Journal of Energy Storage 73 (2023) 108993

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research Papers

Optimal scheduling and management of pumped hydro storage integrated with grid-connected renewable power plants

Natalia Naval [a,*], Jose M. Yusta [a], Raul Sánchez [b], Fernando Sebastián [b]

[a] University of Zaragoza, Department of Electrical Engineering, C/Maria de Luna 3, 50018 Zaragoza, Spain
[b] Atalaya Generación, C/Argualas, 40, 1 D, 50012 Zaragoza, Spain

ARTICLE INFO

Keywords:
Pumped hydro energy storage
Optimal dispatch
Renewable energy
Self-consumption
Mixed-integer optimization

ABSTRACT

Pumped hydro-energy storage will become a fundamental element of power systems in the coming years by adding value to each link in electricity production and the supply chain. The growth of these systems is essential for improving the integration of renewables and avoiding dependence on fossil fuel sources, such as gas or oil. This paper presents the modeling and application of an optimal hourly management model of grid-connected photovoltaic and wind power plants integrated with reversible pump-turbine units to maximize the monthly operating profits of the energy system and meet electricity demand. The techno-economic dispatch model is formulated as a mixed-integer optimization problem. To assess the proposed model, it is applied to a Spanish case study system, and the results are obtained for an entire year. The combination of renewable energy and pumped hydro energy storage reduces energy dependence by decreasing energy costs by 27 % compared with a system without storage to satisfy the required electricity demand. The findings confirm that storage plays a key role in energy transition to ensure the security and stability of power systems with a higher share of renewable generation.

1. Introduction

An energy system based on 100 % renewable energy will only be possible in the near future if perfect integration between renewable generation and storage systems is achieved. Many studies have assessed different technologies to store excess renewable energy and use it when natural resources are unavailable. Among these, pumped hydro-energy storage (PHES) [1,2], lithium-ion batteries, lead-acid batteries [3,4] and compressed air [5,6] stand out. Although hydrogen has been extensively studied in recent years, it is still in the maturation phase [7,8].

In 2020, the world's installed pumped hydroelectric storage capacity reached 159.5 GW and 9000 GWh in energy storage, which makes it the most widely used storage technology [9]; however, to cope with global warming [10], its use still needs to double by 2050. This technology is essential to accelerating energy transition and complementing and taking advantage of the intermittency of renewable energy. These storage plants can easily replace natural gas-based technologies as backup systems for power systems. Currently, this is the most mature, efficient, and long-term storage technology that has been developed on a large scale.

Recently, several studies have assessed the evolution of renewable-energy power plants combined with PHES from various perspectives. These integrated systems make it possible to solve the inherent variability and unpredictability of wind and photovoltaic (PV) generation, and manage imbalances. Ali et al. [11] study both the negative and positive impacts of its implementation from socioeconomic and techno-environmental perspectives. Similarly, the authors in [12] review the technical, environmental, and economic assessments of photovoltaic and wind power plant hybrid systems with PHES. Reference [13] presents the main existing PHES configurations and their advantages and disadvantages, in addition to proposing new arrangements. Barbour et al. [14] present a global vision of the interaction between this type of storage and the electricity market with a high penetration of renewables.

As stated by the authors of [12], models of solar-wind hybrid systems with PHES can be divided into two categories according to the objective problem:

Feasibility models: The authors propose feasibility studies of PHES deployment by including economic indicators such as the cost of energy (COE), net present value (NPV), and payback.

Energy management models: Other papers propose the optimization of the energy management of solar-wind-PHES systems to minimize operational costs.

* Corresponding author.
E-mail address: naval@unizar.es (N. Naval).

https://doi.org/10.1016/j.est.2023.108993
Received 26 June 2023; Received in revised form 6 September 2023; Accepted 10 September 2023
Available online 16 September 2023

Nomenclature

Indexes

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

Data

N_H	total number of hours in the time window
Nv	total number of variable speed reversible pump-turbine units
NF	total number of fixed speed reversible pump-turbine units
ρ^h_{exp}	hourly price of energy sales $\left(\frac{€}{MWh}\right)$
ρ^h_{imp}	hourly price of energy purchase $\left(\frac{€}{MWh}\right)$
f_W	operating costs of wind technology $\left(\frac{€}{MWh}\right)$
f_{PV}	operating costs of photovoltaic technology $\left(\frac{€}{MWh}\right)$
f_{pump}	pumping operating costs $\left(\frac{€}{MWh}\right)$
f_{turb}	turbining operating costs $\left(\frac{€}{MWh}\right)$
E^h_{PV}	hourly energy from photovoltaic generation (MWh)
E^h_W	hourly energy from wind generation (MWh)
E^h_{dem}	hourly energy demand (MWh)
$E^h_{st,min}$	minimum capacity of the storage system (MWh)
E^h_{max}	maximum capacity of the storage system (MWh)
P^h_{cap}	grid access capacity (MW)
$P^h_{turb,min,i}$	minimum power of variable speed machine i in the turbining mode (MW)
$P^h_{pump,min,i}$	minimum power of variable speed machine i in the pumping mode (MW)
$P^h_{turb,nom,i}/P^h_{turb,nom,j}$	rated power of variable-/fixed-speed machine i/j in the turbining mode (MW)
$P^h_{pump,nom,i}/P^h_{pump,nom,j}$	rated power of variable/fixed-speed machine i/j in the pumping mode (MW)
$\eta^h_{p,i}/\eta^h_{p,j}$	hourly pumping performance of each variable/fixed-speed machine i/j
$\eta^h_{t,i}/\eta^h_{t,j}$	hourly turbining performance of each variable/fixed-speed machine i/j
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)
I^h_{exp}	binary variable equal to 1 if energy is exported to the grid and 0 otherwise
I^h_{imp}	binary variable equal to 1 if energy is imported from the grid and 0 otherwise
$I^h_{pump,i}/I^h_{pump,j}$	binary variable equal to 1 if the variable/fixed-speed unit i/j runs in the pumping mode and 0 otherwise
$I^h_{turb,i}/I^h_{turb,j}$	binary variable equal to 1 if the variable/fixed-speed unit i/j runs in turbining mode and 0 otherwise
$I^h_{start_i}/I^h_{start_j}$	binary variable equal to 1 if the variable/fixed-speed unit i/j starts up and 0 otherwise
E^h_{st}	hourly energy stored (MWh)
$E^h_{pump,i}/E^h_{pump,j}$	hourly energy demanded by variable/fixed-speed unit i/j working in the pumping mode (MWh)
$E^h_{turb,i}/E^h_{turb,j}$	hourly energy produced by variable/fixed-speed unit i/j working in the turbining mode (MWh)
$E^h_{pump,total}$	total hourly energy demanded in the pumping mode (MWh)
$E^h_{turb,total}$	total hourly energy generated in the turbining mode (MWh)
$C^h_{start,i}/C^h_{start,j}$	cost of hourly start-up of variable/fixed-speed pump turbine unit i/j (€)
B	operating profit (€)

According to this classification, the model proposed in this paper addresses energy management problems.

On the one hand, research incorporates the calculation of the optimal sizing of the components of the system assessing different criteria. Technical criteria are included in these models, such as the loss of power supply probability [15–17], monthly and annual oversupply [15], and annual ratio of renewable power to supply power [15]. Along with technical criteria, economic aspects are important to guarantee cost-effective optimal operation by incorporating the life cycle cost [15,18], levelized cost of energy [15,16,19], and cost of energy [17].

On the other hand, other previous papers focus on the optimal management of electrical systems based on renewable energy with pumped hydro storage. The authors in [20] analyze the challenges in the optimal operation of PHES-based energy systems, considering the type and number of integrated energy sources, the integration of other types of storage systems, grid connectivity, and solving methods.

