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Assessment of the impact of electricity market prices on pumped hydro storage operation with renewable generation

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A R T I C L E I N F O

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A B S T R A C T

The growth of renewable energy plants and storage systems challenges future energy management. This paper analyzes the impact of hourly electricity price variations in Spain from 2023 to 2050 on the operation of pumped hydro storage systems with renewable energy. A mixed-integer hourly mathematical model that maximizes the monthly operating profit of a pumped hydro storage plant with grid-connected wind and photovoltaic generation facilities over an entire year is formulated. Subsequently, a regression model is estimated to represent the price profile of the Spanish electricity market in 2023, considering hourly electricity price data and technical and economic variables that affect price formation. The model is applied to the different hourly electricity market price profiles obtained in the proposed scenarios up to 2050. Results show an increase of 75 % of the energy imported from the grid in 2050 compared to 2023, as a consequence of the continuous reduction of electricity market prices. In addition, the use of storage is increased by 12 % because the energy produced from renewable energy facilities is used to fill the storage and ensure energy available at times of insufficient renewable generation and higher electricity market prices to maximize the system's profit.

1. Introduction

1.1. Pumped hydro storage systems

Pumped hydro energy plants account for 90 % of global energy storage capacity according to the International Hydropower Association in 2021 [1]. This type of storage has a high potential for hybridization with other power generation technologies and can operate by integrating intermittent production from wind and solar facilities. In addition to managing surplus renewable generation, it enables large-scale energy storage from hours to days, maintains grid stability and reliability, and helps load balancing by shifting electricity production from low-demand to high-demand periods, improving overall grid efficiency [2].

Depending on orographic conditions and flow availability, these facilities can be configured in closed or open loop [3]. A closed-loop facility is constructed off-stream with two reservoirs, one lower and one upper, in which water is pumped and turbined typically in daily or even weekly cycles. Water inflows are only necessary at the time of start-up and to refill the difference between evaporation and annual rainfall. The location of reservoirs far from rivers and their limited surface area significantly reduce their environmental impact [4]. It also eliminates the need to manage river flow variations, which significantly reduces construction costs. A recent research paper, which performed a life-cycle analysis of closed-loop pumped hydro storage plants in the USA, concludes that they offer environmental advantages over other energy storage technologies [5]. Thus, closed-loop facilities are growing since their potential for artificial development outside the watercourse and, in general, because of their greater flexibility from environmental, social, geological, hydrological, and logistical perspectives compared to open-loop facilities [2].

According to the report by National Hydropower Association [6], PHS is a suitable solution for balancing large amounts of intermittent renewable energy, reducing the need to build more fossil fuel generation, and potentially decreasing the amount of new transmission required. PHS technology has advanced, with improvements in the efficiency of reversible pump-turbine units and the development of variable speed units. The latter allows modulation of pumping power and the provision of frequency regulation in both pumping and generation modes, which is especially valuable with the increasing amount of renewable energy. Despite its benefits, the development of PHS faces significant challenges, for example, a lengthy regulatory process and permit acquisition can take three to five years or more. Additionally,

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Nomenclature

Indexes

h index for number of hours
i index for number of variable speed reversible pump-turbine units
y index for number of time windows

Data

$\mathrm{N_H}$ total number of hours in the time windows
N_V total number of variable speed reversible pump-turbine units
$\rho^{\mathrm{h}}_{\mathrm{exp}}$ hourly price of energy sales $\left(\frac{€}{\mathrm{MWh}}\right)$
$\rho^{\mathrm{h}}_{\mathrm{imp}}$ hourly price of energy purchase $\left(\frac{€}{\mathrm{MWh}}\right)$
$\mathrm{f_{wind}}$ operating costs of wind technology $\left(\frac{€}{\mathrm{MWh}}\right)$
$\mathrm{f_{PV}}$ operating costs of photovoltaic technology $\left(\frac{€}{\mathrm{MWh}}\right)$
$\mathrm{f_{pumping}}$ operating costs of pumping $\left(\frac{€}{\mathrm{MWh}}\right)$
$\mathrm{f_{turbining}}$ operating costs of turbining $\left(\frac{€}{\mathrm{MWh}}\right)$
$\mathrm{E^h_{PV,max}}$ hourly energy availability from photovoltaic generation (MWh)
$\mathrm{E^h_{wind,max}}$ hourly energy availability from wind generation (MWh)
$\mathrm{E^h_d}$ hourly energy demand (MWh)
$\mathrm{P^h_{cap}}$ grid connection capacity (MW)
$\mathrm{E^h_{storage,min}}$ minimum capacity of the storage system (MWh)
$\mathrm{E^h_{storage,max}}$ maximum capacity of the storage system (MWh)
$\mathrm{P^h_{turb,min,i}}$ minimum power of variable speed unit *i* in turbining mode (MW)
$\mathrm{P^h_{pump,min,i}}$ minimum power of variable speed unit *i* in pumping mode (MW)
$\mathrm{P^h_{turbining,nom,i}}$ rated power of variable speed unit *i* in turbining mode (MW)
$\mathrm{P^h_{pumping,nom,i}}$ rated power of variable speed unit *i* in pumping mode (MW)
$\eta^{\mathrm{h}}_{\mathrm{pumping,i}}$ hourly pumping performance of variable speed unit *i* in pumping mode
$\eta^{\mathrm{h}}_{\mathrm{turbining,i}}$ hourly turbining performance of variable speed unit *i* in pumping mode
$\mathrm{k_{start}}$ start-up costs of the reversible pump-turbine units (€)

Variables

E^h_{exp} hourly energy exported to the grid (MWh)
E^h_{imp} hourly energy imported from the grid (MWh)
E^h_{PV} hourly energy from photovoltaic generation (MWh)
E^h_{wind} hourly energy from wind generation (MWh)
I^h_{exp} binary variable equal to 1 if energy is exported to the grid, otherwise it will be equal to 0
I^h_{imp} binary variable equal to 1 if energy is imported from the grid, otherwise it will be equal to 0
$I^h_{\mathrm{pumping},i}$ binary variable equal to 1 if the variable speed unit *i* runs in pumping mode, otherwise it will be equal to 0
$I^h_{\mathrm{turbining},i}$ binary variable equal to 1 if the variable speed unit *i* runs in turbining mode, otherwise it will be equal to 0
I^h_{pumping} binary variable equal to 1 if the reversible units run in pumping mode in each hour, otherwise it will be equal to 0
$I^h_{\mathrm{turbining}}$ binary variable equal to 1 if the reversible units run in turbining mode in each hour, otherwise it will be equal to 0
$I^h_{\mathrm{pumping,total}}$ integer variable representing the total number of units in pumping mode in each hour
$I^h_{\mathrm{turbining,total}}$ integer variable representing the total number of units in turbining mode in each hour
$I^h_{start_i}$ binary variable equal to 1 if the variable speed unit *i* starts up and 0 otherwise
E^h_{storage} hourly energy stored (MWh)
$E^h_{\mathrm{pumping},i}$ hourly energy of variable speed unit *i* in pumping mode (MWh)
$E^h_{\mathrm{turbining},i}$ hourly energy of variable speed unit *i* in turbining mode (MWh)
$E^h_{pumping,total}$ total hourly energy in pumping mode (MWh)
$E^h_{turbining,total}$ total hourly energy in turbining mode (MWh)
$C^h_{\mathrm{start},i}$ hourly start-up cost of variable speed pump-turbine unit *i* (€)
B operating profit (€)
R^h_{exp} hourly income from the sale of energy in the electricity market (€)
C^h_{imp} hourly costs for importing energy from the grid (€)
$C^h_{pumping}$ total hourly pumping costs (€)
$C^h_{turbining}$ total hourly turbining costs (€)
C^h_{pv} hourly photovoltaic production costs (€)
C^h_{wind} hourly wind production costs (€)
C^h_{start} total hourly start-up costs (€)

existing market structures and regulatory frameworks often fail to adequately recognize or compensate for the multiple benefits that PHS provides to the grid.

Paper [7] highlights the potential of closed-loop systems. Globally, approximately 616,000 suitable off-river sites have been identified for reservoir development. These locations are notable for their ability to store large volumes of water using relatively small amounts of rock for wall construction. They are also distinguished by the presence of nearby site pairs with significant altitude differences, which maximize hydraulic head. Ideally, these sites should be located outside major urban areas or protected zones and be widely distributed to support regional networks. The capital cost of closed-loop PHS systems is divided into energy and power costs, which can be minimized with high hydraulic head and an efficient ratio of useable water to rock needed to build the reservoirs.

Energy storage is increasingly needed to support growing solar and wind generation, helping to balance supply and demand on different time scales. A renewable grid requires approximately one day of storage per energy consumption, estimated at 20 GWh and 1 GW per million people in Australia [7]. Closed-loop PHS systems offer an efficient solution with low land and water requirements, being significantly less than other energy technologies. Open-loop pumped hydro storage plants can be built from existing hydroelectric systems by replacing their turbines with reversible turbines [8].

1.2. Integration renewable energy and pumped hydro storage systems

The intermittency of solar and wind energy, along with the increasing saturation of electrical grids, makes it necessary to develop energy storage projects in order to ensure demand coverage and supply security with minimal use on fossil fuel-based electricity generation. Some research focuses on the use of composite materials based on phase change materials (PCMs) to optimize solar energy systems. Article [9] focuses on theoretical modeling, while paper [10] includes experimental validation.

Other articles have explored the integration of pumped hydro storage with renewable generation and combined with non-renewable energy sources to minimize operating costs. Paper [11] aims to minimize the daily operating cost of a grid-connected hybrid energy system composed of photovoltaic (PV) energy and pumped hydro storage (PHS). Additionally, it evaluates the impact of water level on the system's operating cost. The authors of [12] include pumped hydro storage using groundwater. The authors of [13] compare the operation of a wind-hydroelectric hybrid system, analyzing two configurations: one with a conventional hydroelectric power plant and the other with a pumped hydro storage. The authors of [14] include wind uncertainty management. Other works combine both renewable energy or non-renewable energy sources. The authors of [15] study the integration of wind and photovoltaic plants with PHS connected to the power grid. Work [16] focuses on the combination of wind, photovoltaic, and PHS in an abandoned mine. The authors of [17] include thermal energy. Paper [18] optimizes the operation of a hybrid energy system composed of PV-PHS and a diesel generator to minimize fuel consumption.

As stated by the authors of [19], models of solar-wind hybrid systems with PHS are primarily classified based on the following system objectives: reliability, feasibility, and energy management. Regarding reliability, many studies evaluate the system's reliability by calculating indicators such as Loss of Power Supply Probability (LPSP), Expected Energy Not Served (EENS), and other related metrics. In terms of feasibility, several works focus on the economic viability of implementing PHS by incorporating economic indicators like Cost of Energy (COE), Net Present Value (NPV), and payback period, among others. Lastly, other articles explore strategies to optimize the energy management of solar-wind-PHS systems, aiming to minimize operating costs and improve overall system performance. According to these categories, the model proposed in this article focuses on the objective of energy management in solar-wind-PHS systems.

Therefore, the integration of renewables with pumped hydro storage systems leads to different directions of study: technical, techno-economic, economic, and energy management. Paper [20] studies an economic valuation of water for short-term generation scheduling in a stand-alone hybrid system. The authors of [21] develop a multi-objective model that considers both economic benefits and system stability through the minimization of fluctuations. Article [22] optimizes the capacities of the components of an isolated microgrid, explicitly incorporating the concept of demand response as a means to reduce investment. The authors of [23] propose a robust stochastic optimization model for the scheduling of a hybrid system including gas turbines, addressing the uncertainty of renewables.

