Importantly, no imports are required in any scenario, suggesting that Spain's projected capacity should ensure electricity self-sufficiency.

4.2 Iberian market prices 2030

The forecasted market prices for 2030 display substantial decreases compared to the 2015-2020 period. These reductions are primarily driven by the increased installed capacity of renewable energy sources. Notably, the average scenario sees a 66% decrease, while the wet scenario experiences an even more substantial 76% decrease due to abundant water resources. In contrast, the dry scenario has a more modest decrease of 48%. The availability of water resources plays a crucial role in these variations. During dry years, when renewable energy penetration is reduced, especially in the summer months, significant market price fluctuations occur, mirroring the availability of solar energy. Prices tend to decrease during the day when solar generation is abundant but surge at night when non-renewable sources are required. In the wet and reference scenarios, hydropower plays a vital role in stabilizing prices at lower levels during these months by peak shaving. The beginning and end of the year are characterized by extreme price fluctuations for all scenarios, coinciding with the highest load requirements that cannot be entirely met by available renewable capacity. The increased presence of renewables results in electricity prices closely mirroring the patterns of renewable generation, indicating a more linear relationship compared to current conditions.

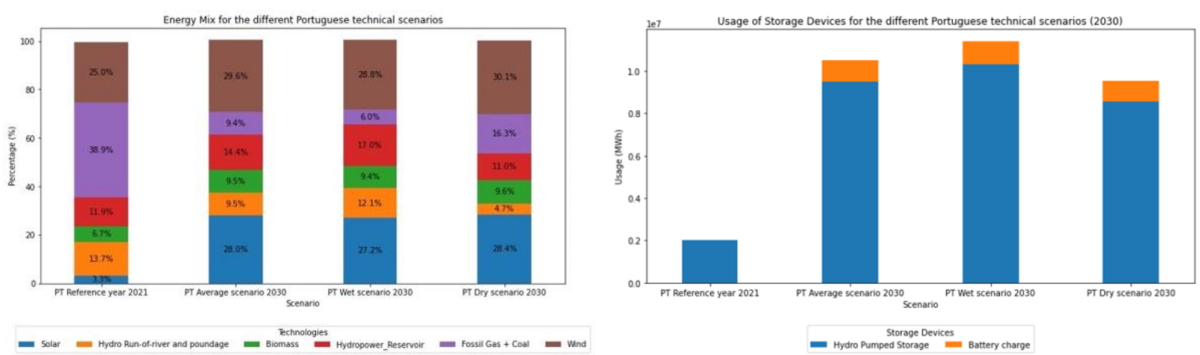

Figure 2. Energy mix (left) and usage of storage devices (right) for Portugal in technical simulation.

4.3 Economical Simulation

The Iberian market price forecast was used to conduct simulations that examined how the Portuguese market would respond to external factors, including high penetration of renewables and lower average prices. These simulations shed light on how economic considerations, particularly cost optimization, could reshape energy consumption patterns. The study is limited to Portugal, as data for Spain's external market dynamics involving France was not accessible.

The distribution of technology shares in various scenarios closely resembles the technical scenario, with notable shifts related to dispatchable sources. In these simulations (see Figure 3), hydropower reservoirs allocate a significant portion of their share to imports due to lower market prices resulting from increased renewable energy penetration. This makes importing electricity more cost-effective than generating it from reservoirs. In the dry scenario, hydropower reservoir share increases to compensate for the decrease in run-of-river generation and to give response to higher market prices. A similar pattern is observed for Fossil Gas, which is primarily utilized when transmission lines and hydropower generation cannot meet the load requirements. A significant increase in pump consumption is observed in the dry scenario. This trend becomes more apparent when examining reservoir storage and external market prices. During the start of the year, market peaks coincide with spikes in demand across all scenarios. Both the reference and wet scenarios can respond by relying on reservoirs, with smoother responses in the wet scenario due to higher river hydro and water supply percentages. Subsequently, they can charge the reservoirs to their maximum capacity, anticipating end-of-year market peaks when it becomes cost-efficient to use reservoirs for peak shaving rather than natural gas. In the dry scenario, the shortage of hydropower leads to higher market prices, delaying the attainment of maximum storage capacity due to increasing turbine generation and pump consumption. The pump storage consumption values in these simulations are notably lower than those in the technical scenario, primarily due to the inclusion of imports and exports. Import and export balances vary, with higher dependence on external imports in the dry scenario and greater exports in the wet and average scenarios, reflecting the impact of renewable generation levels. The model is designed to optimize overall profits, often choosing to import during low-price hours, even when water is available in the reservoir, and generating excess electricity to be sold during high-price hours.

4.4 Verification of values against the objectives of the PNIEC-PNEC

When compared to the targets set in the energy and climate plans, all scenarios demonstrate significantly reduced levels of CO_2 emissions. Portugal consistently falls below its 10 Mton emissions target in all scenarios, while Spain maintains emissions below its 50 Mton goal in all technical scenarios. Portugal's primary objective is to achieve an 85% share of renewable energy in the electricity generation mix, a target successfully met in all scenarios except the dry one, despite being closer in the market simulation with the incorporation of transmission line capacity. In Spain, the target is an 81% share of renewable energy in the electricity generation mix, which is attained in all technical scenarios assessed. Cost implications are particularly noticeable during dry years, with expenses tending to rise, sometimes exceeding those of the reference year, especially in Portugal. This cost increase is largely attributed to higher expenses related to CO_2 emissions. However, the market simulation, incorporating exchange capacity, stabilizes these cost fluctuations and keeps expenses manageable by effectively utilizing renewable energy sources and market dynamics to mitigate cost spikes. In contrast, Spain's results are notably more stable than Portugal's in the technical simulation, suggesting that Spain is better equipped to withstand the impacts of climate change, primarily due to the limited contribution of non-dispatchable hydropower in Spain. Nevertheless, price fluctuations in response to water resource scarcity are still apparent.

