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Impact of Hydroelectric Power Plants on the Electricity Market and Stability of the Electrical System

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Abstract.

Hydroelectric power plants are an extremely important part of the electricity market and one of the most reliable sources of renewable energy. The demand for electricity has gone up and so will the requirement of efficient and sustainable electricity generation. The role of hydroelectric power plants on the electricity market is in their contribution to a steady and stable supply of electricity which can reduce the intermittency of solar and wind power which is another renewable energy source. With the increasing integration of renewable energy sources, future energy systems will necessitate enhanced mechanisms for balancing supply and demand. The variability of renewable energy is leading to challenges in providing a stable and continuous supply of electricity to end users, as well as maintaining grid stability. This study evaluates the influence of hydroelectric plants on price dynamics in the Iberian Electricity Market (MIBEL). Furthermore, it examines their role in integrating renewable energy sources, enhancing system flexibility during periods of significant fluctuations in wind and solar power generation.

Key words. Hydroelectric Power Plants, Pumped-Storage Hydropower, Renewable Energy, Electricity Market, Ancillary Services, Power Systems Stability.

1. Introduction

Modern power systems are undergoing a rapid transformation, marked by the increasing integration of renewable energy generators that rely on intermittent sources like wind and solar [1]. Hydroelectric power plants play a crucial role in modern electricity markets and the stability of electrical systems, serving not only as a primary source of electricity generation, but also as a key component in ensuring grid reliability and facilitating the integration of variable renewable energy sources [2], [3]. Hydropower plants can be classified into three main types [1], [4]:

- Reservoir-storage hydropower plants (RSHP) – Also known as storage hydropower plants or dam hydropower, these facilities store water in reservoirs behind dams, allowing control over the downstream flow and, consequently, electricity generation. Reservoirs can be artificial or utilize existing lakes.
- Run-of-river (ROR) hydropower plants – These rely on the natural flow of water bodies and have limited storage capacity. If the storage capacity is below the mean daily inflow, the plant is typically classified as run-of-river.
- Pumped-storage hydropower (PSH) – A pumped hydro storage system is a large-scale, reversible energy storage technology that leverages the potential energy of water to store and generate electricity. By converting electrical energy into potential energy and back, PSH systems play a crucial role in modern power grids, ensuring grid stability, balancing supply and demand, and supporting the integration of renewable energy sources. Water is pumped into the upper reservoir during periods of low electricity demand or low electricity prices and later used to generate electricity by releasing it back to the lower reservoir through turbines.

This paper aims to present and discuss the impact of hydroelectric power plants on both the electricity market and the stability of the power system. The following sections provide an overview of the Portuguese electrical system, with a particular focus on analyzing the influence of hydroelectric generation on market dynamics, supporting the operational integration of renewable energy sources, and contributing to overall system stability.

2. Portugues Electric Power Systems

The Portuguese Electric Power System has undergone significant transformation over the past three decades, evolving from a vertically integrated and state-controlled structure into a liberalized, competitive, and increasingly renewable based system. This evolution was driven by legal and regulatory reforms, infrastructure modernization, and strong alignment with European Union directives on market integration and decarbonization.

In 2024, electricity consumption in mainland Portugal totaled 51.4 TWh. This value reflects the aggregate of net production injected by electricity production centers, of renewable and non-renewable origin, and the balance of international exchanges. As of the end of 2024, the total installed capacity exceeded 26,000 MW. In figure 1, it is possible to analyze the evolution of installed power over the last 24 years. There was a significant increase in installed power from renewable sources. They currently represent more than 70% of the installed capacity, with emphasis on the installed power in hydroelectric, wind and solar plants. It is also possible to see that the technology that has most increased its installed power in the last 3 years was solar photovoltaic.