Work [24] proposes a two-stage optimization structure that incorporates an hourly contractual agreement and a frequency-based pricing mechanism for the operation of a grid-connected hybrid system. Paper [25] analyzes the unused potential of an open well as an energy storage system in a small-scale hybrid system. The authors of [26] investigate multi-objective optimization for different configurations of grid-connected hybrid systems, in order to minimize emissions and voltage security as well as operating cost. Article [27] proposes the techno-economic management of an isolated microgrid, considering the uncertainty of renewable energy and demand response.

As pumped-solar-wind systems consist of different power generation and storage components, the challenge is to obtain optimal operation, [25]. This is necessary to ensure that the maximum profit is reached and costs of investment, operation and maintenance of the system can be recovered. To achieve this, it is essential to design an operational strategy that manages the complementarity of the system components. The authors of [26] focus on very short-term operation (hourly and real-time), adapting to changing conditions and minimizing deviations from the previous day's contracts. Paper [27] is based on long-term planning and assessment to determine the optimal capacity of the hybrid offshore wind-pumped hydro storage system. In addition, decision variables, objective function and constraints must be selected, for which appropriate mathematical models must be established [28].

1.3. Optimization methods

In the literature reviewed, heuristic or mathematical methods are used to obtain the optimal operation of pumped hydro storage systems. Heuristic methods are fast techniques that seek satisfactory solutions without guaranteeing the optimum, using approximations for complex problems. The authors of [11] use a variant of crow search algorithm to minimize the daily operation cost. Similarly, the authors of [18] apply another modification of crow search algorithm to minimize the diesel generator fuel cost. These variations improve the ability to find optimal solutions and provide more robust and accurate results than genetic algorithms. Paper [21] uses genetic algorithms to optimize storage size. Article [27] uses genetic algorithms to handle multi-objective optimization. On the other hand, mathematical optimization methods ensure that the solution found is optimal. They are based on a precise mathematical formulation of the problem, and explore the entire space of possible solutions. They provide results that can be verified and validated by mathematical proofs. These methods include techniques such as linear programming [12], integer programming [14], and interior point algorithms [29], among others. Mathematical optimization methods are suitable when accuracy and guarantee of the optimal solution are crucial. For this reason, a mixed integer mathematical optimization model is used in this paper. According to these articles, operating costs can be reduced by 15–50 % in pumped hydro storage systems, depending on climatic conditions and system configuration.

1.4. Impact of electricity market price on pumped hydro storage systems with renewable generation

The profitability of investments in energy production and storage infrastructures in liberalized market environments depends, among other factors, on the evolution of the average price and the hourly price profile of the electricity market, so it is interesting to have estimates of these prices in the long term. The literature on long-term hourly electricity price forecasting is sparse compared to short-term research. Several articles focus on studying the impact of renewables in different electricity markets, Germany [30], Spain [31], India [32]. On the other hand, other papers establish short-term forecasting of the day-ahead electricity market price, in Australian, Pennsylvania-New Jersey-Maryland (PJM) and Spanish electricity markets [33], Nord Pool spot electricity market [34], Iranian electricity market [35], and Italian market [36].

The volatility of electricity market prices offers opportunities to optimize the operation of storage systems. Accurately predicting electricity prices allows users and producers better decision making that enables them to load storage units when prices are low and discharge energy to the grid when prices are high, thus reducing costs and earning higher income [34]. This also helps stabilize the system and improve profitability, especially in hydropower generation, where reservoirs can function as "virtual batteries" to maximize profits [35].

The growing integration of renewable energy sources into electricity markets has a direct impact on price formation. With near-zero marginal costs, renewables are typically granted dispatch priority, displacing more expensive generation sources and generally leading to lower electricity prices [32]. This effect has been confirmed in markets such as Germany [30], Spain [31], Australia [33], and Italy [36]. However, the intermittency of wind and PV sources can also increase price volatility. In particular, wind generation has been associated with higher price fluctuations, while solar generation can contribute to stabilize prices by coinciding its production with peak demand hours [37].

Renewable generation presents asymmetric variations that impact wholesale market prices unevenly. An increase in production tends to reduce prices, while a decrease can raise them more significantly and for a longer duration. In particular, negative shocks to solar and wind generation tend to have more pronounced effects than positive ones. This asymmetry in volatility introduces risks for market participants and can influence investment decisions within the electricity sector [32].

In short, price variability in the electricity market directly impacts the operation and optimization of energy storage, opening up opportunities for strategic purchasing and selling. The integration of renewable sources tends to reduce prices, although their intermittent nature can increase volatility. Therefore, understanding and anticipating these fluctuations is key for decision making, as well as for efficient planning and management of supply and demand in energy systems with high penetration of renewables.

1.5. Research gaps, objective and contributions

From the literature reviewed, the need for research on the technical and economic dispatch that integrates different types of renewable generation with reversible pumped hydro storage connected to the grid to guarantee an industrial demand, in addition to its adaptation to future scenarios of variability of hourly prices in the electricity market, is verified. In addition, it is necessary to propose optimal long-term management models to improve the profitability of pumped hydro storage projects. The penetration of wind and photovoltaic production in the electricity mix will introduce changes in the maximum and minimum prices throughout the day, which will have an impact on the operating strategies of reversible pumped hydro storage plants.

Therefore, the main gaps identified are.

- Previous studies have addressed management optimization, but few works have focused on its application in specific real-world scenarios, assessing both its optimality and operational feasibility. The model proposed in this paper is applied to a project under development in Spain.
- Previous papers do not assess the techno-economic behavior of reversible pumped hydro storage under future electricity market conditions.
- The lack of studies that include long-term price projections.

In this context, the primary objective is to address the following research question: What is the impact of the estimated evolution of hourly electricity prices in Spain up to 2050 on the strategic planning of pumped hydro storage systems?

The main objective of this paper is to assess the effect of the variation of the annual hourly profile of electricity market prices on the operation of reversible pumped hydro storage plants. For this purpose, an hourly model for the optimal management of a reversible pumped hydro storage plant with grid-connected wind and photovoltaic production facilities is developed and applied to a project under development in Spain. The model seeks to benefit the opportunities for purchasing and selling energy and maximize the monthly economic profit of the system. Subsequently, the evolution of hourly electricity market prices from 2023 to 2050 is estimated, as a consequence of renewable energy and storage expansion plans. Based on this estimate, the operation optimization will be spread over the twelve months of a year with the different price profiles up to 2050.

Therefore, the main contributions of this paper are as follows.

- Development of an hourly mathematical model for optimal operation of a closed-loop reversible pumped hydro storage plant with grid-connection photovoltaic and wind generation. The energy system can benefit market opportunities through the strategic purchase and sale of energy in the electricity market.
- Application of the model to real data from a project in Spain, providing practical insights and validating the model's effectiveness in real-world conditions.
- Assessment of the optimal management of pumped hydro storage with renewables under different estimated price profiles from 2023 to 2050. These profiles reflect the dynamic nature of energy markets and provide a comprehensive view of how energy storage systems should adapt to future price fluctuations.

This paper presents not only a theoretical model, but also a real-world application model. It assesses the long-term operation of pumped hydro storage with renewable generation under realistic future electricity market dynamics in Spain. This prospective operational analysis, in particular on an hourly basis over the next few years, offers investors and policy makers practical insights that go beyond theoretical modeling.

The rest of the paper is structured as follows: Section 2 formulates the hourly mathematical model for the operation of pumped hydro storage plants with renewable generation. Section 3 estimates the hourly electricity market price profile. Section 4 defines the case study. Subsequently, the results obtained for electricity market price variation scenarios from 2023 to 2050 are analyzed in Section 5. Finally, Section 6 summarizes the main conclusions of this research.

2. Formulation of mathematical model

The objective of this paper is to obtain the optimal hourly operation of a system composed of grid-connected photovoltaic and wind generation plants together with a pumped hydro storage system to maximize the monthly operating profit of the system, and to satisfy an electricity demand (see Fig. 1). In addition, the optimization is extended for the 12 months of a year to provide an in-depth operational analysis. Since the model must continuously meet the hourly electricity demand, it is connected to the grid to ensure operational flexibility. This connection allows the system to purchase electricity from the Spanish wholesale market during periods of low renewable generation and when storage levels are insufficient. Conversely, when there is surplus energy and market prices are favorable, the system can sell electricity to the energy market in order to maximize operating profit. The storage system consists of reversible pump-turbine units, which can operate in either pumping or generating mode, depending on the system's requirements at any given time.

2.1. Model assumptions

The assumptions included in this work are as follows.

- The model incorporates grid-connected self-consumption photovoltaic and wind facilities with pumped hydro storage to meet demand. In this regard, the system can exploit opportunities to exchange energy with the wholesale electricity market by purchasing and selling energy when it is most economically profitable.
- The purchase price of energy in the wholesale electricity market is based on a pass-through contract indexed to wholesale electricity market prices, which allows large consumers to benefit from hourly changes in electricity prices.
- Production costs of wind and photovoltaic energy are included in the objective function. Based on the system's optimal hourly operation, the energy generated from these technologies is optimized to maximize the profit, or, alternatively, to meet the technical conditions of the system. The optimization model can help determine whether it is more cost-effective to operate a renewable plant or purchase energy from the wholesale electricity market at a given time, according to the operating costs.
- Wind and photovoltaic production forecasts, along with hourly electricity purchase and sale prices in the day-ahead market, are

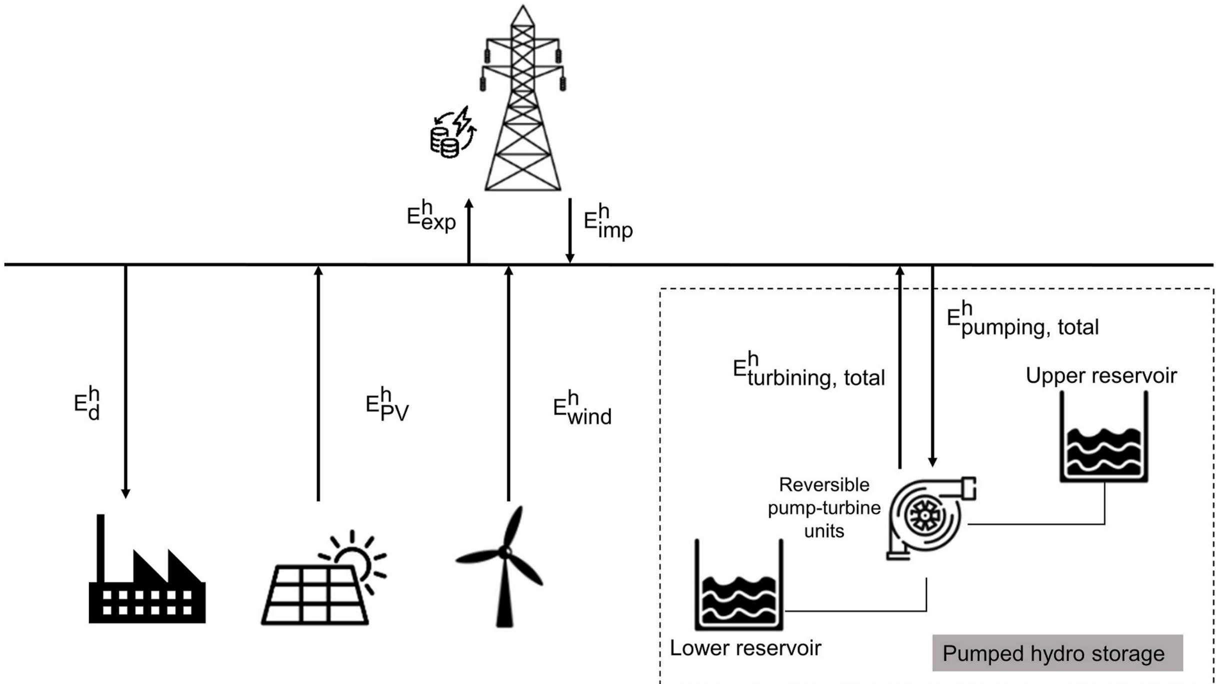

Fig. 1. Scheme of the proposed techno-economic model.

available the day before to obtain the system's optimal scheduling [38]. To study of the variability of electricity market prices, the optimization of the techno-economic management of the system is calculated. This calculation uses price estimates from 2023 to 2050. Price estimates will be explained in Section 3.