Most of the previous studies incorporates a single energy source with PHES, mainly PV-PHES [21–23] and wind-PHES [24–26]. References [21,22] minimize the operating cost of a grid-connected photovoltaic system with a PHES for one day. Kusakana [21] uses a heuristic method, whereas Makhdoomi and Askarzadeh [22] use a mathematical method to solve the problem. In [23], a distributed photovoltaic system with pumped hydro storage in residential buildings in Shanghai is studied. The authors of [24] propose the optimal daily operation of a system consisting of a wind power plant and a small pumped hydro storage system that maximizes profit. References [25,26] use a Virtual Power Plant approach to maximize the profit of the system. In addition, other models have included PHES with PV or wind combined with other renewable or nonrenewable energy sources. References [27,28] propose optimal daily operating models that aim to minimize the use of fuel from a diesel generator. The authors in [27] study a system composed of a photovoltaic plant, diesel generator, and PHES using heuristic methods. Additionally, the system in [28] includes a wind farm and is solved using an interior-point algorithm. Ghasemi and Enayatzare [29] analyze the optimal management of an isolated microgrid based on photovoltaic and wind power plants, considering pumped hydro-energy storage and a demand response program to compensate for generation and demand imbalances during a study day. Other studies analyze the influence of thermal power plants combined with PHES [30–32]. These models are complex because they incorporate several equality and inequality technical constraints to obtain optimal dispatch and minimize total operating costs.

Mathematical methods are mainly used to solve energy scheduling problems because they guarantee convergence to an optimal solution (if it exists). These include mixed-integer programming [25,32–34], nonlinear programming [35,36], dynamic programming [37,38], and quadratic programming [39]. It should be noted that the most widely applied optimization method is mixed-integer programming because it fits well with the characteristics of energy scheduling models. Currently, most modeling and optimization software include efficient solvers to obtain the optimal solution of mixed-integer models.

According to the application of the PHES optimal operation problems, many of the reviewed papers assess power systems with a high share of renewable energy from different countries, including Brazil [30], Argentina [40], and Southeast Asia [41]. Reference [42] studies the role of storage systems in the transition to a 100 % renewable energy electricity sector by 2050 in Europe.

The main gaps identified in the literature are as follows:

- Limited integration of several grid-connected renewable self-consumption plants with pumped hydro energy storage and reversible pump turbine units.
- Previous models include short-term study periods, which do not allow for the analysis of the scope of pumped hydro implementation in real projects.

The goal of this study is to develop an hourly mathematical model that allows for the optimal management of grid-connected renewable generation facilities and pumped hydro-energy storage with reversible pump turbine units to maximize the monthly economic profit of the system's operation and meet electricity demand. The calculation is extended over an entire year. The model can take advantage of opportunities in the electricity market through the purchase and sale of excess energy generated to the grid. This paper proposes a model including photovoltaic and wind generation integrated with PHES that is applicable to energy projects. It not only satisfies electricity demand but may interact with the electricity market. The model is applied to a Spanish case study, with one-year Spanish real data market prices.

To overcome the previous gaps, the main scientific contributions of this study can be summarized as follows:

- Development of a new optimal techno-economic scheduling for energy systems to satisfy electricity demand at maximum profit.
- Integration of self-consumption renewable power generation plants (wind and photovoltaic) connected to the grid and a pumped hydro energy storage system with fixed and variable speed reversible pump-turbine units in the proposed model.
- Application of this model to Spanish energy system operation throughout the year.

The remainder of this paper is organized as follows. Section 2 presents the limitations of this study and the formulation of the mathematical model. Section 3 describes the case study. Section 4 presents and discusses the results. Finally, Section 5 summarizes the main conclusions drawn from this study and the scope for further research.

2. Methodology

Pumped hydro energy storage must be turned into a support for renewable energy to achieve a stable, flexible, and secure electrical system with 100 % renewable integration. This article aims to develop an optimal hourly model for technical and economic dispatch applied to power systems with photovoltaic, wind, and pumped hydro energy storage connected to the grid to meet the required demand. This model takes advantage of the opportunities in the electricity market every hour through the purchase and sale of energy and thus can maximize the profit of the system for a month. To test the model, it is applied to a system with data on generation, electricity demand, technical data of reversible pump-turbine units, and real prices for the purchase and sale of energy in the electricity market. The optimum operating results of the system were obtained over the entire year. Fig. 1 shows a diagram of the proposed model.

2.1. Assumptions of the study

To model this problem, the following assumptions have been taken into account:

- The proposed model integrates pumped hydro energy storage with grid-connected self-consumption generation facilities. Consequently, if renewable power generation and PHES are insufficient, the system can purchase energy from the electricity market to meet its electricity demand at all times.
- The model incorporates the purchase of energy through a contract indexed to electricity prices in the wholesale market. This assumption allows us to obtain an optimal economic dispatch for every hour. In addition, the model includes the possibility of selling surplus production at a price set in the electricity market every hour.
- Power renewable production forecasts and electricity prices for importing/exporting energy to the grid each hour are available the day before to obtain optimal management of the system. Nevertheless, the hourly prices of the Spanish wholesale electricity market for an entire year are used to assess the behavior of the study system [43].
- The problem only incorporates reversible pump-turbine units.
- The model includes fixed and variable speed reversible pump-turbine units.
- The performance of the reversible pump-turbine units is assumed to be constant for the entire operating range considered in both the pumping and turbining modes [44].
- The affinity laws of the centrifugal pumps are used to calculate the minimum power values of the units in both the pumping and

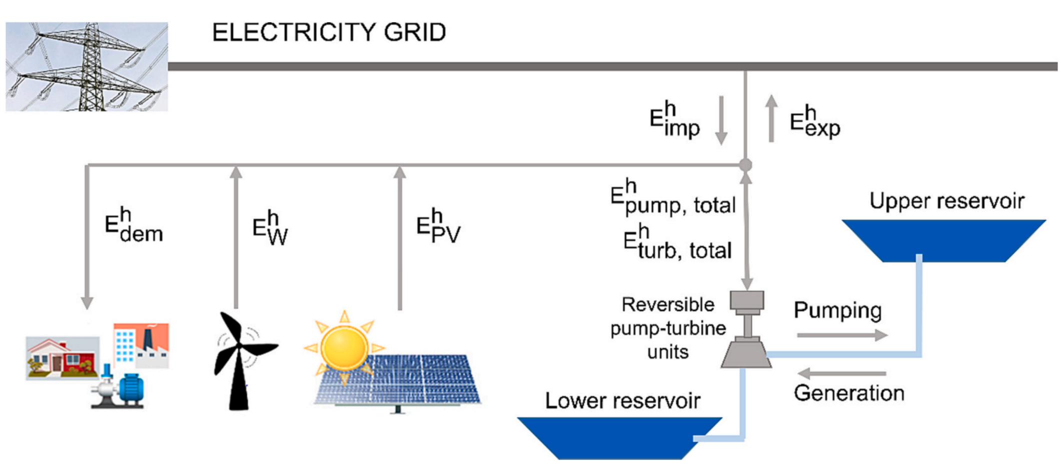


Fig. 1. General diagram of the proposed techno-economic dispatch model.

turbining modes. Water pumping facilities generally operate above 35 Hz to avoid mechanical failures and reduce the lifespan of these units.

- The model assumes that evaporation losses do not affect the behavior of the system because the storage volume and water withdrawal system operation are designed such that these losses do not affect useful volume availability.
- Wind and photovoltaic power plants are designed to prioritize meeting the electricity demand required by the system each hour, irrespective of their generation costs, and to inject any surplus power into the storage system or electricity distribution network. Therefore, wind and photovoltaic generation costs are not included in the objective function.
- The proposed dispatch model penalizes the start-up and shutdown processes of the units because many on-off transitions result in accelerated degradation of the units.

2.2. Mathematical formulation

As previously mentioned, the objective of this model is to calculate the optimal hourly dispatch of electrical systems based on the integration of renewables with pumped hydro-energy storage connected to the grid, which maximizes the operating profit during the established time window. Thus, the model, together with the technical and economic constraints of the system components, is defined by an objective function.