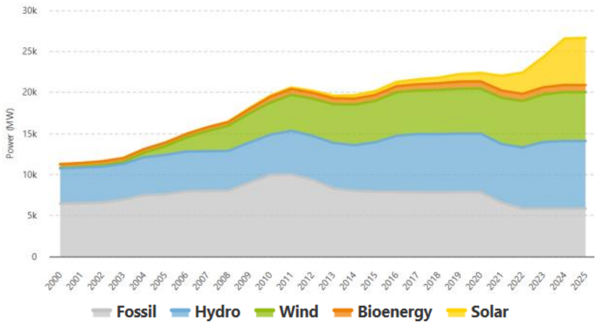

Fig. 1. Power capacity installed in Portugal [5]

Figure 2 shows the evolution of monthly electricity production for the period from February 2023 to December 2024. An examination of the figure reveals the strong contribution of energy production from renewable sources such as hydro, solar and wind. Another relevant aspect is associated with the contribution of production from hydroelectric plants at certain times of the year. The year 2023 was characterized being a year with a weak contribution of production from hydroelectric plants, a situation that was reversed from November onwards. In the period between November 2023 and May 2024, there was a very important contribution of production from hydroelectric plants, which decreased during the following months until December 2024.

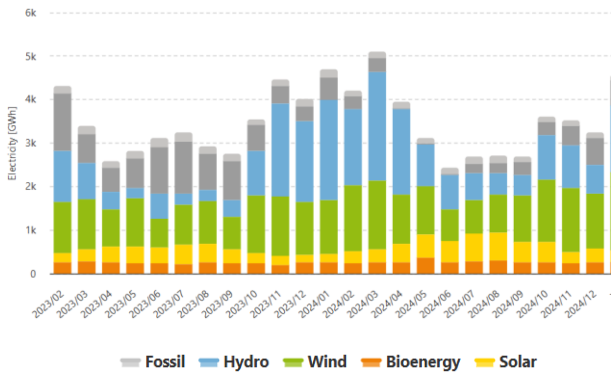

Fig. 2. Monthly Electricity Production (February 2023 – December 2024) [5]

According to data reported by system operator, Portugal achieved a record level of electricity generation from renewable sources in 2024. Regarding national electricity consumption in 2024, renewable energy accounted for 80.42 % of the total, representing a 10.8 % increase compared to 2023. On the other hand, electricity generation from fossil fuels decreased by 49 % compared to 2023. The largest contribution to renewable production came from hydroelectric plants, accounting for 31.87 % of total production, followed by wind power with a 30.97 % share. Solar photovoltaic generation represented 10.69 % of the total electricity consumed (Figure 3). It is important to highlight that electricity consumption reached the second highest value of all time and was 51.4 TWh.

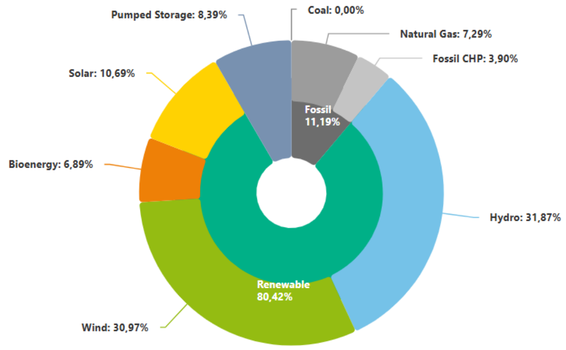

Fig. 3. Electrical energy produced in Portugal, 2024 [6]

The latest data indicate that in March 2025, renewable electricity generation totaled 4,812 GWh, exceeding mainland Portugal's electricity consumption of 4,647 GWh. This scenario demonstrates that renewable energy production exceeded demand, accounting for 103.6% of total electricity consumption. During this period, hydroelectric power plants played a dominant role, supplying 55% of total consumption, while wind power contributed 42% of the electricity supply.

Another key aspect is the impact of this increased renewable energy share on the average electricity market price. A comparative analysis shows that the average market price in March 2025 was €39.75/MWh, compared to €43.94/MWh in March 2024, when renewable generation accounted for 62% of total consumption.

3. Electricity Market and Hydroelectric Power Generation

Restructuring the electricity market and moving from monopoly to competition in different aspects has changed the industry and increased uncertainty. The Iberian Electricity Market, which includes Portugal and Spain, experienced a significant increase in electricity prices in recent years.