- The storage volume and the water withdrawal system are designed so that evaporation losses do not affect its useful volume.
- All the modeled units are reversible, allowing either pumping or turbining operation mode, depending on demand and available resources. These units help improve operational efficiency, provide flexibility to the grid, and facilitate the integration of renewable energy sources [39].
- The pump-turbine units are variable speed to improve operating efficiency and adjust to the needs of the system. Compared to conventional fixed speed technology, variable speed units offer faster response to load changes, higher efficiency and flexibility in both pumping and turbining modes, and improved operating and regulation characteristics [40].
- As a consequence of the use of variable speed units, restrictions have been included to impose the same operating regime of the units in each hour to avoid short-circuiting of the variable speed reversible units. Therefore, in this way, it is avoided that some of them run in pump mode and others in turbine mode in the same hour. Hydraulic short circuit can cause fluctuations in water flow, affecting the stability of the machines and the system as a whole.
- The efficiency of reversible pump-turbine units is considered constant for the entire operating range, both in pumping and generating modes. It is assumed that water is always released from a constant head and there is no loss of water in the PHS system due to evaporation [41]. In addition, the variation of performance against speed changes is assumed to be negligible since the speed variation is less than 33 % of the nominal speed of the units [42].
- The model takes into account start-up costs of the pump-turbine units in the objective function, since a high number of start-ups can reduce their lifespan. The inclusion of start-up costs in operational planning provides a more accurate representation of economic expenditures, and also encourages dispatch strategies that lead to minimizing units' degradation and improving long-term operating sustainability.

2.2. *Mathematical model*

The objective of the proposed model is to optimize the hourly energy management of production, storage and consumption facilities in order to maximize the monthly economic profit of the system. The monthly optimization will be extended for a full year. Furthermore, the system is connected to the grid to take advantage of the opportunities to purchase and sell energy in the wholesale electricity market, in addition to being able to meet the required electricity demand at all times. As shown in Fig. 1, the whole system consists of a photovoltaic and wind generation plant, the electricity grid, a reversible pumped hydro storage and an industrial consumer.

The mathematical model is formulated as a mixed-integer problem with 25 variables to be optimized every hour for the twelve months of the year. Seven of them are of binary integer type (value 0, 1) for decision making in the problem, as will be explained below. From the optimization of the mathematical model, the optimal technical and economic scheduling of the proposed system is obtained. The input data will include actual power generation and demand data, technical data on reversible pump-turbine units, as well as purchase and sale prices in the electricity market.

The main continuous variables of the model are as follows.

- Hourly wind and photovoltaic power production (E^h_{wind}, E^h_{pv})
- Hourly amount of energy imported/exported to the grid (E^h_{imp}, E^h_{exp})
- Hourly energy pumped/turbined from each variable speed unit ($E^h_{pumping,i}, E^h_{turbining,i}$)
- Hourly stored energy level ($E^h_{storage}$)
- Hourly start-up cost for each unit ($C^h_{start,i}$)

The binary variables of the model are as follows.

- Modes of energy exchange with the grid: import/export (I^h_{imp}, I^h_{exp})
- Operating modes of each of the reversible units: pumping/turbining ($I^h_{pumping,i}, I^h_{turbining,i}$).
- Operating mode of reversible units in each hour $\left(I^h_{pumping}, I^h_{turbining}\right)$

- Start-up of reversible units ($I^h_{start,i}$)

Fig. 2 represents the flowchart of the proposed model.

The objective function in addition to economic and technical constraints of the proposed problem are explained below.

- Objective function

The objective function maximizes the economic profit (B) resulting from the difference between income and costs of the system (Equation (1)). Index *y* indicates the calculation period, having a value from 1 to *Y*, wherein *Y* corresponds to the total number of periods considered for the analysis. In this case, since the optimal operation of the system is sought for one month and the optimization is extended to a whole year, a period *y* is associated with one month, and, therefore, there are 12 periods (Y). Equations (2)–(8) detail the calculation of income and costs included in the objective function. Income is generated from the hourly sale of excess energy to the day-ahead electricity market. On the other hand, costs include the hourly energy purchased from the electricity market when the system's own production is insufficient to meet demand and energy prices are competitive, the energy used for pumping or generated through turbining in the storage system, start-up costs of reversible units, and the hourly energy produced by each renewable generation facility.

Equation (2) establishes the hourly income (R^h_{exp}) obtained from the sale of surplus generated energy to the grid. It is equal to the product of the hourly energy exported and the hourly price fixed in the wholesale electricity market $\left(\rho^h_{exp} \cdot E^h_{exp}\right)$.

Equation (3) defines the hourly cost of importing energy (C^h_{imp}) from the grid. It is equal to the product of the hourly energy imported and the hourly price of energy purchase in the electricity market $\left(\rho^h_{imp} \cdot E^h_{imp}\right)$.

Equation (4) calculates the total hourly costs associated with pumping ($C^h_{pumping}$) as the product of the pumping operation and maintenance costs and the total energy pumped to the storage $\left(f_{pumping} \cdot E^h_{pumping,total}\right)$. Equation (5) formulates turbining costs ($C^h_{turbining}$) as the product of the turbining operation and maintenance costs and the total hourly amount of energy turbined from the storage $\left(f_{turbining} \cdot E^h_{turbining,total}\right)$.

Equation (6) indicates the total start-up costs (C^h_{start}) of the reversible units in each hour ($C^h_{start,total}$).

Finally, Equations (7) and (8) calculate the hourly costs of photovoltaic (C^h_{pv}) and wind energy production (C^h_{wind}), respectively. These equations are the result of multiplying the amount of energy produced by each technology by its operation and maintenance costs ($f_{pv} \cdot E^h_{pv} / f_{wind} \cdot E^h_{wind}$).

$$\max((B)) = \sum_{y=1}^{Y} \times \sum_{h=1}^{N_H} \left(R^h_{exp} - C^h_{imp} - C^h_{pumping} - C^h_{turbining} - C^h_{start} - C^h_{pv} - C^h_{wind}\right)_y \tag{1}$$

$$R^h_{exp} = \rho^h_{exp} \cdot E^h_{exp} \tag{2}$$

$$C^h_{imp} = \rho^h_{imp} \cdot E^h_{imp} \tag{3}$$

$$C^h_{pumping} = f_{pumping} \cdot E^h_{pumping,total} \tag{4}$$

$$C^h_{turbining} = f_{turbining} \cdot E^h_{turbining,total} \tag{5}$$

$$C^h_{start} = C^h_{start,total} \tag{6}$$

$$C^h_{pv} = f_{pv} \cdot E^h_{pv} \tag{7}$$

$$C^h_{wind} = f_{wind} \cdot E^h_{wind} \tag{8}$$

- Constraints
- Energy balance:

The sum of the hourly energy input and output of the system from the different sources must be equal to the energy demanded in each hour (E^h_d). The energy input sources include imported energy from the grid (E^h_{imp}), wind generation (E^h_{wind}), photovoltaic production (E^h_{pv}) and total

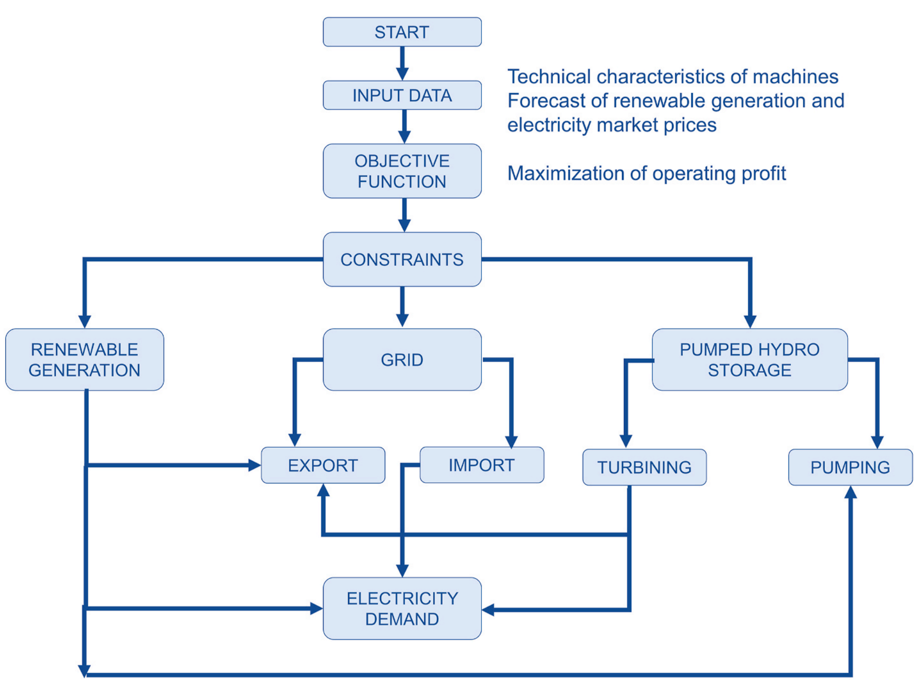

Fig. 2. Flowchart of the proposed model.

energy turbined ($E^h_{turbining,total}$) from the storage system. On the other hand, as sources of energy output, the energy exported to the grid (E^h_{exp}) and the total energy pumped to storage ($E^h_{pumping,total}$) are considered. These input and output flows must satisfy the energy balance constraint, as shown in Equation (9).

$$E^h_d = E^h_{imp} - E^h_{exp} + E^h_{wind} + E^h_{pv} + E^h_{turbining,total} - E^h_{pumping,total} \tag{9}$$

- Wind and photovoltaic generation constraints:

Hourly renewable generation is limited by the maximum production availability of each technology, wind and photovoltaic ($E^h_{wind,max}$, $E^h_{pv,max}$). Thus, Equation (10) limits the hourly wind power generation (E^h_{wind}) between zero and the maximum production value, while Equation (11) sets the hourly PV power generation limit (E^h_{pv}) between zero and the maximum production value.

$$0 \leq E^h_{wind} \leq E^h_{wind,max} \tag{10}$$

$$0 \leq E^h_{pv} \leq E^h_{pv,max} \tag{11}$$

- Electricity import/export to the grid constraints:

Equation (12) imposes that the purchase and sale of energy in the electricity market cannot occur simultaneously in each hour. To avoid this situation, two binary variables represent the decision making regarding the import (I^h_{imp}) or export (I^h_{exp}) of energy to the grid. Therefore, there are three possible situations in each hour: energy is being imported $\left(I^h_{imp} = 1, I^h_{exp} = 0\right)$, energy is being exported $\left(I^h_{imp} = 0, I^h_{exp} = 1\right)$, or, there is neither export nor import $\left(I^h_{imp} = 0, I^h_{exp} = 0\right)$.

$$I^h_{imp} + I^h_{exp} \leq 1 \tag{12}$$

There are also hourly limits on the amount of energy imported and exported to the grid. Equation (13) states that, if the system is importing energy, and, therefore, the import binary variable, I^h_{imp}, is equal to 1, the hourly energy imported (E^h_{imp}) cannot exceed the hourly energy demanded (E^h_d). This ensures that the system does not import more energy than required. On the other hand, Equation (14) indicates that, if the system is exporting energy, the export binary variable, I^h_{exp}, is equal to 1, the maximum energy that can be exported will be limited to the grid connection capacity ($P^h_{cap} \cdot \Delta t$). This limitation ensures that the energy exported does not exceed the technical limits of the connection to the grid.