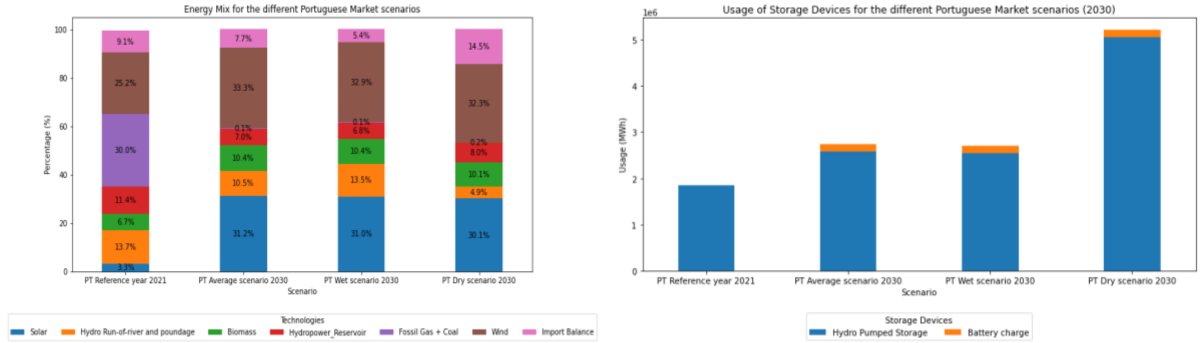

Figure 3. Energy mix (left) and usage of storage devices (right) for Portugal in economical simulation.

4.5 Hydropower consumption and generation patterns for 2030

The technical results show a consistent pattern of pump consumption during the day and turbine generation at night to reduce reliance on non-renewable sources, with the wet scenario exhibiting the highest magnitude for both variables due to abundant water resources. The primary objective of this simulation is to minimize the use of non-renewable sources. Pumping plays a vital role in achieving more consistent generation patterns, highlighting the symbiotic relationship between pump and turbine. In Spain, the results follow a similar pattern on a larger scale, with two distinctions. Turbine generation in Spain has two peaks, one in the early morning and another at the end of the day due to earlier demand increases and lower solar generation during those hours. Pump consumption in Spain remains relatively consistent across all scenarios due to a lower proportion of run-of-river hydro.

Economic results align with the conclusions in section 4.3, showing patterns similar to the technical simulation. Pumping is more dispersed, with the model initiating pumping whenever electricity prices are low. However, pump storage will be notably required in the future from a cost perspective. For this strategy, pump consumption profiles are more stable throughout the day, influenced by market variations and exhibiting year-round fluctuations. This reflects real-world situations when importing energy for pump storage is economically and strategically advantageous.

5 Conclusion

This work aimed to evaluate the impact of climate change on hydropower in the Iberian power system. It considered two critical factors: the increasing capacity of renewable energy sources and the effects of global warming on water resources, potentially leading to more frequent "dry years."

EnergyPLAN simulations provided key insights. In the 2030 technical simulations, Portugal and Spain were analyzed as isolated energy systems. Both countries are expected to significantly increase their use of renewable energy sources, reducing CO_2 emissions. However, the influence of drier years is more pronounced in Portugal, where reliance on run-of-river power plants, known for their variation across scenarios, intensified the impact. In a dry year in Portugal, there was an 8.2% reduction in hydropower output compared to an average year, leading to a 75% increase in CO_2 emissions and additional costs of 626 million euros, exceeding the 2021 reference year. In Spain, similar conditions resulted in significant but proportionally smaller impacts, with a 3.5% reduction in hydropower generation, a 68% increase in CO_2 emissions, and a cost increase of 905 million euros, still smaller than the reference scenario. Pump storage consumption played a critical role in both countries. Portugal saw a more than 400% increase, while Spain experienced substantial growth. This underscores the importance of pump storage in achieving sustainability goals and positions dammed hydropower as the primary dispatchable energy source for the future. The economic simulation favoured Portugal due to import integration instead of relying on natural gas. Anticipations suggested that renewable energy dominance in Spain would increase imports, leading to lower Iberian prices. In a dry year, market prices exhibited significant oscillations compared to the reference and wet scenarios. In this context, pump storage became even more crucial, effectively managing water resources, mitigating the impact of market price fluctuations, ensuring cost stability, and reducing CO2 emissions, contributing to the reliability and flexibility of the Iberian power system.

In summary, the comprehensive analysis suggests that hydropower, particularly when combined with reservoirs, will shift towards a regulatory role from its current status as a power system contributor. This transformation is driven by the crucial role of pump storage, which capitalizes on the growing surplus of renewables while reducing reliance on non-renewable sources. Pump storage adopts a more periodic function, aligning its operations with reservoir generation cycles. The significant increase in hydro-pumped storage signals a shift toward dammed hydropower becoming the primary dispatchable energy source in the future Iberian power system, reducing dependence on natural gas and advancing sustainable, renewable energy generation. Notably, changes occur in hydropower pumping and generation patterns, with pumping being more prevalent during the daytime, coinciding with peak solar generation, and hydropower generation mainly occurring at night when renewable generation is scarcer and electricity prices are higher.

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