In figure 4, it is possible to visualize the evolution of average electricity prices in MIBEL since 2007. Between 2007 and 2021, prices varied between a maximum of 112 €/MWh in 2008 and a minimum of 34 €/MWh in 2020. A maximum price of 168 €/MWh was observed in 2022.This scenario of high prices was greatly influenced by the start of the war between Russia and Ukraine, which led to an exponential increase in fossil fuels, with a particular impact on the increase in the price of natural gas. The average price decreased to 88 €/MWh in 2023 and continued its downward trend, reaching 64 €/MWh in 2024.

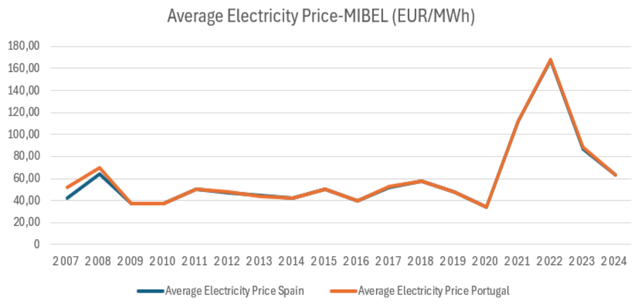

Fig. 4. Average electricity prices in MIBEL 2007-2024 [7]

Figure 5 shows the evolution of hydroelectric production contribution over the past 2 years. As can be observed, there is significant variation in the share of hydro production throughout the year. A clear seasonal pattern can be identified, with higher contributions occurring during the autumn and winter months. Hydropower generation was particularly strong from November 2023 through April 2024, but experienced a sharp drop in the following months, from May to December 2024.

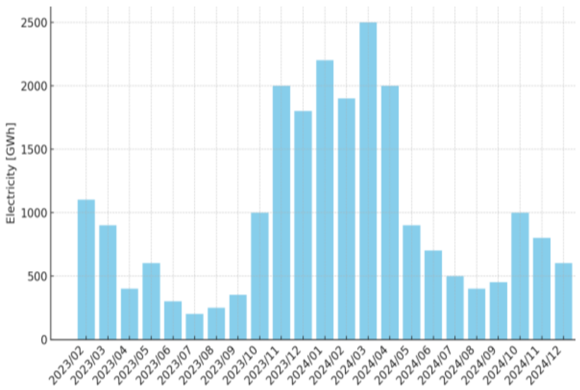

Fig. 5. Hydroelectric Generation – February 2023 to December 2024 [6]

Figures 6 and 7 illustrate the evolution of average prices in the MIBEL market for the years 2023 and 2024. As can be observed, there is a strong correlation between the variation in hydroelectric generation and the trend in market prices. Average prices in MIBEL were lower during the period from November 2023 to April 2024, which coincided with a higher contribution from hydroelectric generation. It is also worth highlighting the gradual increase in prices from May 2024 to December 2024. Once again, this upward trend was influenced by reduced hydro production, with a particularly significant impact on the prices observed in November and December 2024.

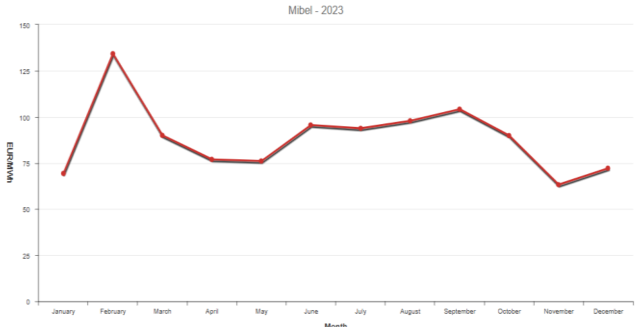

Fig. 6. Average prices in the MIBEL - 2023 [7]

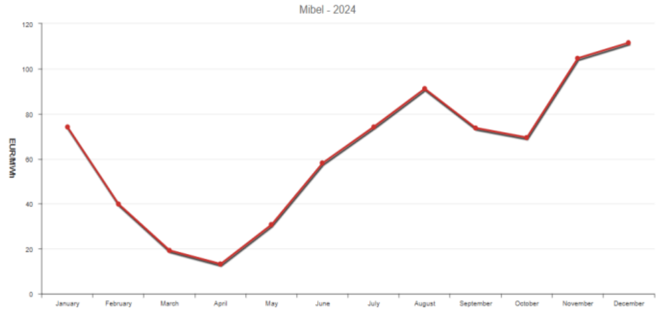

Fig. 7. Average prices in the MIBEL – 2024 [7]