2.2.1. Objective function

The objective function maximizes the economic benefit of operating a system based on renewable energy generation plants combined with pumped-storage hydropower. Eq. (1) is expressed as the difference between the hourly sale of the excess generation to the electricity market ($\rho^{h}_{exp}\cdot E^{h}_{exp}$) and the hourly costs of all the agents that make up the system. These costs correspond to the ones associated with the pumping/turbine operations ($f_{pump}\cdot E^{h}_{pump,total}$, $f_{turb}\cdot E^{h}_{turb,total}$), the hourly cost of importing energy from the grid ($\rho^{h}_{imp}\cdot E^{h}_{imp}$), and the start-up costs of the pump-turbine units ($C^{h}_{start,i}$, $C^{h}_{start,j}$). Index y indicates the time window and can have a value from 1 to Y, where Y is the total number of time windows considered in the analysis. In this study, the time window corresponds to one month; therefore, the total number of time windows is 12 because the optimization is extended to an entire year to analyze the real scope of the management of systems involving renewables and storage.

$$max(Profit(B)) = \sum_{y=1}^{Y} \times \sum_{h=1}^{N_H} \left(\begin{array}{c} \rho^{h}_{exp}\cdot E^{h}_{exp} - \rho^{h}_{imp}\cdot E^{h}_{imp} - f_{pump}\cdot E^{h}_{pump,total} - f_{turb}\cdot E^{h}_{turb,total} \\ - \sum_{i=1}^{NV} C^{h}_{start,i} - \sum_{i=1}^{NF} C^{h}_{start,j} \end{array} \right)_y \tag{1}$$

2.2.2. Constraints

- System energy balance

The sum of the energy supplied by the different sources must be equal to the electricity demand (E^{h}_{dem}) each hour, as shown in Eq. (2). The system demand must be satisfied at all times. First, the electricity imports from the grid (E^{h}_{imp}), wind and photovoltaic generation energy (E^{h}_{W}, E^{h}_{PV}), and the contribution from storage ($E^{h}_{turb,total}$) are considered system inputs. On the other hand, energy exports to the grid (E^{h}_{exp}) and energy pumped to storage ($E^{h}_{pump,total}$) are considered system outputs. Wind and photovoltaic production (E^{h}_{W}, E^{h}_{PV}) are data in this model because the maximum energy available from each renewable technology during each hour is used to meet the system demand as much as possible. If a surplus is produced, it is used to meet storage needs or injected directly into the electricity distribution network.

$$E^{h}_{dem} = E^{h}_{imp} - E^{h}_{exp} + E^{h}_{W} + E^{h}_{PV} + E^{h}_{turb,total} - E^{h}_{pump,total} \tag{2}$$

- Constraints imported from/energy exported to the grid

Eq. (3) indicates that the purchase and sale of energy in the electricity market cannot occur simultaneously. I^{h}_{imp}, I^{h}_{exp} are binary variables associated with the hourly decision to import or export energy to the grid. Therefore, there are three possible combinations: energy imports ($I^{h}_{imp} = 1$, $I^{h}_{exp} = 0$), energy exports ($I^{h}_{imp} = 0$, $I^{h}_{exp} = 1$), or either imports or exports ($I^{h}_{imp} = 0$, $I^{h}_{exp} = 0$).

$$I^{h}_{imp} + I^{h}_{exp} \leq 1 \tag{3}$$

The hourly limits of the energy imported (E^{h}_{imp}) and exported (E^{h}_{exp}) to the electricity distribution network are presented in Eqs. (4) and (5), respectively. The maximum values of these variables are conditioned by the values of the binary decision variables (I^{h}_{imp}, I^{h}_{exp}). Consequently, if the system is under the import condition $I^{h}_{imp} = 1$, the upper limit of the imported energy variable (E^{h}_{imp}) is the energy demand (E^{h}_{dem}). In contrast, if the system is under the export condition, $I^{h}_{exp} = 1$, the exported energy variable (E^{h}_{exp}) will be limited to the connection capacity to the grid ($P^{h}_{cap}\cdot\Delta t$).

$$0 \leq E^{h}_{imp} \leq I^{h}_{imp}\cdot E^{h}_{dem} \tag{4}$$

$$0 \leq E^{h}_{exp} \leq I^{h}_{exp}\cdot P^{h}_{cap}\cdot\Delta t \tag{5}$$

- Pumped hydro storage system constraints

Eq. (6) calculates the available stored energy (E^{h}_{st}) at the end of each hour in the upper reservoir.

$$E^{h}_{st} = E^{h-1}_{st} + E^{h}_{pump,total} - E^{h}_{turb,total} \tag{6}$$

Depending on the number of established time windows for the analysis, the levels of the storage system have certain constraints, as expressed by Eqs. (7) and (8).

Eq. (7) implies that the stored energy available in the initial hour must be equal to that existing at the end of the last time window considered in assessment (Y); that is, the storage finishes as it starts.

$$E^{h}_{st,1}(h=1) = E^{h}_{st,Y}(h=N_H) \tag{7}$$

Eq. (8) establishes that the stored energy available in the final hour of a time window is the same as the one that exists in the first hour of the following time window.

$$E^{h}_{st,y}(h=N_H) = E^{h}_{st,y+1}(h=1) \tag{8}$$

Hourly limits of energy stored ($E^{h}_{st,min}$, $E^{h}_{st,max}$) are defined in Eq. (9).

$$E^{h}_{st,min} \leq E^{h}_{st} \leq E^{h}_{st,max} \tag{9}$$

As discussed in Section 2.1, a constant performance of the reversible pump turbine units for the entire operating range is considered in both the pumping and turbining modes (Eqs. (10)–(13)).

Eq. (10) shows the hourly capacity range of the variable-speed units in the turbine mode ($E^{h}_{turb,i}$). The binary variable $I^{h}_{turb,i}$ determines whether the variable-speed units in turbine mode run hourly. $\eta^{h}_{t,i}$ is the hourly turbining performance of each variable speed machine. The lower limit is conditioned by the minimum power of the variable-speed machine in the turbining mode ($P^{h}_{turb,min,i}$), whereas the upper limit corresponds to the rated power of the variable-speed units ($P^{h}_{turb,nom,i}$).

$$\eta^{h}_{t,i} \cdot P^{h}_{turb,min,i} \cdot I^{h}_{turb,i} \cdot \Delta t \leq E^{h}_{turb,i} \leq \eta^{h}_{t,i} \cdot P^{h}_{turb,nom,i} \cdot I^{h}_{turb,i} \cdot \Delta t \tag{10}$$

The energy generated in the turbining mode by the fixed-speed units ($E^{h}_{turb,j}$) is presented in Eq. (11). It is assumed that fixed-speed turbines cannot change their loads. Therefore, if a fixed-speed unit operates, the generated energy corresponds to its rated power ($P^{h}_{turb,nom,j}$); otherwise, its value is zero. The binary variable $I^{h}_{turb,j}$ determines whether the fixed-speed units in the turbine mode run every hour. $\eta^{h}_{t,j}$ is the hourly turbining performance of each fixed-speed machine.

$$E^{h}_{turb,j} = \eta^{h}_{t,j} \cdot P^{h}_{turb,nom,j} \cdot I^{h}_{turb,j} \cdot \Delta t \tag{11}$$

Eq. (12) indicates the hourly energy limits of the variable-speed units in the pumping mode ($E^{h}_{pump,i}$). The binary variable $I^{h}_{pump,i}$ determines whether the variable-speed units in the pump mode run hourly. $\eta^{h}_{p,i}$ is the hourly pumping performance of each variable-speed machine. The lower limit is associated with the minimum power of the variable-speed machine in pumping mode ($P^{h}_{pump,min,i}$), whereas the upper limit corresponds to the rated power of the variable-speed units ($P^{h}_{pump,nom,i}$).

$$\left(P^{h}_{pump,min,i} \Big/ \eta^{h}_{p,i}\right) \cdot I^{h}_{pump,i} \cdot \Delta t \leq E^{h}_{pump,i} \leq \left(P^{h}_{pump,nom,i} \Big/ \eta^{h}_{p,i}\right) \cdot I^{h}_{pump,i} \cdot \Delta t \tag{12}$$

The calculation of the hourly energy of the fixed-speed units in pumping mode ($E^{h}_{pump,j}$) is shown in Eq. (13). If a fixed-speed unit operates, the pumped energy is associated with its rated power ($P^{h}_{pump,nom,j}$); otherwise, its value is zero. The binary variable $I^{h}_{pump,j}$ determines whether the fixed-speed units in pumping mode run hourly. $\eta^{h}_{p,j}$ is the hourly pumping performance of each fixed-speed machine.

$$E^{h}_{pump,j} = \left(P^{h}_{pump,nom,j} \Big/ \eta^{h}_{p,j}\right) \cdot I^{h}_{pump,j} \cdot \Delta t \tag{13}$$