$$0 \leq E^h_{imp} \leq I^h_{imp} \cdot E^h_d \tag{13}$$

$$0 \leq E^h_{exp} \leq I^h_{exp} \cdot P^h_{cap} \cdot \Delta t \tag{14}$$

-Pumped hydro storage constraints:

The system includes a reversible pumped hydro storage plant to make better use of renewable energy and benefit more from the variability of electricity market prices. Equation (15) calculates the hourly storage level ($E^h_{storage}$) as the energy stored in the previous hour ($E^{h-1}_{storage}$) plus the total energy pumped by the reversible units to fill the storage, $\left(E^h_{pumping,total} \cdot \eta^h_{pumping}\right)$, minus the total energy generated through the turbining process in the current hour $\left(E^h_{turbining,total}/\eta^h_{turbining}\right)$.

$$E^h_{storage} = E^{h-1}_{storage} + E^h_{pumping,total} \cdot \eta^h_{pumping} - E^h_{turbining,total} \Big/ \eta^h_{turbining} \tag{15}$$

The storage level at the initial hour of the next calculation month ($E^h_{storage,y+1}(h = 1)$) must be equal to the storage level at the final hour of the previous month ($E^h_{storage,y}(h = N_H)$), (see Equation (16)).

$$E^h_{storage,y}(h = N_H) = E^h_{storage,y+1}(h = 1) \tag{16}$$

It is assumed that the storage level at the initial hour of the study period ($E^h_{storage,1}$ $(h = 1)$) is equal to the storage level at the final hour in the last period considered ($E^h_{storage,Y}$ $(h = N_H)$), (see Equation (17)). This constraint is included to obtain a consistent operation scheme for the reservoir.

$$E^h_{storage,1}\ (h = 1) = E^h_{storage,Y}\ (h = N_H) \tag{17}$$

The storage system has a minimum and maximum capacity ($E^h_{storage,min}$, $E^h_{storage,max}$,), so the level of energy stored in each hour must be between both limits (Equation (18)).

$$E^h_{storage,min} \leq E^h_{storage} \leq E^h_{storage,max} \tag{18}$$

Regarding constraints of the variable speed pump-turbine units, a constant efficiency over their entire operating range is considered for both pumping $\eta^h_{pumping}$ and turbining $\eta^h_{turbining}$. The hourly binary variable ($I^h_{turbining,i}$) determines whether the unit runs in turbining mode. The hourly energy generated by the units in turbine mode during each hour must be within a defined range. The lower bound is determined by the unit's minimum turbining power output, ($P^h_{turbining,min,i} \cdot \Delta t$), while the upper bound corresponds to the nominal power of the units in turbining mode ($P^h_{turbining,nom,i} \cdot \Delta t$), as shown Equation (19):

$$\begin{aligned}\eta^h_{turbining} \cdot P^h_{turbining,min,i} \cdot I^h_{turbining,i} \cdot \Delta t \leq E^h_{turbining,i} \\ \leq \eta^h_{turbining} \cdot P^h_{turbining,nom,i} \cdot I^h_{turbining,i} \cdot \Delta t\end{aligned} \tag{19}$$

Equation (20) shows the operating range of the variable speed units in pumping mode. The hourly binary variable ($I^h_{pumping,i}$) determines whether the unit runs in pumping mode. $\eta^h_{pumping}$ represents the hourly efficiency in pumping mode. The hourly energy pumped by the units during each hour must be within a defined range. The lower bound corresponds to the unit's minimum pumping power output ($P^h_{pumping,min,i} \cdot \Delta t$), while the upper bound is associated with the nominal power of the units in pumping mode ($P^h_{pumping,nom,i} \cdot \Delta t$).

$$\left(\frac{P^h_{pumping,min,i}}{\eta^h_{pumping}}\right) \cdot I^h_{pumping,i} \cdot \Delta t \leq E^h_{pumping,i} \leq \left(\frac{P^h_{pumping,nom,i}}{\eta^h_{pumping}}\right) \cdot I^h_{pumping,i} \cdot \Delta t \tag{20}$$

The pumping ($I^h_{pumping,i}$) and turbining ($I^h_{turbining,i}$) mode cannot occur simultaneously in each hour, so the sum of the binary variables must always be less than or equal to 1, as can be seen in Equation (21). The variable $I^h_{pumping,i}$ indicates that the system is pumping and filling the storage for further use, therefore, if this variable is equal to 1, the system is pumping. On the other hand, the variable $I^h_{turbining,i}$ indicates that the system is turbining and emptying the storage to provide the necessary energy to the system, therefore, if the variable $I^h_{turbining,i}$ is equal to 1, the system is turbining energy.

$$I^h_{pumping,i} + I^h_{turbining,i} \leq 1 \tag{21}$$

Equations (22)–(26) show the constraints for all the variable speed reversible units in the pumped hydro storage system to run in the same operating regime (pumping, turbining or shutdown). These constraints prevent the short-circuiting of variable speed reversible units, i.e., units operate in pump mode and units operate in turbine mode at the same hour. For the decision making, binary variables are included $I^h_{pumping}$, $I^h_{turbining}$. Parameter NV represents the number of variable speed units. Thus, if the variable $I^h_{pumping}$ is equal to 1, all units operating during an hour will be in pump mode, whereas if the variable $I^h_{turbining}$ is equal to 1, all units operating during an hour will be in turbine mode.

$$I^h_{pumping} + I^h_{turbining} \leq 1 \tag{22}$$

$$I^h_{pumping,total} = \sum_{i=1}^{NV} I^h_{pumping,i} \tag{23}$$

$$-NV\cdot\left(1 - I^h_{pumping}\right) \leq I^{h}_{pumping,total} \leq NV\cdot I^h_{pumping} \tag{24}$$

$$I^h_{turbining,total} = \sum_{i=1}^{NV} I^h_{turbining,i} \tag{25}$$

$$-NV\cdot\left(1 - I^h_{turbining}\right) \leq I^{h}_{turbining,total} \leq NV\cdot I^h_{turbining} \tag{26}$$

Finally, Equations (27) and (28) calculate the total energy turbined by the units ($E^h_{turbining,total}$) and the total energy pumped by the units ($E^h_{pumping,total}$) in each hour, respectively.

$$E^h_{turbining,total} = \sum_{i=1}^{NV} E^h_{turbining,i} \tag{27}$$

$$E^h_{pumping,total} = \sum_{i=1}^{NV} E^h_{pumping,i} \tag{28}$$

- Start-up cost constraints:

The binary variable $I^h_{start,i}$ is used to decide whether pump-turbine unit *i* is started up during hour *h*, as expressed in Equation (29). This equation calculates the change in operational status of unit *i* from the previous hour to the current hour, both in pumping and turbining modes. If there is a transition from 0 to 1, in either mode, the expression becomes positive, therefore, the binary variable $I^h_{start,i}$ will be activated.

The start-up cost for each unit is represented by the parameter k_{start}, which reflects the economic penalty associated with starting a unit, and is calculated in Equation (30) as the product of k_{start} and the binary variable $I^h_{start,i}$. Equation (31) calculates the total start-up costs for the system in each hour. These constraints help minimize unnecessary state transitions, thereby enhancing both the economic efficiency and the lifetime of the units.

$$I^h_{pumping,i} - I^{h-1}_{pumping,i} + I^h_{turbining,i} - I^{h-1}_{turbining,i} \leq I^h_{start,i} \tag{29}$$

$$C^h_{start,i} = k_{start}\cdot I^h_{start,i} \tag{30}$$

$$C^h_{start,total} = \sum_{i=1}^{NV} C^h_{start,i} \tag{31}$$

The mixed-integer mathematical model is formulated and optimized using GAMS (General Algebraic Modeling System), with the LINDO solver. This solver employs branching and cutting methods to decompose a nonlinear model into a list of sub-problems to obtain the optimal solution. If the solution of a sub-problem does not improve the best known integer solution or does not satisfy the integer constraints, it is discarded. This process of branching and cutting continues iteratively until all relevant possibilities have been explored or a stopping condition is met, thereby ensuring that the best solution found is optimal within the feasible space. Therefore, LINDO can guarantee that the solution obtained is optimal within the proposed model [43].

3. Estimated electricity market price profile

3.1. Spanish day-ahead electricity market

Since the liberalization of the electricity sector in 1997, the Spanish electricity system is based on competition in generation and commercialization, while transmission is managed by the State [39]. The electricity market is divided into two large blocks.

- Wholesale market: where electricity supply and demand are matched through hourly auctions following a marginalist model. The final price of electricity is set by the last generation unit (the most expensive) that enters the auction to cover demand.
- Retail market: where end consumers purchase electricity through retailers.

In this context, the price of electricity fluctuates significantly throughout the day due to factors such as.

- The variability of demand
- The availability of renewable energy (mainly wind and solar)
- The price of fossil fuels

Renewable energies have a direct impact on prices: when there is high renewable generation, the marginal price goes down (as these technologies offer energy at almost zero cost), while at times of low renewable production, the price goes up, as more expensive technologies such as combined cycle plants enter the market.

3.2. Statistical model of electricity market price

In the literature reviewed, there are articles that predict the short-term price of different electricity markets. Work [44] aims to identify the electricity market variables that most influence the marginal price, developing short-term prediction models based on regression trees. This approach allows estimates to be made both 1 h and one day in advance. The study is applied to the Spanish-Iberian electricity market. Paper [45] proposes a new functional forecasting method, using an ARMAX model adapted to functional time series. The study focuses on the short-term prediction of daily price profiles in the German market. The authors of [46] analyze whether disaggregated hourly prices contain useful information for predicting the next day's average daily price. This study focuses on the Nord Pool market, comparing univariate and multivariate models. Article [47] develops a model to predict the short-term electricity price from the analysis of electricity market supply and demand curves. This model is applied to the German and Austrian market. The authors of [48] use a long-term model based on Fourier analysis and evaluates the model in the United Kingdom.

However, this paper proposes a statistical regression model for predicting hourly prices of the Spanish electricity market in the long term. In this way, this model can contribute to improve the decision making of energy projects.

In order to analyze the behavior of the Spanish electricity market and evaluate how the hourly price of electricity varies, a multiple regression model has been developed based on data from the year 2023, since it includes complete and representative information. This year was especially relevant due to the strong growth of renewable generation, which exceeded 50 % of the total, allowing us to study its influence on prices.

The model incorporates variables that directly or indirectly affect the price of electricity, including.

- External factors: prices of natural gas, Brent barrel, and CO_2 tax.

- Production by technology: hourly generation data by source (wind, solar, hydro, nuclear, combined cycle plants, coal, etc.).
- Available generation power and demand.

The inclusion of all these variables allows addressing the complexity of the Spanish market, whose price is determined by a marginalist system that is sensitive to the variability of renewables, fossil fuel costs, as well as demand and available generation capacity.

To obtain an annual hourly profile of Spanish electricity market prices up to 2050, a statistical regression model has been estimated that includes the variables that influence price formation. Previously, a correlation study was carried out to evaluate the relationship between the response variable and the predictor variables. Additionally, a best subsets analysis was performed to determine the optimal set of 15 variables for the study, balancing model fit and complexity using Mallows' Cp criterion. In the estimation of the regression model, it was found that the Thermal Solar production variable was not statistically significant. As a result, this variable was removed from the final regression study, which now includes 14 predictor variables.