The contribution of electricity generation from hydroelectric power plants also has a highly positive impact on the integration of other renewable energy sources and plays a key role in helping to control market prices. From this perspective, a specific day, January 22nd, 2025, was analyzed to illustrate this contribution.

In Figure 8, it is possible to verify the average electricity prices, for January 22nd, 2025, in the main European countries, with organized and competitive markets. It is possible to see that prices are very high. One of the main reasons for these high prices is associated with the fact that, on this day, production from renewable sources (wind and solar) throughout Europe reached very low value, which meant that more production from thermal power plants had to be used.

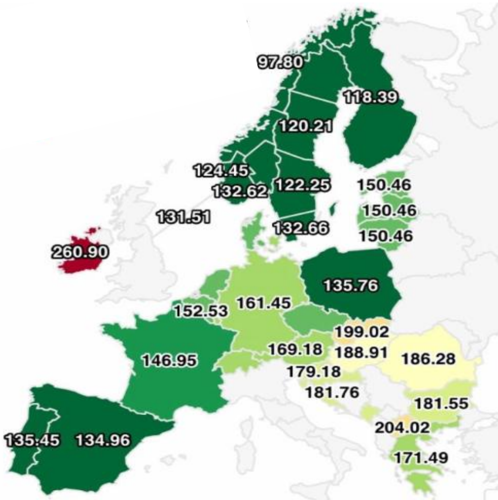

Fig. 8. Average electricity prices, for January 22nd, 2025- Europe [7]

Figure 9 shows the evolution of the hourly price for the day-market in MIBEL, for January 22nd, 2025.

Fig. 9. Average electricity prices, for January 22nd, 2025- MIBEL [7]

Figures 10 and 11 show the contribution of electricity production from renewable sources in Portugal, for January 2nd, 2025.

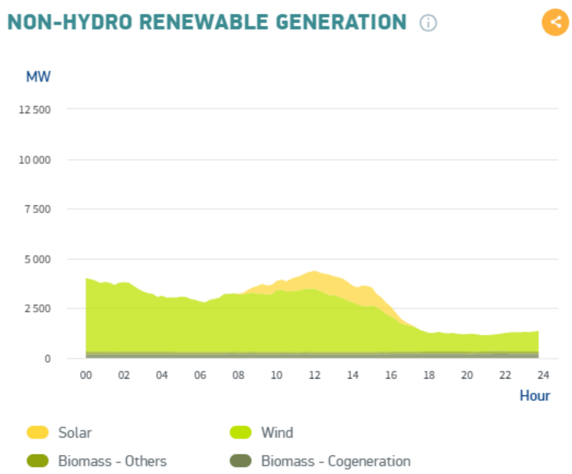

Fig. 10. Renewable Generation, for January 22nd, 2025- Portugal [6]

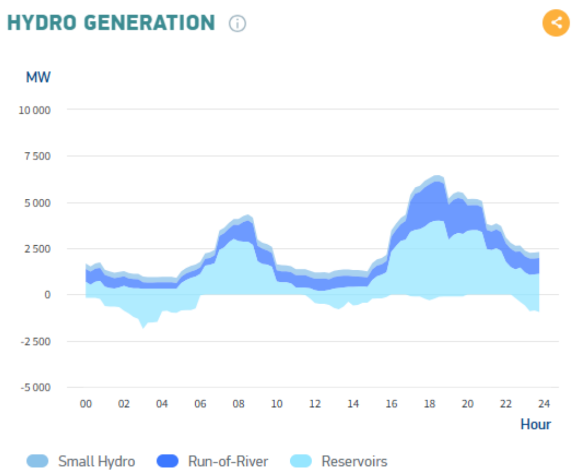

Fig. 11. Hydro Generation, for January 22nd, 2025- Portugal [6]