The pumping/turbining operating modes in the variable/fixed-speed units cannot occur simultaneously, as defined by Eqs. (14) and (15).

$$I^{h}_{pump,i} + I^{h}_{turb,i} \leq 1 \tag{14}$$

$$I^{h}_{pump,j} + I^{h}_{turb,j} \leq 1 \tag{15}$$

Eqs. (16) and (17) calculate the total turbined and pumped energies ($E^{h}_{turb,total}, E^{h}_{pump,total}$) per hour, respectively:

$$E^{h}_{turb,total} = \sum_{i=1}^{NV} \frac{E^{h}_{turb,i}}{\eta^{h}_{t,i}} + \sum_{i=1}^{NF} \frac{E^{h}_{turb,j}}{\eta^{h}_{t,j}} \tag{16}$$

$$E^{h}_{pump,total} = \sum_{i=1}^{NV} E^{h}_{pump,i} \cdot \eta^{h}_{p,i} + \sum_{i=1}^{NF} E^{h}_{pump,j} \cdot \eta^{h}_{p,j} \tag{17}$$

- Start-up cost constraints

Eqs. (18)–(21) present the constraints associated with the startup costs of reversible pump-turbine units with fixed and variable speeds. The binary variables ($I^{h}_{start,i}$) and ($I^{h}_{start,j}$) make it possible to decide the start of the variable- and fixed-speed units, respectively. Parameter k_{start} is the cost associated with the start-up of the pump-turbine units.

$$I^{h}_{pump,i} - I^{h-1}_{pump,i} + I^{h}_{turb,i} - I^{h-1}_{turb,i} \leq I^{h}_{start,i} \tag{18}$$

$$C^{h}_{start,i} = k_{start} \cdot I^{h}_{start,i} \tag{19}$$

$$I^{h}_{pump,j} - I^{h-1}_{pump,j} + I^{h}_{turb,j} - I^{h-1}_{turb,j} \leq I^{h}_{start,j} \tag{20}$$

$$C^{h}_{start,j} = k_{start} \cdot I^{h}_{start,j} \tag{21}$$

From the objective function and the constraints of the formulated optimization problem, the model is of the mixed-integer type, as there are integer decision variables corresponding to the import/export of electricity and the operation mode of the units (pump/turbine), in addition to continuous variables. To efficiently model and optimize the proposed mathematical problem, GAMS® software (General Algebraic Modeling System) is used. It applies branching and cutting techniques, thus allowing the original model to be divided into sub-problems for their resolution. The proposed model is applied to 12 time windows associated with the 12 months of a year. As a consequence, the resolution of the proposed mixed-integer model has a 10-hour and 15-minute runtime using a computer with an Intel® Core i7 processor, 3.00 GHz CPU, and 16 GB of RAM.

3. Case study definition

The case study for the assessment of the model's behavior comprises a set of photovoltaic plants, a set of wind farms, and a pumped hydro-energy storage plant that satisfies the determined electricity demand of an electro-intensive industry. The system is grid-connected to purchase energy from the electricity market if necessary to meet electricity demand. In addition, the facility can sell the excess generation in exchange for additional income.

The scope of the model provides the necessary flexibility to address other study scenarios and/or other locations, such as the combination of reversible pump-turbine units with fixed and variable speeds, the integration of different types of renewable or non-renewable energy, or variable system demand.

Table 1 lists the input data for the case study system. The performance data for the pump-turbine units include their hydraulic performance and those associated with the motor generator and transformer. As previously mentioned, this performance is considered constant under all storage working conditions. Regarding the unit typology, only variable-speed units are incorporated, as they are better suited to the integration of renewable generation because they enable the power consumed in the pumping mode to be varied and the turbine to operate at peak efficiency over a larger portion of its operating band. In addition, the number of start-ups is lower than that in fixed-speed machines, thus more efficient and economical operation can be achieved.

Table 2 lists the operation and maintenance costs of each technology included in the system. These data are the average values from Atalaya's projects and technology providers information.

Figs. 2 and 3 show the hourly net wind and photovoltaic generation profiles, respectively, from existing plants in the Ebro Valley (Saragossa, Spain) in 2019. In total, 1352 GWh of energy is produced per year from wind farms and 2065 GWh from the photovoltaic plants.

Regarding the purchase and sale of electricity prices, the hourly prices of the Spanish wholesale electricity market in 2019, published by the market operator OMIE [43], were considered to analyze the

Table 1
Study system data.

Demand (MW)	396
Grid connection capacity (MW)	396
Rated wind power (MW)	465
Rated photovoltaic power (MW)	860
Quantity and type of reversible pump-turbine units	4 variable speed units, no fixed speed units
Delivered turbine power to the grid per pump/turbine unit (MW)	99
Absorbed pumping power from the grid per pump/turbine unit (MW)	113.5
Maximum stored energy (MWh)	5750
Pump/turbine system performance	0.90
Start-up costs (€)	10

Table 2
Operation and maintenance costs of the technologies used (€/MWh).

Wind generation	15
Photovoltaic generation	8
Pumped hydro storage plant	3.5

behavior of the system.

4. Results and discussion

The proposed mixed-integer model of techno-economic operation maximizes the monthly profit generated by the study system, and the results are obtained for all months of the year. This model obtains the optimal hourly number of units in operation and their operating mode (turbining or pumping) with their respective values of energy ($E^h_{turb,i}$, $E^h_{pump,i}$), level of stored energy (E^h_{st}), and amount of energy imported (E^h_{imp}) or exported (E^h_{exp}) to the grid for each hour during the 8760 h of a year. Integer variables (value 0 or 1) are included such that the model determines the operating mode of the machine pump-turbine units (turbine $I^h_{turb,i}$ or pump $I^h_{pump,i}$), their start-up ($I^h_{start,i}$), and the mode of grid use (import (I^h_{imp}) from or export (I^h_{exp}) to) according to the hourly operation of the assessed system, which maximizes its operating profit.

The following sections discuss the role of pumped hydro energy storage, the increased or decreased availability of renewable energy generation, and the economic results obtained from the application of the model to the study system.

4.1. Impact of pumped hydro energy storage

First, this section compares the results obtained with and without pumped hydro energy storage in order to assess the importance of storage to the operation of grid-connected renewable systems. The following two cases are considered:

Case 0. No pumped hydro energy storage.

Case 1. Integration of pumped hydro energy storage.

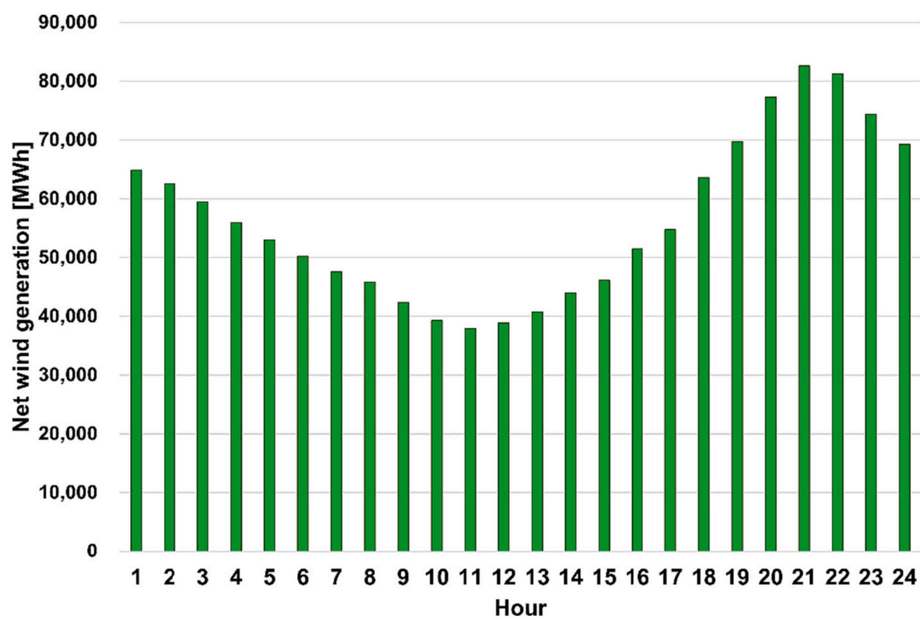


Fig. 2. Hourly net wind generation (2019).