- Brent price [49].
- Natural gas price [50].
- CO_2 price [51].
- Wind production [52].
- PV generation [52].
- Thermal solar production [52].
- Hydro generation [52].
- Turbine-pumping generation [52].
- Other renewables production [52].
- Nuclear [52].
- Combined cycle gas turbine [52].
- Cogeneration [52].
- Coal [52].
- Waste [52].
- Available power

The World Energy Outlook 2023 [42] has been used as a reference for estimating the future prices of Brent barrel, gas and CO_2. This study by the International Energy Agency analyzes energy projections for the coming years. Three scenarios based on different projections for emissions and climate policies can be found in the report. In the case of this pricing model, the intermediate scenario, i.e., the APS (Announced Pledges Scenario), has been selected as the most likely horizon.

Regarding installed capacity in Spain will follow a significant evolution towards 2050, with a large increase in renewable technologies according to the Integrated National Energy and Climate Plan [53] and Mark Z. Jacobson's report [54]. This report has a methodology to identify the installation needs of the different technologies to achieve a 100 % renewable electricity supply. By 2030, 63 GW in wind and 76 GW in solar PV are expected, increasing to 109,340 MW and 99,670 MW, respectively, by 2050. Non-renewable technologies such as nuclear and cogeneration will decline progressively, with the total closure of nuclear power plants expected by 2035 [55].

The evolution of prices and installed capacity of the different predictor variables established in this study until 2050, based on the sources mentioned above, are shown in Tables 1 and 2.

In the scenario foreseen for 2050, wind and photovoltaic energy will dominate all other power generation technologies. It also stands the progressive increase in storage, which will play a decisive role in integrating the high penetration of renewables while guaranteeing security of supply.

The Spanish peninsular system can still be considered an energy island in terms of coverage due to its limited exchange capacity with Europe, which means that mainly national resources would be needed to meet the reliability standard. Moreover, island systems (Balearic and Canary Islands) depend on non-renewable sources. For this reason, in the model, it has continued considering the power installed in cogeneration and combined cycles to meet part of the electricity generation needs in the year 2050 [56].

Table 3 indicates the estimated average electricity price from the regression analysis.

Table 1
Evolution of prices and installed capacity up to 2050 for different technologies. Part I.

Year	Brent Price ($/barrel)	Natural Gas (€/MWh)	CO_2 $_{(€/tCO_2)}$	Wind (MW)	PV (MW)	Thermal solar (MW)	Hydro (MW)
2023	83.55	46.11	84.46	29746	22681	2304	17096
2024	82.19	42.51	88.54	35945	39709	2302	15678
2025	80.82	38.91	92.62	42144	56737	2300	14261
2026	79.46	35.30	96.70	46124	60667	2800	14311
2027	78.09	31.70	100.78	50104	64597	3300	14361
2028	76.73	28.10	104.86	54084	68527	3800	14411
2029	75.36	24.49	108.94	58064	72457	4300	14461
2030	74.00	20.89	113.02	62044	76387	4800	14511
2031	73.30	20.71	113.86	64409	77551	4800	14511
2032	72.60	20.53	114.71	66774	78715	4800	14511
2033	71.90	20.36	115.56	69138	79879	4800	14511
2034	71.20	20.18	116.41	71503	81044	4800	14511
2035	70.50	20.00	117.25	73868	82208	4800	14511
2036	69.80	19.83	118.10	76233	83372	4800	14511
2037	69.10	19.65	118.95	78598	84536	4800	14511
2038	68.40	19.47	119.80	80962	85700	4800	14511
2039	67.70	19.30	120.64	83327	86864	4800	14511
2040	67.00	19.12	121.49	85692	88029	4800	14511
2041	66.30	18.94	122.06	88057	89193	4800	14511
2042	65.60	18.77	122.62	90422	90357	4800	14511
2043	64.90	18.59	123.19	92786	91521	4800	14511
2044	64.20	18.41	123.75	95151	92685	4800	14511
2045	63.50	18.24	124.32	97516	93849	4800	14511
2046	62.80	18.06	124.88	99881	95013	4800	14511
2047	62.10	17.88	125.45	102246	96178	4800	14511
2048	61.40	17.71	126.01	104610	97342	4800	14511
2049	60.70	17.53	126.58	106975	98506	4800	14511
2050	60.00	17.35	127.14	109340	99670	4800	14511

Table 2
Evolution of prices and installed capacity up to 2050 for different technologies. Part II.

Year	Turbine-pumping (MW)	Other renewables (MW)	Nuclear (MW)	Combined cycle gas turbine (MW)	Cogeneration (MW)	Coal (MW)	Waste (MW)
2023	3331	1087	7117	24562	5589	3223	387.18
2024	6413	1087	7117	25587	4829	1612	361.63
2025	8828	1087	7117	26612	4068	0	337.76
2026	10771	1087	7117	26612	4011	0	315.47
2027	12714	1087	6068	26612	3954	0	294.65
2028	14657	1087	5024	26612	3898	0	275.20
2029	16600	1087	5024	26612	3841	0	257.04
2030	18543	1087	3181	26612	3784	0	240.07
2031	19116	1087	3181	26612	3784	0	224.23
2032	19689	1087	2154	26612	3784	0	209.43
2033	20262	1087	2154	26612	3784	0	195.61
2034	20834	1087	2154	26612	3784	0	182.70
2035	21407	1087	0	26612	3784	0	170.64
2036	21980	1087	0	26612	3784	0	159.38
2037	22553	1087	0	26612	3784	0	148.86
2038	23126	1087	0	26612	3784	0	139.03
2039	23699	1087	0	26612	3784	0	129.86
2040	24272	1087	0	26612	3784	0	121.29
2041	24844	1087	0	26612	3784	0	113.28
2042	25417	1087	0	26612	3784	0	105.80
2043	25990	1087	0	26612	3784	0	98.82
2044	26563	1087	0	26612	3784	0	92.30
2045	27136	1087	0	26612	3784	0	86.21
2046	27709	1087	0	26612	3784	0	80.52
2047	28281	1087	0	26612	3784	0	75.20
2048	28854	1087	0	26612	3784	0	70.24
2049	29427	1087	0	26612	3784	0	65.60
2050	30000	1087	0	26612	3784	0	61.27

4. Case study definition

The proposed model is applied to real data from a project under development in Spain. The system has a pumped hydro storage with grid-connected photovoltaic and wind generation plants to meet an hourly industrial demand (see Fig. 1) in the province of Zaragoza (Spain). The hourly demand is constant since it corresponds to an electro-intensive industry that works continuously. The storage system has 4 variable speed pump-turbine units, allowing it to run in a range of frequencies with variable powers according to the demand required to maximize the electricity from the photovoltaic and wind power plant, and thus, achieve a more efficient pumping operation. Therefore, if electricity generation with renewable energy plants or the level of storage is insufficient, the system can purchase energy in the electricity market and meet its needs at any time. On the other hand, additional income can be obtained from the sale of excess energy to the electricity market.

Table 3
Estimated average electricity price.

Year	Estimated average electricity price (€/MWh)
2023	95.35
2024	75.78
2025	59.09
2026	56.27
2027	54.00
2028	52.12
2029	50.48
2030	49.28
2031	47.88
2032	46.65
2033	45.45
2034	44.33
2035	43.45
2036	42.50
2037	41.63
2038	40.82
2039	40.07
2040	39.38
2041	38.70
2042	38.06
2043	37.47
2044	36.92
2045	36.41
2046	35.94
2047	35.50
2048	35.10
2049	34.73
2050	34.39

Data of renewable production facilities and technical of the reversible units for the calculation of the hourly optimal operation are shown in Table 4. These values were provided by a Spanish company of development in pumped hydro storage and renewable generation facilities.

The values of the minimum power in turbining and pumping modes have been calculated from the affinity laws, taking into account that the nominal frequency (f_{nom}) is 50 Hz and the minimum frequency (f_{min}) corresponds to 35 Hz for water pumping facilities. Thus, the minimum hourly turbining and pumping power obtained for each unit is calculated by Equations (33) and (34), respectively. The values of $P^{h}_{turbining,nom}$ and $P^{h}_{pumping,nom}$ are 99 MW, 113.5 MW, respectively.

Table 4
Study system data.

Parameter	Value
Demand	396 MW
Grid connection capacity	396 MW
Rated wind power	465 MW
Rated photovoltaic power	860 MW
Reversible pump-turbine units	4 variable speed units
Power delivered to the grid per unit	99 MW
Power absorbed to the grid per unit	113.5 MW
Minimum turbine mode power of each unit	33.96 MW
Minimum pump mode power of each unit	38.93 MW
Maximum storage capacity	5750 MWh
Efficiency pumping/turbining	0.90
Annual yield loss photovoltaic panels	0.5 % [57]
Annual yield loss of wind turbines	0.5 % [58]
Start-up cost	10 € [59]

$$\left(\frac{P^h_{turbining,nom}}{P^h_{turbining,min}}\right)=\left(\frac{f_{nom}}{f_{min}}\right)^3 \tag{33}$$

$$\left(\frac{P^h_{pumping,nom}}{P^h_{pumping,min}}\right)=\left(\frac{f_{nom}}{f_{min}}\right)^3 \tag{34}$$

The operating and maintenance costs of the renewable sources are shown in Table 5.

As mentioned above, the system is connected to the grid to meet demand at all times. The purchase price is a pass-through contract indexed to the wholesale electricity market. Therefore, in this type of contract, in addition to the energy price set in the OMIE market, other components must be considered to obtain the final energy purchase price in each hour. Equation (35) shows this calculation:

$$\rho^h_{imp}(€ / MWh)=[(OMIE_h+POS_h+Constraints_h+INT_h+\ POMyOS_h+PC_h)\cdot(1+k)\cdot(coefficient)]+Grid\ Access+Fee \tag{35}$$

Wherein.

- $OMIE_h$ = hourly electricity price from the OMIE day-ahead market
- POS_h = hourly market price of ancillary services of the system operator
- $Constraints_h$ = hourly technical constraints on the market price
- INT_h = interruptible service cost
- $POMyOS_h$ = market operator and system operator costs
- PC_h = capacity cost
- k = grid loss coefficient
- coefficient = coefficient that varies according to the supplier (usually from 1.15 to 1.18)
- Grid Access = regulated energy term for the grid access tariff
- Fee = management cost that depends on the supplier

The selling price of electricity is calculated through Equation (36), considering the 7 % tax on electricity generation [60].

$$\rho^h_{exp}(€ / MWh)=OMIE_h\cdot(1-7\%) \tag{36}$$

Finally, Fig. 3 represents the hourly net wind and photovoltaic generation profiles.

5. Results and discussion

The mixed-integer model proposed in this paper aims to optimize the hourly operation of a pumped hydro storage system with integration of renewable energy power plants (photovoltaic and wind) to meet an industrial demand by maximizing the monthly operating profit. The optimization is extended for a whole year to analyze the behavior of storage with the variation of hourly day-ahead electricity market prices estimated from 2023 to 2050. The system is connected to the grid to benefit of market opportunities by purchasing and selling energy to meet demand and achieve additional income.

From the simulation, the optimal hourly value of renewable generation, the energy imported/exported to the grid and the energy pumped/turbined by each reversible unit to manage storage are mainly obtained. In addition, it should be remembered that the internal logic for decision making is determined by 7 binary variables (value equal to 0 or 1) according to the optimal situation of the system. These variables are associated with the operations of purchase/sale of energy, pumping/turbinining, and start-up.

In the following sections, the results obtained are analyzed in terms of energy and economics, and the operation of pumped hydro storage is assessed for the estimated electricity market price profile scenarios from 2023 to 2050. These hourly profiles are obtained through the regression equation in Section 3.

Table 5
Operating and maintenance costs of renewable technologies and storage.