Comparative analysis of figures 9, 10 and 11 indicates a strong positive correlation between electricity production from renewable sources and corresponding prices in the daily market. The reduction in wind and solar energy generation was mitigated by the increase in hydroelectric production, demonstrating the complementarity between these energy sources and the relevance of hydroelectric plants for maintaining the security and stability of the electrical system. Additionally, it is observed that the increase in prices at the end of the period analyzed was limited by the dynamic response capacity of hydroelectric plants, which acted as a market regulation mechanism. It is important to highlight that this type of occurrence, characterized by high electricity demand combined with a significant reduction in wind and solar generation, is becoming increasingly frequent. This underscores the critical importance of having responsive capacity from hydroelectric power plants, not only to help limit energy price increases in the market, but also to provide a rapid response to fluctuations in generation, thereby ensuring the stable operation of the electrical system.

As previously mentioned, pumped hydro storage systems have emerged as essential energy storage solutions due to their ability to support renewable energy integration and enhance grid stability. However, these types of power plants can also benefit from periods when market electricity prices are very low, or even negative, due to excess generation, mainly from wind and solar renewable sources. By pumping water back into the reservoirs during these periods, they effectively store energy that can later be used to generate electricity during times of higher market prices. In this way, they are able to maximize the return on investment and ensure highly attractive revenues for their owners. From this perspective, March 31st, 2025, is taken as an illustrative example.

Figure 12 shows the evolution of MIBEL prices over a 24-hour period. As can be observed, there were several hours during which the market price was zero or very low. This scenario was then leveraged by power plants with pumping capability which, in the case of the Portuguese system, represent an installed capacity of 2,026 MW, to carry out pumping operations.

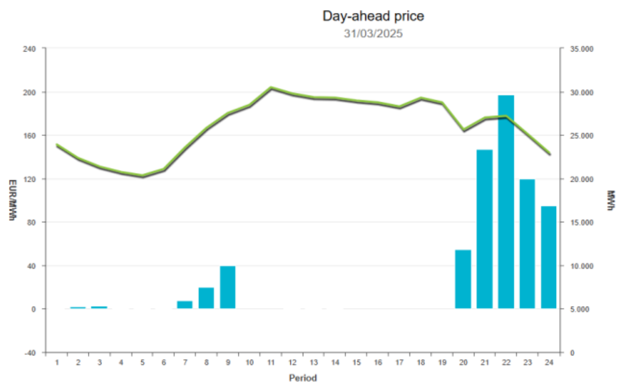

Fig. 12. Average electricity prices, March 31st, 2025 [7]

In figure 13, it is possible to see that between 9 am and 5 pm there was a high consumption by the pumping systems. During this day, the total pumping consumption was 21 GWh. On the other hand, from 7 pm onwards, when prices increased significantly, hydroelectric production took advantage of the opportunity to produce energy, thus managing to significantly profit from this production. Prices reached a maximum value of approximately 200 €/MWh in the period corresponding to 10 pm.

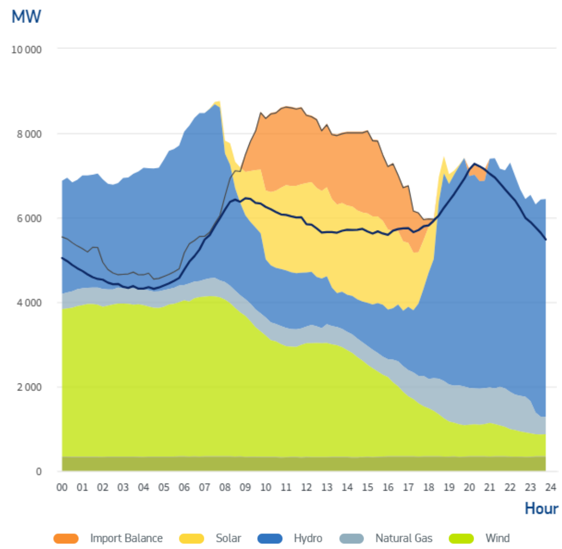

Fig. 13.Electricity generation evolution, March 31st, 2025 [6]

From the analysis of Figure 13, it is also possible to observe the contribution of hydroelectric power plants to the electrical system's ability to adapt to large fluctuations in wind and solar generation. As previously mentioned, between 9 am and 5 pm there was a significant contribution from photovoltaic plants, which were used for pumped storage. However, after 6 pm, photovoltaic generation dropped off entirely, and at the same time, wind generation also experienced a sharp decline. This reduction was fully offset by increased generation from hydroelectric power plants.