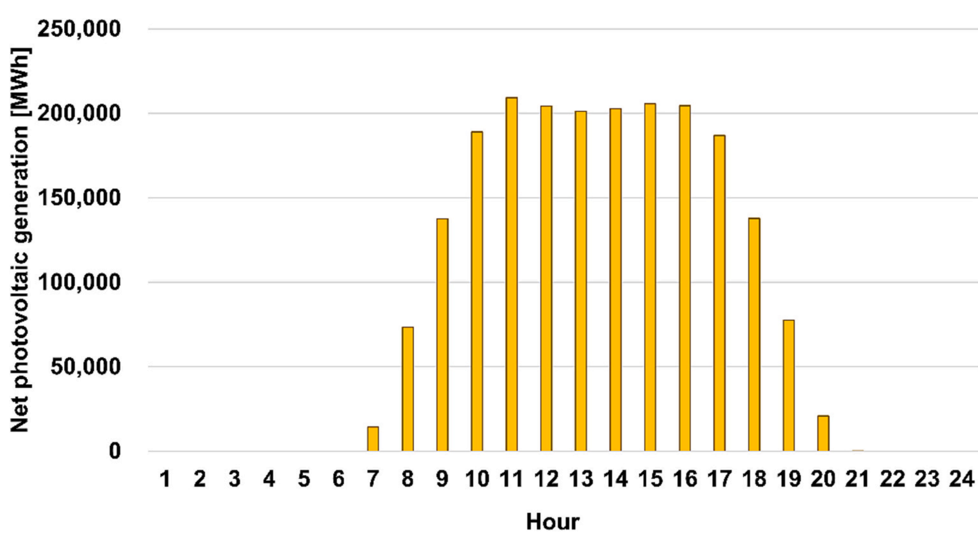


Fig. 3. Hourly net photovoltaic generation (2019).

Table 3 presents the optimal monthly results. An important advantage of the incorporation of pumped hydro-energy storage is the reduction in the risk of energy curtailment. Energy curtailment is an order from the market operator for large-scale photovoltaic (PV) and wind power plants, and self-consumption facilities reduce production for grid capacity reasons. This is because there are times when the differences between the stochastic energy supply and demand are very large.

In Case 0, the energy system would not be able to take advantage of all the renewable energy available to meet the electricity demand; therefore, energy curtailment would occur. In this scenario, wind and photovoltaic power production is reduced in most months of the year to comply with the restrictions on the maximum amount of energy exported to the grid in the model. By reducing renewable production owing to grid capacity issues, the energy system would have to increase the amount of energy purchased in the electricity market during all months to meet the system's electricity demand at all times.

However, in Case 1, the incorporation of reversible pump-turbine units allows for the surplus of renewable production to be stored when needed, and the economic results are optimized. The model self-consumes as much energy as possible from renewable generation plants, either directly or indirectly, by using a storage plant to meet the electricity demand. In this scenario, energy curtailment is not produced; therefore, all the available renewable power generation is used to satisfy the electricity demand, and if a surplus is generated, it is used to fill the storage system or exported directly to the grid. In addition, the system avoids exports and receives additional income from the sale of surplus. In the summer months, with greater renewable generation, it is possible to meet the electricity demand with renewable energy by almost 90 %. By contrast, in winter months with less photovoltaic generation, the system must purchase more energy from the electricity market to cover the required electricity demand.

To illustrate the storage operation, Fig. 4 shows the management for one day in July, when there is greater renewable power generation. As can be seen, in the central hours of the day with excess photovoltaic generation and less wind power generation, the storage is filled by the units working in pumping mode so that the stored energy can be used in the hours when there is not enough renewable generation and the power purchase prices in the electricity market are high. On the other hand, during the night hours, when there is only wind energy with low production, the storage is emptied to meet the electricity demand; therefore, in these hours, the units work in turbining mode, adapting their power to system needs.

In summary, in addition to supporting the operation of electricity generation systems with renewables and providing greater reliability and efficiency, the storage system can avoid situations in which wind or photovoltaic production must be reduced to lend stability to the power system when there is little demand and excess renewable generation.

4.2. *Impact of renewable energy*

This section examines the impact of renewable energy generation on the results obtained from the four-week analysis conducted over the study year.

Fig. 5 shows the hourly results attained to meet the demand during a week in four different months (January (Fig. 5a), April (Fig. 5b), July (Fig. 5c), and October (Fig. 5d)), which correspond to periods with greater or less available renewable generation, to better assess the behavior of the model.

In weeks with less available photovoltaic production, such as January and October in the figures presented (Fig. 5a and d, respectively), more energy is needed from the electrical grid in the first hours of the day to satisfy the demand of the system. These hours correspond to the lowest energy costs, considering the price figures used in this case. Consequently, during these periods, the units run in the pumping mode to fill the upper storage reservoir. Similarly, in the hours with high excess generation, the model also takes advantage of filling the upper reservoir even when the sale price is beneficial, because the maximum exported quantity is limited by the connection capacity to the electrical grid (396 MW). Therefore, the usefulness of pumped hydro-storage is verified, as it ensures security in the power system and reduces the energy costs for the system. If it is not available, part of the photovoltaic and wind production would be lost owing to the limitation of the access point and connection to the grid when the demand is much lower than the generation.

In weeks with higher photovoltaic generation and wind generation, the need to purchase energy from the electricity market to satisfy the required demand of the system is considerably reduced. In addition, the hours of maximum possible surplus energy exported to the grid increase with consequent additional income.

Table 3
Optimal monthly energy results for Cases 0 and 1 (MWh).

Month	Case	Eimp	Eexp	Epv	Ew	Epump, tot	Eturb, tot	Δ Eimp	Δ Eexp	Δ Epv	Δ Ew	% demand coverage
1	0	161,598	34,178	80,057	87,147	–	–	–	–	–	–	45
	1	144,014	15,409	80,057	90,357	34,960	30,565	−11 %	−55 %	0 %	4 %	51
2	0	91,379	59,978	107,345	127,367	–	–	–	–	–	–	66
	1	73,042	48,699	107,345	141,181	35,576	28,820	−20 %	−19 %	0 %	11 %	73
3	0	73,189	83,718	162,001	114,639	–	–	–	–	–	–	75
	1	67,723	75,961	173,012	142,214	40,831	28,467	−7 %	−9 %	7 %	24 %	77
4	0	75,702	102,694	196,564	115,549	–	–	–	–	–	–	73
	1	42,340	100,402	201,892	146,294	50,047	45,043	−44 %	−2 %	3 %	27 %	85
5	0	97,172	108,983	230,462	66,470	–	–	–	–	–	–	67
	1	65,003	107,764	243,684	105,734	52,263	40,229	−33 %	−1 %	6 %	59 %	78
6	0	73,128	121,324	254,298	79,018	–	–	–	–	–	–	74
	1	49,874	115,926	259,453	96,681	30,853	25,892	−32 %	−4 %	2 %	22 %	83
7	0	64,017	128,109	261,859	87,353	–	–	–	–	–	–	78
	1	38,448	136,027	277,093	122,681	38,919	31,348	−40 %	6 %	6 %	40 %	87
8	0	82,382	116,305	245,197	83,351	–	–	–	–	–	–	72
	1	64,237	113,342	249,487	100,130	24,790	18,902	−22 %	−3 %	2 %	20 %	78
9	0	106,912	82,776	188,129	72,855	–	–	–	–	–	–	63
	1	81,069	75,018	191,309	91,842	33,593	29,511	−24 %	−9 %	2 %	26 %	72
10	0	107,382	61,550	129,245	110,042	–	–	–	–	–	–	64
	1	93,270	45,868	133,188	119,189	29,014	23,858	−13 %	−25 %	3 %	8 %	68
11	0	156,938	28,308	80,322	76,169	–	–	–	–	–	–	45
	1	146,430	14,699	80,322	79,343	30,294	24,018	−7 %	−48 %	0 %	4 %	49
12	0	139,843	26,245	65,564	105,958	–	–	–	–	–	–	52
	1	140,506	20,327	68,514	116,062	44,219	34,088	0 %	−23 %	4 %	10 %	52