Parameter	Value
Wind generation	15 €/MWh
Photovoltaic production	8 €/MWh
Pumped hydro storage operation	3.5 €/MWh

5.1. *Optimal one week energy results*

Fig. 4a, 4b, 4c and 4d correspond to the scenarios for 2023, 2030, 2040 and 2050, respectively. Each figure shows one week in July. This allows for a detailed analysis of the optimal energy results, focusing on hourly energy imports and exports to the grid as well as renewable production during the study week.

In 2023 (see Fig. 5), with higher prices in the OMIE electricity market, there is high wind generation, consequently, there is also an increase in energy exported to the grid. This incentivizes wind plant to generate as much as possible, since it can sell the electricity at profitable prices. As generation exceeds local demand, the surplus is exported to the grid. This represents an increasing trend in exported energy, driven by the economic profit. The key is that the cost of generating wind energy is lower than the price at which it is sold, so it is profitable to generate and sell more energy (also occurs with solar photovoltaic production).

Nonetheless, in the following scenarios shown (years 2030, 2040 and 2050), wind generation is reduced by 80 % and there is no sale to the grid. In these scenarios, the electricity market price is lower even reaching 0 €/MWh in several hours. As the selling price is lower than the cost of generation, it is no longer profitable to generate wind energy for sale. Therefore, only what is needed to meet local demand is generated and exports are discontinued. Since photovoltaic solar energy is cheaper (8 €/MWh) than wind energy (15 €/MWh), it becomes the main source of generation. Its use is maximized and the use of other more expensive sources is minimized.

Regarding the import of energy from the grid, the 2050 scenario increases purchases in the market to fully meet the demand (396 MW) for a greater number of hours. This trend is due to a greater decrease in market prices compared to 2023, and therefore, importing energy is more profitable than generating it locally at certain times. Importing cheap energy makes it possible to better manage own resources (such as storage or generation) and maximize the system's economic profit.

In relation to storage, the general trend of the model is that the units run in pumping mode during the central hours of the day. During this period, photovoltaic generation is higher, allowing the use of this low-cost, readily available energy to pump water to the upper reservoir, thereby storing energy for further use. This strategy maximizes the use of solar energy, minimizes waste, and prepares the system to meet demand during periods of lower renewable generation. The incorporation of variable speed units allows a more efficient management of the system. These units allow greater operational flexibility by better adapting to consumption and generation profiles. Thanks to this dynamic adjustment capability, storage operation is optimized, the system's energy independence is increased and significant savings in operating costs

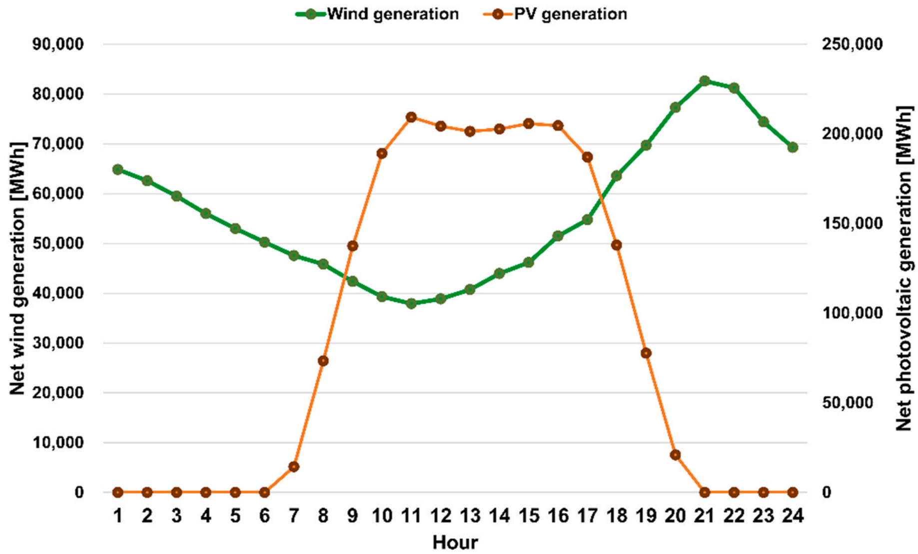

Fig. 3. Net wind and photovoltaic generation profiles.

are achieved.

On the other hand, when energy sales prices are higher, the units run in turbining mode. In this case, the previously stored water is used to generate electricity, thus maximizing economic profit. In addition, this energy is also used to meet electricity demand during hours when there is insufficient photovoltaic or wind generation, ensuring compliance with the model's requirement to meet hourly demand at all times.

5.2. Optimal operation of pumped hydro storage

Renewable energy sources (photovoltaic and wind) are intermittent and do not always generate electricity in line with demand. To balance this variability and ensure a constant supply of energy, pumped hydro storage is crucial.

Fig. 6a, 6b, 6c and 6d show the optimal operation of the pumped hydro storage system for a July week in 2023, 2030, 2040 and 2050, respectively. As a consequence of the variability of the hourly electricity market prices throughout the day, there is an alternation between pumping and generation in all the years analyzed. During hours of lower electricity prices, the units run in pumping mode, lifting water to fill the storage for further use. On the other hand, when prices in the OMIE day-ahead electricity market are higher, the units operate in turbine mode to export surplus to the grid and maximize the system's operating profit. In addition, due to the absence or lower photovoltaic or/and wind generation, stored water is turbined to produce electricity and meet the required demand, since satisfying hourly demand is a constraint imposed by the model.

The integration of variable speed units into pumped hydro storage provides greater flexibility and efficiency in pumping and generation modes, as well as allowing for better integration of wind and photovoltaic production. Thanks to this technology, water flow can be controlled more precisely by varying the operating speed of the units to suit the system's instantaneous needs, whether for storage or power generation.

Finally, a comparison between the 2023 and 2050 scenarios shows that there is a growing trend in the use of the storage system, with an increase of 13 %. This evolution is closely related to the variability in electricity market prices. During the central hours of the day, when there is a high availability of photovoltaic energy, electricity prices tend to be low. In contrast, during other time slots, especially when renewable generation decreases, prices can be significantly higher. In several hours, prices even drop to 0 €/MWh, as shown in Fig. 5.

In this context, the storage system plays an essential role by storing surplus energy produced during hours with low prices or excess generation, and releasing it (selling the energy) when prices are higher. This process is known as price arbitrage, which leads to maximizing operating profit and optimizing available energy resources.

In short, the combination of low prices during periods of high renewable generation, the possibility of arbitrage and technological progress with variable speed units, favors greater use of storage in the energy system. This trend not only improves operational profitability, but also strengthens the resilience of the system to the variability of renewable sources, making storage a key component of the energy transition to a more sustainable and efficient model.

5.3. Optimal annual energy results

Table 6 presents the optimal annual energy results obtained in the different scenarios. As can be seen, the 2050 scenario shows a 75 % increase in energy imports from the grid compared to 2023, as a consequence of the continuous reduction in OMIE electricity market prices. As a result, it becomes more cost-effective to purchase the energy needed to meet the required demand directly on the electricity market instead of generating it through renewable plants, given their associated production costs (15 €/MWh for wind and 8 €/MWh for photovoltaic). In contrast, energy exports decrease by 30 %, leading to a situation where imported energy is 3 times greater than exported energy. This shift is primarily driven by fluctuations in the hourly electricity market price.

Regarding wind and photovoltaic generation, their production decreases steadily until the 2050 scenario. In the case of photovoltaic, it is reduced by 16.4 % and wind power by 35.9 % compared to 2023 (see Fig. 7). It should be remembered that in each year there is a reduction of 0.5 % in their performance, which causes 13.5 % less performance in 2050.

Despite this decrease in performance, energy production remains lower in both cases due to other factors. The main factor is that electricity market prices decrease during the central hours of the day, allowing energy to be imported at low prices to cover demand. This, in turn, reduces the need to generate energy locally. Specifically, the reduction is more pronounced for wind energy, as the hours with low prices in the electricity market tend to coincide with hours of high availability of photovoltaic generation.

Wind energy has a generation cost of 15 €/MWh, a price higher in many hours than price of imports. On the other hand, the price of photovoltaic generation is practically half the price of wind generation, making the operation and maintenance costs of photovoltaic technology

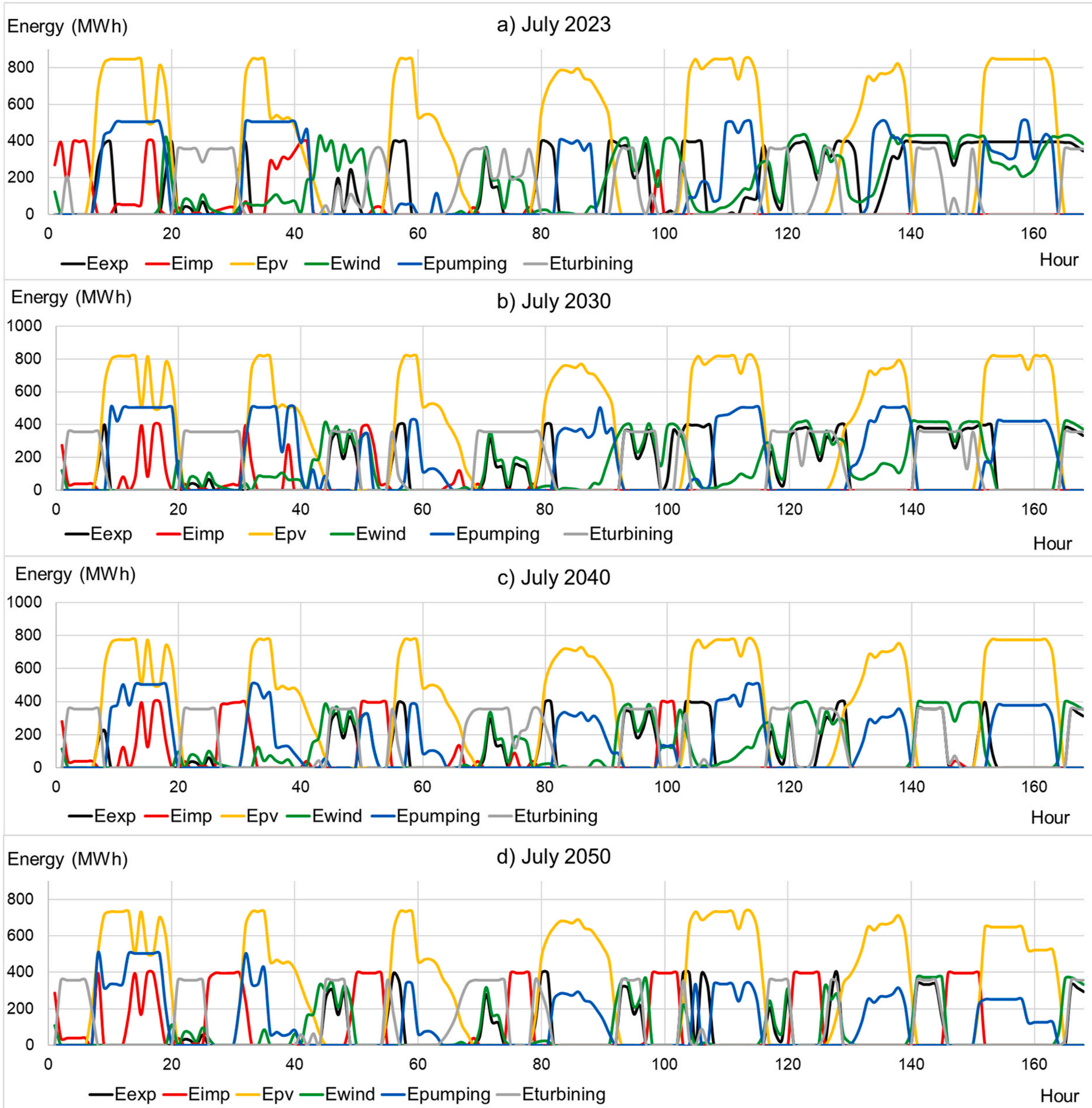

Fig. 4. Optimal energy results for one week in July in the scenarios 2023, 2030, 2040 and 2050.