4. Hydroelectric Power Generation and Stability of Electric Power Systems

The integration of renewable energy sources and the increasing complexity of modern power grids have amplified the importance of ancillary services in maintaining grid stability and reliability [8]. Ancillary services are essential for maintaining the security and reliability of a power system, particularly in the context of competitive electricity markets where the balance between generation and demand is continuously challenged by forecasting errors. These services encompass a range of functions that support the transmission of electricity from generators to consumers, addressing various operational requirements such as frequency regulation, voltage control, and black start capability [9].

Hydropower plants are essential to the stability of the electrical grid, as they can supply both baseload and flexible generation capacity. However, the true advantage of hydroelectric energy lies in its flexibility. Unlike thermal power plants, which require a considerable amount of time to ramp production up or down, hydro facilities can quickly adapt to changes in demand and fluctuations in the supply from other renewable sources [4]. This adaptability enables hydropower plants to engage in ancillary service markets, delivering crucial grid stabilization services like frequency regulation and voltage support. Additionally, pumped hydro storage systems enhance this flexibility by storing surplus energy during low demand periods and releasing it during peak demand, effectively capitalizing on price variations in the electricity market.

The electric power system stability time horizon spans from milliseconds for electrical short circuit response, to several seconds for frequency support, and up to hours or even years for long term energy storage (figure 14). The ancillary services that hydroelectric power plants can provide include [9]:

- Synchronous Inertia;
- Fast Frequency Response (FFR);
- Frequency Containment Reserve (FCR);
- Automatic Frequency Restoration Reserve (aFRR);
- Manual Frequency Restoration Reserve (mFRR);
- Replacement Reserve (RR);
- Voltage/Reactive Power;
- Black Start.

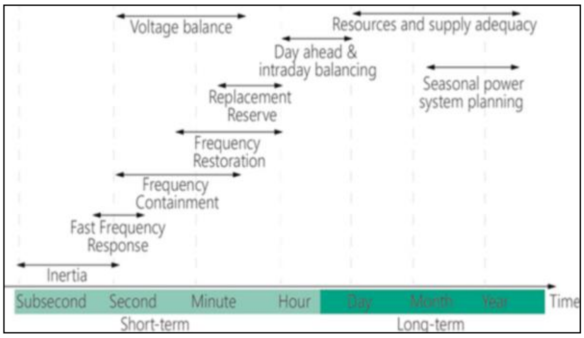

Fig. 14. Time horizon of the flexibility services provided by hydroelectric power plants [8]

The flexibility that hydro power plants offer is substantial, encompassing both power and energy. Its benefits are numerous, as hydropower generators can [1]:

- quickly adjust the power produced (often in the range of seconds);
- start and stop their units (in the range of few minutes);
- sustain production for long periods (typically for several hours or days);
- efficiently store a large amount of surplus energy volumes produced by renewable.

Based on the technical data provided by the Portuguese system operator, in 2023 a total of 2,565 GW of power were contracted for secondary regulation services. In 2024, this value increased to 4,142 GW. In 2023, hydroelectric power plants accounted for 64% of the contracted capacity (1,644 GW), while thermal power plants represented 36% (921 GW). In 2024, hydroelectric plants contributed 76% of the contracted capacity (3,139 GW), with thermal plants accounting for the remaining 24% (963 GW). The average price in 2023 was 37.03 €/MW, while in 2024 it decreased to 29.81 €/MW. The data presented highlights the significant contribution of hydroelectric power plants.