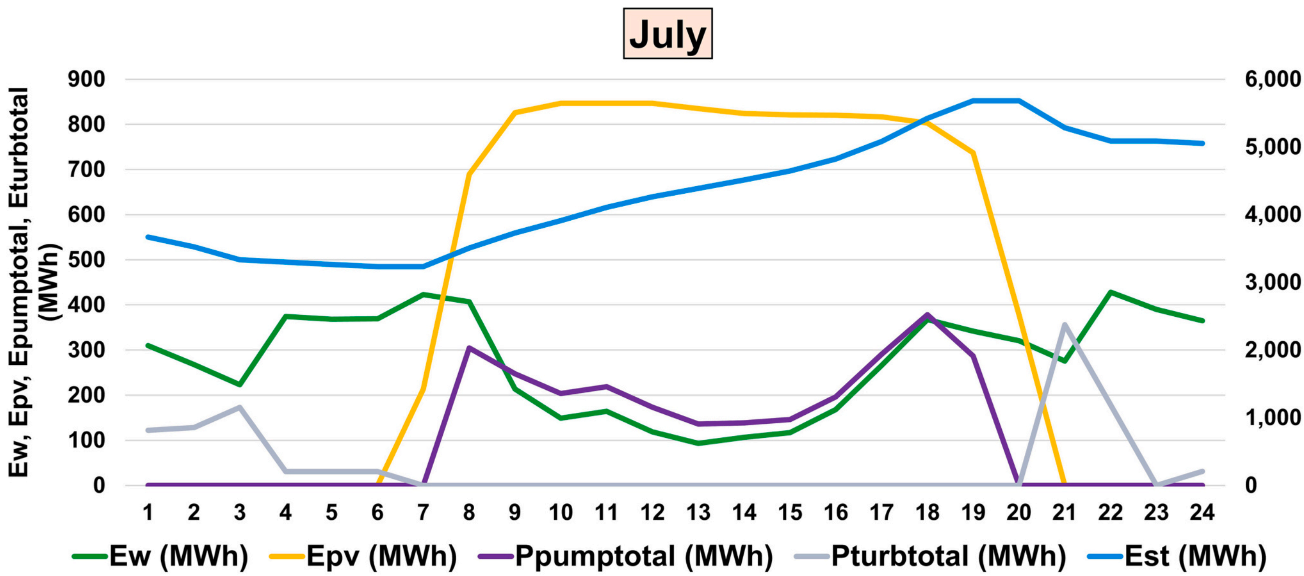


Fig. 4. Optimal operation of PHES during a day in July.

Within the central hours of the day, the ones with higher energy costs in the assessed case, the pump turbine units run in turbine mode to take advantage of the energy from the storage reservoir, in addition to renewable generation (mainly photovoltaic) to meet the demand without using the grid.

However, great variability was observed in wind generation. Climatic instability in autumn and winter causes energy generation bursts during these periods. In the hours with maximum wind-generated values, there is a greater export of energy to the grid, whereas in the hours with lower wind-generated values and without photovoltaic generation, the system must purchase energy from the electricity market to meet demand.

Finally, storage is essential for reducing the uncertainty in renewable energy generation. The energy stored can be used on cloudy days with low solar radiation or times with low wind resources to guarantee electricity demand without the need to purchase energy during hours with high energy costs. Additionally, the system can sell energy to the electricity market to obtain additional income. The model makes the most appropriate decision for each hour to maximize the operating profit in each month of the study year.

4.3. Impact of annual economic results

This section analyzes the annual energy and economic results obtained from applying the model to the case study.

Table 4 presents the annual energy consumption and economic results. Considering the 2019 Spanish electricity market prices, power renewable generation plants, together with pumped hydro energy storage (Case 1), satisfy the demand of the system for 56 % of the hours of a year (4901 h) without having to purchase energy from the electricity market. Compared to the case without storage (Case 0), the integration of PHES reduces the amount of energy to be purchased from the electricity market to satisfy the demand by 20 %, which implies an economic saving in the operation of the system of up to 27 % with respect to Case 0.

The sale price of surplus wind and photovoltaic production is the price set in the wholesale electricity market, whereas the energy purchase price includes the cost of energy acquisition in the electricity market, regulated tariff for using the grid, and corresponding taxes. Hence, it is always necessary to maximize the self-consumption of renewable generation plants to meet demand as a result of the savings that the system achieves by no longer importing energy from the grid.

Some studies have assessed the role of energy storage in renewable power systems [21,22,34]. These studies obtained a reduction in operation cost from 11 to 50 % with an optimal combination of the components of the system. Therefore, the results of this paper are within the range reported in the literature (27 %). A compromise should be made between the installation of additional generation and storage capacities.

Regarding energy curtailment, Case 0 reduces annual photovoltaic generation by 8 % compared with Case 1, whereas annual wind power generation is reduced by 17 %. Owing to the incorporation of PHES, the system takes advantage of all renewable generation available each hour and avoids the risk of energy curtailment.

Therefore, a PHES with reversible pump-turbine units of variable speed achieves better integration of photovoltaic and wind plants, rapidly adapting their production to maintain balanced generation at all times with greater energy independence and consequent operation cost savings.

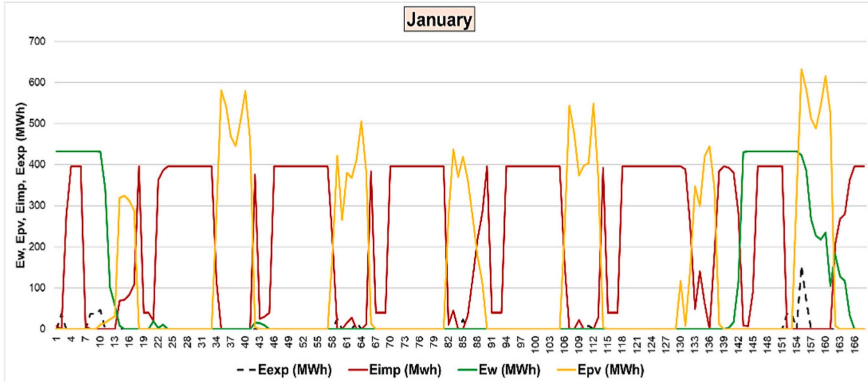
5. Conclusions and further research

The use of pumped hydro-energy storage is essential in current electricity grids with a high share of renewable energy because it allows for the optimization of the use of generated energy and the possible reduction of excess energy discharges. In addition, it can replace combined heat and power plants, which are dependent on gas imports and produce high CO_2 emissions, as a backup system to guarantee electricity supply in combination with renewable energy.

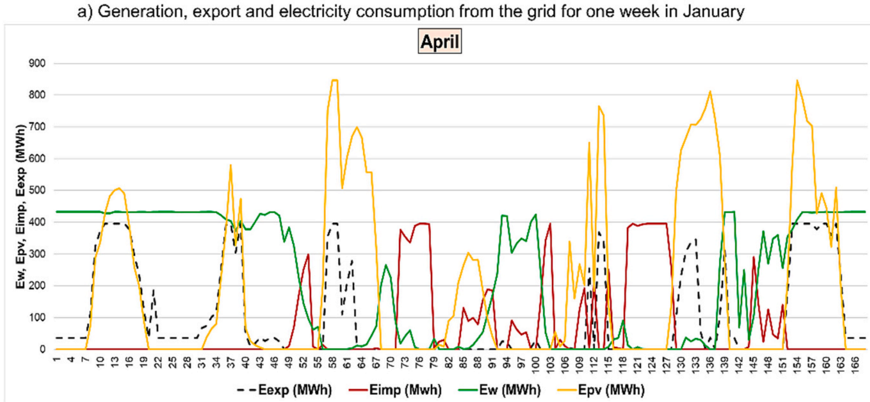
This paper presents a techno-economic hourly model applied to assess the operation of pumped hydro storage projects and large-scale self-consumption renewable generation plants. The model also has the possibility of selling generated surpluses. The model is applied to a case study with real hourly data of photovoltaic and wind generation, and energy purchase and sale prices, in addition to the technical data of the reversible pump turbine units.