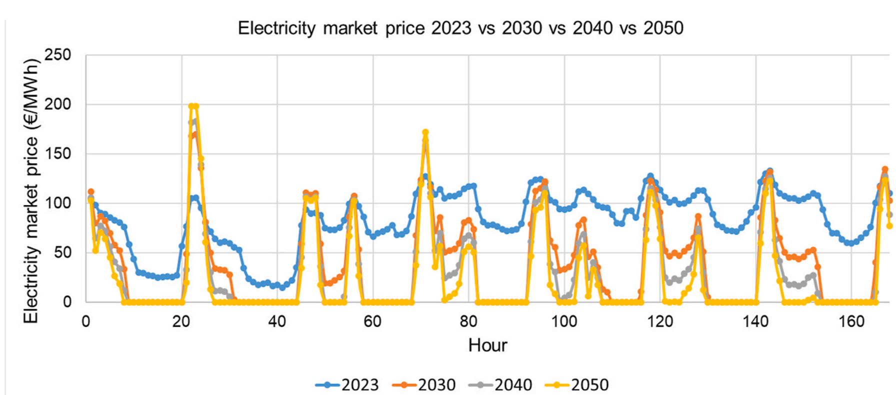

Fig. 5. OMIE prices for a week in July in 2023, 2030, 2040 and 2050.

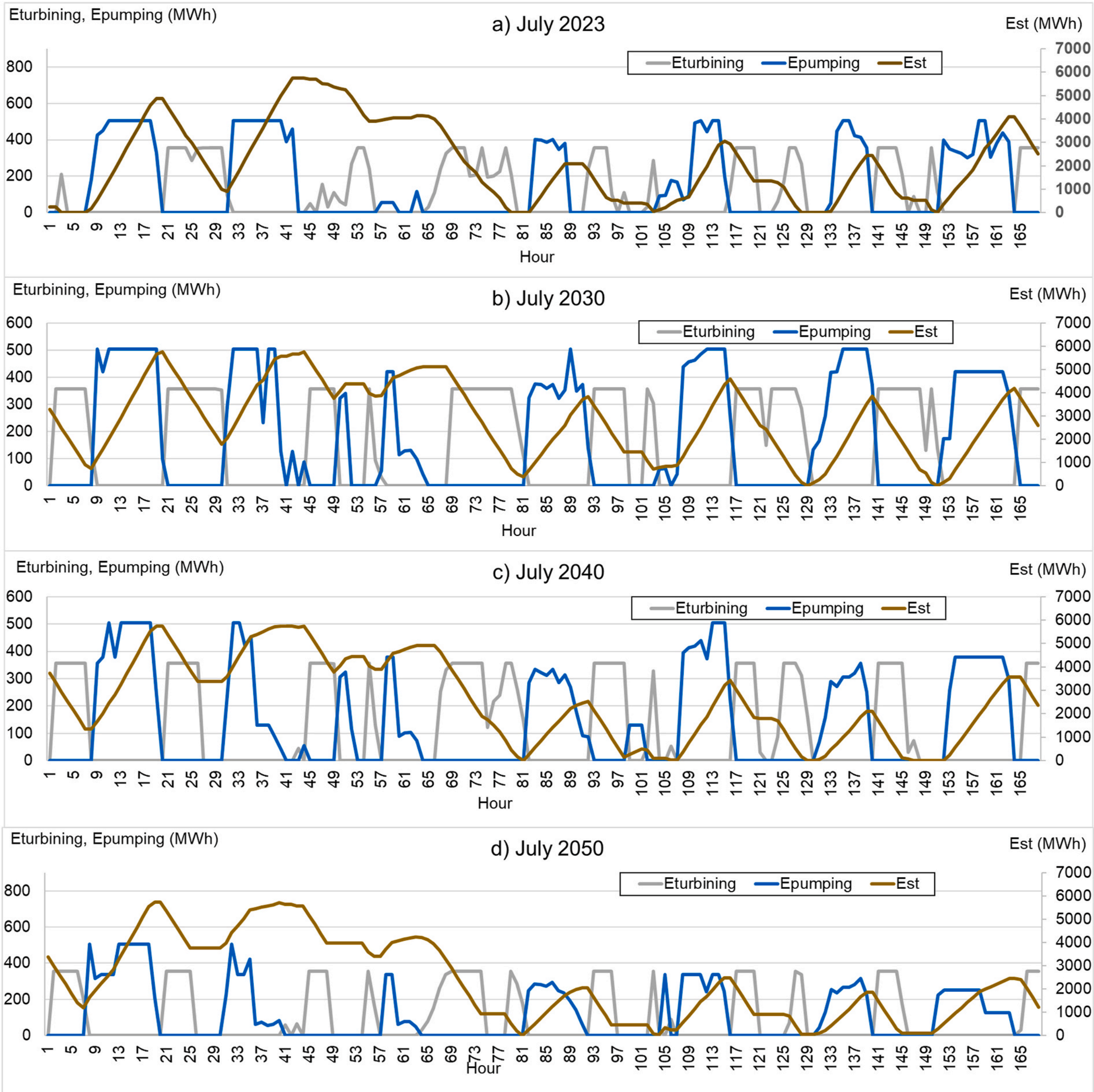

Fig. 6. Pumped hydro storage operation for a July week in 2023, 2030, 2040 and 2050.

much more competitive than wind. This results in a preference for photovoltaic energy when market prices are low, which further reinforces the reduction in wind energy production.

In addition, it is no longer profitable to benefit the sale of surplus generation to obtain additional income as a result of this continuous reduction in market prices. The economic benefit of selling surplus energy has decreased considerably, as electricity sales prices in the market do not cover generation costs, especially in the case of wind power. This trend is reflected in the decreasing generation hours for both technologies. Photovoltaic energy, despite price reductions, has remained practically constant. However, wind energy has experienced a more noticeable drop, since it has varied from 5891 h in the 2023 scenario to 4160 h in the 2050 scenario, corresponding to a reduction in operation hours of 29.4 %.

This analysis reflects how the evolution of market prices, together with the reduction in the competitiveness of wind generation, is transforming the energy landscape towards a greater reliance on cheaper sources such as photovoltaics and a decrease in the profitability of surplus sales.

Finally, regarding the pumped hydro storage system, its use increases by 13 % in each of the modes of operation for the 2050 scenario compared to 2023. This increase reflects a clear trend towards greater reliance on storage technologies as a key tool for energy management in a context of high renewable energy penetration and variable market prices.

As previously mentioned, the reduction of prices in the electricity market, especially during hours of high renewable production, makes it more profitable to import energy from the grid to meet electricity demand. At the same time, surplus renewable production is used to power the system in pumping mode, i.e., to store potential energy by raising water to the upper reservoir. This strategy allows the system to have stored energy available when there is no generation, or else, when selling prices in the OMIE market are competitive to maximize operating profit. In addition, during the first years of the study, when price volatility is more pronounced, there is greater potential for price arbitrage. In this context, the storage system becomes even more valuable, as it

Table 6
Optimal annual energy results.

Year	Eexp (MWh)	Eimp (MWh)	Epumping (MWh)	Eturbining (MWh)	Epv (MWh)	Ewind (MWh)	Demand coverage (%)
2023	613,475	879,992	979,827	793,660	2,060,487	1,328,123	74.63 %
2024	618,843	1,005,524	1,252,135	1,014,229	2,033,075	1,287,109	71.01 %
2025	624,754	1,145,640	1,368,039	1,108,111	1,994,952	1,213,049	66.97 %
2026	625,105	1,179,506	1,380,485	1,118,193	1,981,504	1,195,347	66.00 %
2027	621,730	1,211,747	1,390,046	1,125,937	1,969,787	1,173,265	65.07 %
2028	614,420	1,241,895	1,390,599	1,126,385	1,958,312	1,147,387	64.20 %
2029	613,718	1,271,295	1,385,047	1,121,888	1,946,926	1,127,616	63.35 %
2030	608,542	1,296,325	1,383,069	1,120,286	1,936,816	1,107,144	62.63 %
2031	597,432	1,309,311	1,366,653	1,106,989	1,927,263	1,089,482	62.26 %
2032	590,131	1,323,390	1,352,968	1,095,904	1,917,767	1,074,998	61.85 %
2033	581,077	1,338,401	1,340,446	1,085,761	1,908,568	1,057,754	61.42 %
2034	571,884	1,349,849	1,326,033	1,074,086	1,898,392	1,044,549	61.09 %
2035	564,903	1,362,478	1,316,865	1,066,660	1,888,785	1,032,804	60.72 %
2036	555,414	1,371,498	1,302,569	1,055,081	1,878,995	1,021,369	60.46 %
2037	544,666	1,380,299	1,284,484	1,040,432	1,869,266	1,008,113	60.21 %
2038	532,747	1,389,720	1,267,974	1,027,059	1,858,369	994,533	59.94 %
2039	522,934	1,403,116	1,257,236	1,018,361	1,847,165	980,488	59.55 %
2040	513,889	1,412,854	1,243,483	1,007,222	1,836,812	969,446	59.27 %
2041	502,594	1,423,138	1,227,738	994,468	1,825,664	956,023	58.98 %
2042	494,658	1,435,538	1,211,144	981,027	1,812,287	945,911	58.62 %
2043	487,852	1,447,983	1,200,103	972,084	1,802,039	934,810	58.26 %
2044	480,259	1,461,547	1,186,662	961,196	1,790,593	922,544	57.87 %
2045	470,596	1,477,069	1,170,906	948,434	1,778,498	906,462	57.42 %
2046	461,657	1,493,103	1,157,757	937,783	1,766,599	890,888	56.96 %
2047	454,338	1,503,966	1,149,208	930,858	1,756,888	880,793	56.65 %
2048	446,246	1,515,050	1,133,417	918,067	1,745,031	870,473	56.33 %
2049	438,103	1,522,380	1,117,010	904,778	1,733,334	863,581	56.11 %
2050	430,979	1,536,227	1,104,741	894,840	1,722,520	851,092	55.72 %

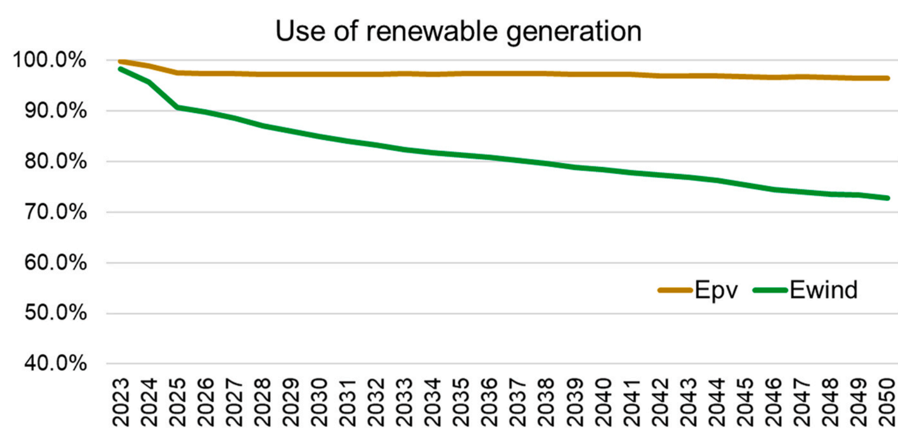

Fig. 7. Use of renewable generation from 2023 to 2050.

enables to purchase electricity at low prices, store it, and later sell it at higher prices, increasing overall profitability.