In 2024, a total of 655.5 GWh of upward Replacement Reserve (RR) energy was utilized. Hydroelectric generation contributed nearly 83% of the total amount. Regarding downward Replacement Reserve energy, the total amounted to 170 GWh, with 71% provided by hydro plants. In 2023, 582 GWh of upward Replacement Reserve (RR) energy was used, with around 81% supplied by hydroelectric sources. As for downward RR energy, the total volume was 185 GWh, of which 68% was supplied by hydro plants.

In 2024, 258 GWh of upward Automatic Frequency Restoration Reserve (aFRR) and 341 GWh of downward aFRR energy were utilized. In both cases, hydroelectric power plants were the main contributors, accounting for 85% of the upward reserve and 79% of the downward reserve. In 2023, 111 GWh of aFRR upward reserve and 190 GWh of downward reserve were used. Hydroelectric plants contributed 73% of the upward aFRR and 70% of the downward aFRR.

Figure 15 illustrates the contribution of the main technologies to electricity generation on January 5th, 2025. This day was marked by a strong output from wind power plants, which, during several hourly periods, exceeded the level of consumption. This scenario was managed using pumped-storage hydro plants, which enabled the absorption of excess energy and avoided the need to curtail renewable generation.

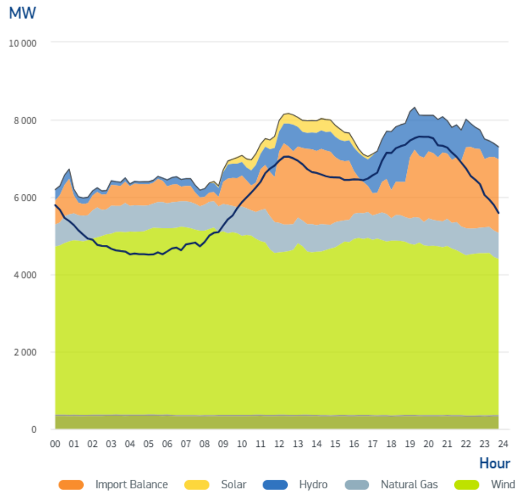

Fig. 15.Electricity generation evolution, January 5th, 2025 [6]

This highlights, once again, the flexibility that hydroelectric power plants bring to the electrical system stability. It is important to emphasize that such scenarios are becoming increasingly common, where excess generation from solar and wind power plants alone has, on certain days, forced the system operator to curtailment generation from these renewable sources.

The current state of power systems, characterized by a high share of renewable energy sources, requires special attention regarding the stability of the electrical grid. This concern is accentuated by the European Network of Transmission System Operators for Electricity (ENTSO-E), an organization that brings together electricity transmission system operators from nearly all European countries. The data presented by ENTSO-E in its Ten-Year Network Development Plans identify a series of future projects, where the focus areas are a reliable, stable, efficient, and integrated European electricity market [10]. The proposed projects include a wide range of systems involving the implementation of various hydroelectric power plants, with particular emphasis on pumped hydro storage power stations.

5. Conclusion

The primary objective of this study was to analyze the role of hydroelectric power plants in optimizing the integration of other renewable energy sources into the power system, evaluating the complementarity between hydroelectric, wind, and solar generation. The research focuses on the impact of these power plants on energy markets, as well as their contribution to improving the stability and reliability of the power system through the provision of ancillary services. An analytical assessment was conducted based on technical data related to the Portuguese power system, which is integrated into the Iberian electricity market. The data was provided by the system operator and the market operator. The analysis highlighted the significant influence of hydroelectric power plants on the operation of the electricity market. The information analyzed revealed a strong correlation between market price trends and hydroelectric power plants production, demonstrating the ability of hydroelectric generation to mitigate price increases in the electricity market. Additionally, when equipped with pumped storage capability, hydroelectric plants can take advantage of periods with lower market prices, typically driven by high generation from solar and wind sources to store energy. This stored energy can then be used during periods of higher demand and elevated prices, enhancing both system flexibility and economic efficiency. Another key aspect addressed was the role of hydroelectric generation in the integration of intermittent energy sources and its contribution to improving system stability and reliability through the provision of ancillary services, such as frequency regulation and reserve capacity.

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