The main findings of this study are as follows:

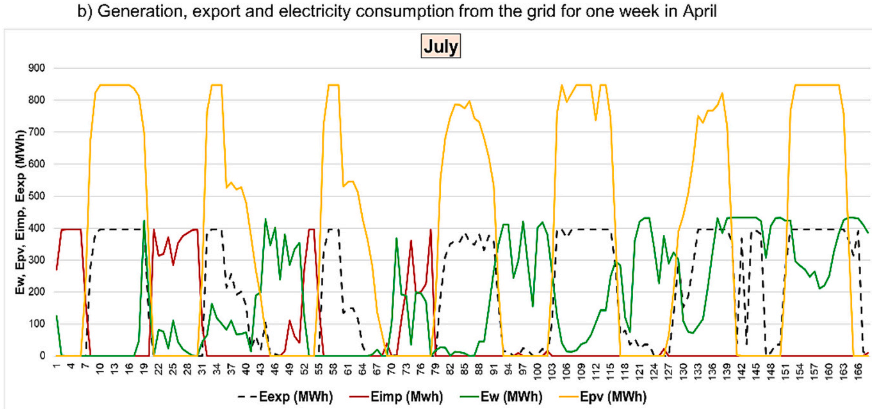
- The model maximizes the use of wind and solar resources. In half of the months of the year, >70 % of the electricity demand is met by stochastic renewable sources and the hydroelectric storage, reducing dependence on the grid.
- Pumped hydro energy storage is a key component in the management of electrical systems. The technical constraints of the grid associated with the secure operation of power systems may cause



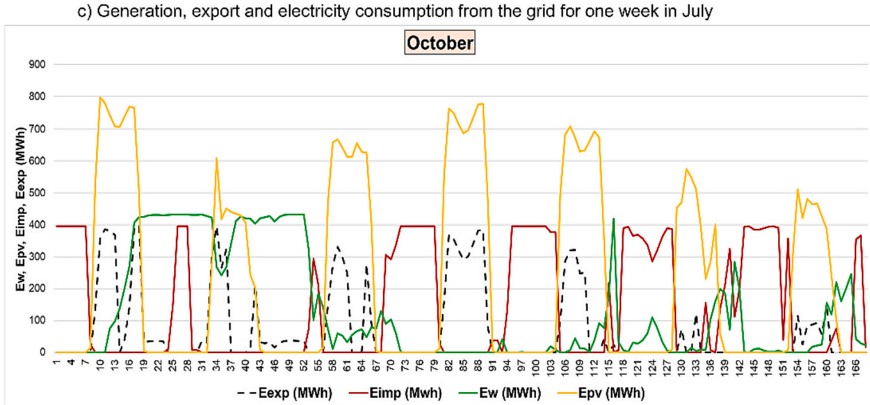
a) Generation, export and electricity consumption from the grid for one week in January



b) Generation, export and electricity consumption from the grid for one week in April



c) Generation, export and electricity consumption from the grid for one week in July



d) Generation, export and electricity consumption from the grid for one week in October

Fig. 5. Optimal hourly energy results obtained in one week in January, April, July, and October (2019).

Table 4
Annual results obtained.

Case	Case 0	Case 1
E_{imp} (MWh)	1,229,642	1,005,956
E_{exp} (MWh)	954,169	869,442
E_{pv} (MWh)	2,001,043	2065,356
E_{w} (MWh)	1,125,916	1,351,708
$E_{turb,\ total}$ (MWh)	–	360,741
$E_{pump,\ total}$ (MWh)	–	445,359
Demand coverage	64 %	71 %
Energy purchase costs in the electricity market (€)	75,594,553	56,163,318
Revenues from the sale of surplus energy(€)	46,375,098	43,360,557

rejections or curtailments during hours when there is a large amount of renewable energy generation. This type of storage reduces these situations.

- By combining one or more renewable energy sources with a storage system, the facility acquires management capacity, in addition to increasing its efficiency and flattening the generation profile.
- The units are run in pumping mode for hours with the lowest energy cost to fill the upper storage reservoir. In contrast, during hours with little or no renewable energy production, water is released from the upper reservoir when the system must satisfy its electrical demand.
- The integration of photovoltaic and wind energy sources, and PHES reduces the cost of purchasing energy in the electricity market by up to 27 % (56,163,318 €) compared with the case without a storage system (75,594,553 €) to meet the required electricity demand.
- The storage system avoids the risk of energy curtailment, as it has been verified that, in the PHES-wind-PV model, the maximum energy generated by the renewable plants in each hour is used, whereas in the case without storage, the annual wind power generation is reduced by 17 % and the photovoltaic generation by 8 %.
- Further research in which variable efficiency is incorporated in the operating range of reversible pump turbine units should be conducted, as the assumption of a variable efficiency value may improve the accuracy of the assessment.

In short, the application of the proposed model for the optimal operation of electrical systems based on renewable generation combined with large-scale pumped hydro storage helps improve the competitiveness and viability of power systems. The best decision is made every hour to reduce high energy costs and obtain efficient and resilient management of water use. Ultimately, pumped hydro energy storage improves energy efficiency and allows a higher share of renewable energy sources to be integrated into electrical systems in a secure, stable, and flexible manner.

CRediT authorship contribution statement

Natalia Naval: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Jose M. Yusta:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Raul Sánchez:** Conceptualization, Methodology, Validation. **Fernando Sebastián:** Conceptualization, Methodology, Validation, Writing – original draft, Supervision.

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.