5.4. Optimal annual economic results

The annual economic results are shown in Table 7.

First, income and costs of the energy system are analyzed, where income came exclusively from the sale of surplus energy to the electricity market, while costs are mainly associated with the import of energy from the grid. Over the years, it can be seen how income almost double compared to energy import costs, but both terms have reduced their value with respect to 2023 as a result of the hourly price of the OMIE electricity market. The penetration of photovoltaic and wind energy in the system causes two large price collapses to form throughout the day, coinciding with the moments of greatest renewable generation. During these hours, the system exploits importing energy from the grid, as it is more economical than generating locally, thus meeting the required demand more efficiently.

Similarly, the system takes advantages of peak electricity prices during the day to export energy surpluses, thereby maximizing the economic profit. The difference between the 68 % drop in import costs and the more moderate 26.6 % reduction in export income in the 2050 scenario is mainly due to the fact that the hourly electricity market price drops to 0 €/MWh.

Although taxes, access tariff, and other associated costs, must be added to purchase prices, it is still relatively more profitable to import energy during those moments than to generate renewable energy for the sole purpose of selling it, since the sale price is directly linked to the OMIE price, which does not cover generation costs during certain hours. This dynamic highlights how market behavior shapes the system's operational strategy, prioritizing economic optimization over constant generation.

On the other hand, the annual costs associated with photovoltaic and wind power generation show a downward trend throughout the scenarios analyzed, due to both the reduction in total production and the progressive decrease in the annual yield of these technologies. In the case of photovoltaic, its total annual costs are reduced by 16.4 % between 2023 and 2050, while in wind energy the reduction reach 35.9 %

Table 7
Optimal annual economic results.

Year	Rexp (€)	Cimp (€)	Cpumping (€)	Cturbining (€)	Cpv (€)	Cwind (€)	Objective function (€)
2023	62,074,925	90,390,437	3,429,393	2,777,809	16,483,897	19,921,840	−70,953,271
2024	59,339,903	77,103,992	4,382,471	3,549,802	16,264,604	19,306,635	−61,292,421
2025	56,625,183	60,294,000	4,788,135	3,878,390	15,959,618	18,195,732	−46,515,512
2026	57,363,724	55,781,723	4,831,699	3,913,676	15,852,035	17,930,198	−40,970,427
2027	58,093,576	51,876,646	4,865,161	3,940,780	15,758,295	17,598,970	−35,971,096
2028	58,773,758	48,542,055	4,867,098	3,942,349	15,666,499	17,210,802	−31,479,865
2029	59,536,427	45,606,099	4,847,666	3,926,609	15,575,409	16,914,240	−27,358,416
2030	60,239,405	43,046,056	4,840,742	3,921,001	15,494,528	16,607,165	−23,694,906
2031	59,033,495	41,543,937	4,783,285	3,874,461	15,418,103	16,342,229	−22,953,340
2032	58,091,832	40,317,083	4,735,386	3,835,663	15,342,133	16,124,965	−22,288,218
2033	57,137,672	39,155,477	4,691,562	3,800,165	15,268,540	15,866,307	−21,669,199
2034	56,163,560	37,965,952	4,641,114	3,759,302	15,187,135	15,668,238	−21,083,001
2035	55,433,989	37,094,059	4,609,026	3,733,311	15,110,276	15,492,065	−20,629,568
2036	54,513,271	36,085,453	4,558,993	3,692,784	15,031,961	15,320,530	−20,201,269
2037	53,576,390	35,193,497	4,495,694	3,641,512	14,954,127	15,121,693	−19,854,953
2038	52,686,047	34,361,956	4,437,910	3,594,707	14,866,956	14,917,993	−19,518,294
2039	51,949,009	33,683,874	4,400,327	3,564,265	14,777,322	14,707,319	−19,208,918
2040	51,239,941	33,000,634	4,352,192	3,525,275	14,694,494	14,541,686	−18,899,161
2041	50,513,347	32,421,638	4,297,084	3,480,638	14,605,311	14,340,340	−18,656,484
2042	49,873,050	31,927,679	4,239,005	3,433,594	14,498,293	14,188,659	−18,438,999
2043	49,323,760	31,465,387	4,200,361	3,402,292	14,416,309	14,022,153	−18,207,563
2044	48,726,928	31,025,447	4,153,316	3,364,186	14,324,744	13,838,158	−18,003,744
2045	48,124,252	30,664,208	4,098,172	3,319,520	14,227,981	13,596,925	−17,807,375
2046	47,538,311	30,295,309	4,052,150	3,282,241	14,132,793	13,363,321	−17,612,323
2047	47,006,356	29,850,193	4,022,227	3,258,004	14,055,103	13,211,901	−17,415,893
2048	46,515,417	29,549,806	3,966,958	3,213,236	13,960,252	13,057,094	−17,256,750
2049	46,012,142	29,189,407	3,909,534	3,166,723	13,866,673	12,953,708	−17,098,724
2050	45,567,216	28,949,051	3,866,593	3,131,940	13,780,162	12,766,379	−16,951,728

in the same time interval. This difference is largely due to the fact that wind energy has a higher generation cost than photovoltaic energy, 15 €/MWh compared to 8 €/MWh, respectively. This reduces economic competitiveness means that the system prefers to generate electricity from the photovoltaic plant, or to import energy from the grid to meet the electricity demand. Additionally, there are hours when it is cheaper to import energy from the grid than to generate it through the photovoltaic installation. This circumstance also contributes to the reduction of total annual photovoltaic generation, although to a lesser extent than wind power. These factors reflect how the combination of generation costs and electricity market prices decisively influences the operating strategies of the energy system.

Annual turbining and pumping costs increase by up to 12.7 % in 2050. This increase is mainly due to the increased use of pumped hydro storage, which is becoming a key component of efficient energy management. Renewable generation is utilized to activate the pumping mode, allowing the upper reservoir to be filled during hours of low prices. This stored energy is then used in generating mode to meet electricity demand at times when renewable generation is not available, or when market prices are higher, thus maximizing the system's operating profitability. In addition, energy is imported from the grid at low prices, which reinforces the strategic role of storage in optimizing the energy and economic balance of the system.

Comparing the objective function of the proposed scenarios, which seeks to maximize the economic operating profit (difference between income and costs), a significant improvement in system performance is shown. It can be seen how it improves to 59.5 % in 2050 compared to 2023, which reflects a favorable evolution in terms of operating efficiency and energy resource utilization.

Moreover, it can be observed how from 2030 onwards, the value of the objective function remains practically constant until 2050. This trend is mainly due to the fact that, between 2023 and 2030, income from the sale of surplus energy remains practically stable, as hourly prices in the OMIE electricity market experience a sharper decline compared to the period from 2030 to 2050.

As a result of this evolution, between 2023 and 2030, a significant reduction in energy import costs is observed, decreasing in the range of 2–10 million euros per year. However, between 2030 and 2050, this reduction is slighter, dropping from 1 million to 100 thousand euros. This difference is explained by a greater reduction in OMIE hourly prices in the first years, especially during the night and the central hours of the day. Under these conditions, the system imports a greater amount of low-cost energy and makes more intensive use of PHS, which is subsequently used to export energy during the hours with higher OMIE prices, obtaining greater income.

From 2030 scenario, although hourly prices continue to fall, they do so mainly at peak hours, while in the bands with already reduced prices (even 0 €/MWh) they cannot be reduced further, which limits optimization opportunities. As a consequence, export income tends to decrease, not only because of the lower profitability of the market, but also because wind production is reduced and a significant share of renewable generation is allocated to pumping mode for further use, rather than being directly exported.

5.5. Study limitations

This article provides valuable insights into the impact of hourly electricity market prices on the operation of pumped storage systems with renewables; however, there are certain limitations that could be addressed in future research:

The operation of reversible machines was modeled with a constant efficiency. For greater accuracy, it would be advisable to consider the variable efficiency of pump-turbine units during both pumping and generation modes.

The results are based on the Spanish wholesale electricity market, which may limit their generalizability to other contexts with different regulatory frameworks or levels of renewable energy penetration.

The study does not account for certain factors that may influence electricity market prices, such as cross-border electricity interconnections.

5.6. Future technological advancements on operation of PHS

Potential future technological advances in renewable energy generation and storage systems could have a significant impact on both the operation and economic benefit of pumped hydro storage systems.

As solar and wind energy continue to expand, so does the need for solutions to mitigate their intermittent nature. In this context, pumped hydro storage (PHS) is positioned as a key tool to ensure a stable and continuous energy supply.

The development of technologies such as artificial intelligence, automated control and machine learning will enable a more efficient and predictive operation of PHS, optimizing its response to energy supply and demand. At the same time, advances in variable speed reversible units and other technical innovations will contribute to improve its performance and expand its operating range [2,19].

In addition, further integration of PHS with other storage technologies, such as batteries, is expected. These hybridized systems will be more flexible and resilient, able to respond more quickly to grid needs. Additionally, these facilities could take a more active role in the electricity market, acting as "prosumers" that manage their own power generation and consumption [19].

From the economic perspective, the value of the ancillary services offered by the PHS will grow as more renewables are incorporated into the system, which could translate into higher income for its operators. Added to this is the potential for energy arbitrage and cost reductions resulting from technological innovation in the design and construction of these facilities, and economies of scale [2].

Finally, public policies aimed at energy transition and harnessing additional uses, such as water supply, further reinforce the cost-effectiveness and viability of PHS as a comprehensive solution for a more sustainable energy system.

6. Conclusion

This research aims to analyze the variation of the annual hourly price of the Spanish electricity market until 2050 due to the expansion plans of renewable energy and storage, and to assess its impact on the operation of reversible pumped hydro storage plants. First, a mixed-integer mathematical model is formulated that optimizes the hourly management of the storage system with grid-connected photovoltaic and wind power plants to maximize the monthly operating profit of the system. The calculation is extended over an entire year to realistically study the optimal operation of pumped hydro storage plants with renewables. Subsequently, a regression model is estimated to explain the price profile of the electricity market in 2023, taking data on the hourly price of electricity and the technical variables that affect its formation. From the model, a forecast of market prices from 2023 to 2050 is obtained and applied to the proposed model.

The main conclusions drawn are as follows.

- Over the years, energy imports have increased due to low electricity market prices, favored by the growth of wind and photovoltaic energy. This reduces import costs by 68 % by 2050, but also decreases export revenues by 26.6 % as a result of the lower profitability of selling energy to the day-ahead electricity market.
- There is a higher utilization of the storage system over the years. This is due to price arbitrage, so the storage system can take advantage of the difference between minimum and maximum prices during the day. In this way, it is pumped during the cheapest hours, and then, the system turbines and sells the energy to the electricity market to increase the operating profit.
- The production costs of wind and photovoltaic energy decrease due to the loss of annual yield and lower energy generation as a result of increased imports at lower cost.
- The objective function, i.e., the economic profit improves by 76.1 %, mainly associated to the reduction in energy import costs over the years.

The integration of renewable energy into power systems poses significant challenges in the coming years. This paper stands out the importance of proposing technical and economic dispatch models that integrate several types of renewable generation with pumped hydro storage connected to the grid. It emphasizes the need to adapt these models to future scenarios of variability of hourly prices in the electricity market to study the feasibility of the storage projects. In addition, it has been verified that the drop in electricity market prices during the middle of the day due to increased renewable generation and price arbitrage makes pumped hydro storage essential for the optimal management of renewable resources and the maximization of economic profit.

As further research, the regression model could be updated with new trends in the energy sector. In addition, the mathematical model of optimal management could study the influence of hydraulic head which could lead to improve the accuracy of the model.

CRediT authorship contribution statement

Natalia Naval: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Jose M. Yusta:** Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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