References

[1] S.V. Papaefthymiou, S.A. Papathanassiou, Optimum sizing of wind-pumped-storage hybrid power stations inisland systems, Renew. Energy 64 (2014) 187–196, https://doi.org/10.1016/j.renene.2013.10.047.
[2] A. Bhimaraju, A. Mahesh, S.N. Joshi, Techno-economic optimization of grid-connected solar-wind-pumped storage hybrid energy system using improved search space reduction algorithm, J. Energy Storage 52 (2022) 104778, https://doi.org/10.1016/j.est.2022.104778.
[3] E.M. Krieger, J. Cannarella, C.B. Arnold, A comparison of lead-acid and lithium-based battery behavior and capacity fade in off-grid renewable charging applications, Energy 60 (2013) 492–500, https://doi.org/10.1016/j.energy.2013.08.029.
[4] A.S. Aziz, M.F.N. Tajuddin, M.K. Hussain, M.R. Adzman, N.H. Ghazali, M.A. M. Ramli, T.E. Khalil Zidane, A new optimization strategy for wind/diesel/battery hybrid energy system, Energy 239 (2022), https://doi.org/10.1016/j.energy.2021.122458.
[5] A. Arabkoohsar, L. Machado, M. Farzaneh-Gord, R.N.N. Koury, Thermo-economic analysis and sizing of a PV plant equipped with a compressed air energy storage system, Renew. Energy 83 (2015) 491–509, https://doi.org/10.1016/j.renene.2015.05.005.
[6] A. Panda, U. Mishra, K.B. Aviso, Optimizing hybrid power systems with compressed air energy storage, Energy 205 (2020) 117962, https://doi.org/10.1016/j.energy.2020.117962.
[7] M.J. Hadidian Moghaddam, A. Kalam, S.A. Nowdeh, A. Ahmadi, M. Babanezhad, S. Saha, Optimal sizing and energy management of stand-alone hybrid photovoltaic/wind system based on hydrogen storage considering LOEE and LOLE reliability indices using flower pollination algorithm, Renew. Energy 135 (2019) 1412–1434, https://doi.org/10.1016/j.renene.2018.09.078.
[8] F. Dawood, G.M. Shafiullah, M. Anda, Stand-alone microgrid with 100% renewable energy: a case study with hybrid solar pv-battery-hydrogen, Sustain. 12 (2020), https://doi.org/10.3390/su12052047.
[9] International Hydropower Association, 2021 Hydropower Status Report: Sector Trends and Insights, 2021.
[10] IRENA, Global Renewables Outlook 2020: Summary. www.irena.org, 2020.
[11] S. Ali, R.A. Stewart, O. Sahin, Drivers and barriers to the deployment of pumped hydro energy storage applications: systematic literature review, Clean. Eng. Technol. 5 (2021) 100281, https://doi.org/10.1016/j.clet.2021.100281.
[12] M.S. Javed, T. Ma, J. Jurasz, M.Y. Amin, Solar and wind power generation systems with pumped hydro storage: review and future perspectives, Renew. Energy 148 (2020) 176–192, https://doi.org/10.1016/j.renene.2019.11.157.
[13] J.D. Hunt, B. Zakeri, R. Lopes, P.S.F. Barbosa, A. Nascimento, N.J. de Castro, R. Brandão, P.S. Schneider, Y. Wada, Existing and new arrangements of pumped-hydro storage plants, Renew. Sust. Energ. Rev. 129 (2020), https://doi.org/10.1016/j.rser.2020.109914.
[14] E. Barbour, I.A.G. Wilson, J. Radcliffe, Y. Ding, Y. Li, A review of pumped hydro energy storage development in significant international electricity markets, Renew. Sust. Energ. Rev. 61 (2016) 421–432, https://doi.org/10.1016/j.rser.2016.04.019.
[15] M. Shabani, E. Dahlquist, F. Wallin, J. Yan, Techno-economic comparison of optimal design of renewable-battery storage and renewable micro pumped hydro storage power supply systems: a case study in Sweden, Appl. Energy 279 (2020) 115830, https://doi.org/10.1016/j.apenergy.2020.115830.
[16] B.A. Bhayo, H.H. Al-Kayiem, S.I.U. Gilani, F.B. Ismail, Power management optimization of hybrid solar photovoltaic-battery integrated with pumped-hydro-storage system for standalone electricity generation, Energy Convers. Manag. 215 (2020) 112942, https://doi.org/10.1016/j.enconman.2020.112942.
[17] M.S. Javed, T. Ma, J. Jurasz, F.A. Canales, S. Lin, S. Ahmed, Y. Zhang, Economic analysis and optimization of a renewable energy based power supply system with different energy storages for a remote island, Renew. Energy 164 (2021) 1376–1394, https://doi.org/10.1016/j.renene.2020.10.063.
[18] T. Ma, H. Yang, L. Lu, Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island, Energy Convers. Manag. 79 (2014) 387–397, https://doi.org/10.1016/j.enconman.2013.12.047.
[19] Y.F. Nassar, M.J. Abdunnabi, M.N. Sbeta, A.A. Hafez, K.A. Amer, A.Y. Ahmed, B. Belgasim, Dynamic analysis and sizing optimization of a pumped hydroelectric storage-integrated hybrid PV/wind system: a case study, Energy Convers. Manag. 229 (2021) 113744, https://doi.org/10.1016/j.enconman.2020.113744.
[20] R.J. Mahfoud, N.F. Alkayem, Y. Zhang, Y. Zheng, Y. Sun, H.H. Alhelou, Optimal operation of pumped hydro storage-based energy systems: a compendium of current challenges and future perspectives, Renew. Sust. Energ. Rev. 178 (2023) 113267, https://doi.org/10.1016/j.rser.2023.113267.
[21] K. Kusakana, Optimal operation scheduling of grid-connected PV with ground pumped hydro storage system for cost reduction in small farming activities, J. Energy Storage 16 (2018) 133–138, https://doi.org/10.1016/j.est.2018.01.007.
[22] S. Makhdoomi, A. Askarzadeh, Daily performance optimization of a grid-connected hybrid system composed of photovoltaic and pumped hydro storage (PV/PHS), Renew. Energy 159 (2020) 272–285, https://doi.org/10.1016/j.renene.2020.06.020.
[23] S. Lin, T. Ma, M. Shahzad Javed, Prefeasibility study of a distributed photovoltaic system with pumped hydro storage for residential buildings, Energy Convers. Manag. 222 (2020) 113199, https://doi.org/10.1016/j.enconman.2020.113199.
[24] E.D. Castronuovo, J.A.P. Lopes, Optimal operation and hydro storage sizing of a wind-hydro power plant, Int. J. Electr. Power Energy Syst. 26 (2004) 771–778, https://doi.org/10.1016/j.ijepes.2004.08.002.

[25] P. Cruz, H.M.I. Pousinho, R. Melício, V.M.F. Mendes, Optimal coordination on wind-pumped-hydro operation, Procedia Technol. 17 (2014) 445–451, https://doi.org/10.1016/j.protcy.2014.10.253.

[26] G. Cavazzini, A. Benato, G. Pavesi, G. Ardizzon, Techno-economic benefits deriving from optimal scheduling of a Virtual Power Plant: pumped hydro combined with wind farms, J. Energy Storage 37 (2021), https://doi.org/10.1016/j.est.2021.102461.

[27] S. Makhdoomi, A. Askarzadeh, Optimizing operation of a photovoltaic/diesel generator hybrid energy system with pumped hydro storage by a modified crow search algorithm, J. Energy Storage 27 (2020) 101040, https://doi.org/10.1016/j.est.2019.101040.

[28] K. Kusakana, Optimal scheduling for distributed hybrid system with pumped hydro storage, Energy Convers. Manag. 111 (2016) 253–260, https://doi.org/10.1016/j.enconman.2015.12.081.

[29] A. Ghasemi, M. Enayatzare, Optimal energy management of a renewable-based isolated microgrid with pumped-storage unit and demand response, Renew. Energy 123 (2018) 460–474, https://doi.org/10.1016/j.renene.2018.02.072.

[30] R.N. Vitorino, D.S. Ramos, K. Tapia-Ahumada, S. Paltsev, J. Reilly, Pumped-hydro storage plants influencing the optimal hourly dispatch in hydro-thermal systems with massive integration of variable renewable energy, Electr. Power Syst. Res. 220 (2023) 109282, https://doi.org/10.1016/j.epsr.2023.109282.

[31] G. Cavazzini, G. Pavesi, G. Ardizzon, A novel two-swarm based PSO search strategy for optimal short-term hydro-thermal generation scheduling, Energy Convers. Manag. 164 (2018) 460–481, https://doi.org/10.1016/j.enconman.2018.03.012.

[32] A.A. Bafrani, A. Rezazade, M. Sedighizadeh, Robust electrical reserve and energy scheduling of power system considering hydro pumped storage units and renewable energy resources, J. Energy Storage 54 (2022) 105310, https://doi.org/10.1016/j.est.2022.105310.

[33] M. Petrollese, P. Seche, D. Cocco, Analysis and optimization of solar-pumped hydro storage systems integrated in water supply networks, Energy 189 (2019) 116176, https://doi.org/10.1016/j.energy.2019.116176.

[34] J.I. Pérez-Díaz, J. Jiménez, Contribution of a pumped-storage hydropower plant to reduce the scheduling costs of an isolated power system with high wind power penetration, Energy 109 (2016) 92–104, https://doi.org/10.1016/j.energy.2016.04.014.

[35] R. Segurado, J.F.A. Madeira, M. Costa, N. Duić, M.G. Carvalho, Optimization of a wind powered desalination and pumped hydro storage system, Appl. Energy 177 (2016) 487–499, https://doi.org/10.1016/j.apenergy.2016.05.125.

[36] K. Kusakana, Hybrid DG-PV with groundwater pumped hydro storage for sustainable energy supply in arid areas, J. Energy Storage 18 (2018) 84–89, https://doi.org/10.1016/j.est.2018.04.012.

[37] L. Sun, Y. Jin, J. Shen, F. You, Sustainable residential micro-cogeneration system based on a fuel cell using dynamic programming-based economic day-ahead scheduling, ACS Sustain. Chem. Eng. 9 (2021) 3258–3266, https://doi.org/10.1021/acssuschemeng.0c08725.

[38] A.M. Foley, P.G. Leahy, K. Li, E.J. McKeogh, A.P. Morrison, A long-term analysis of pumped hydro storage to firm wind power, Appl. Energy 137 (2015) 638–648, https://doi.org/10.1016/j.apenergy.2014.07.020.

[39] G. Chang, H. Lu, H. Su, Short-term distributed energy resource scheduling for a DC microgrid, Energy Power Eng. 5 (2013) 15–21, https://doi.org/10.4236/epe.2013.54B003.

[40] G.E. Alvarez, Optimization analysis for hydro pumped storage and natural gas accumulation technologies in the Argentine Energy System, J. Energy Storage 31 (2020) 101646, https://doi.org/10.1016/j.est.2020.101646.

[41] B. Lu, A. Blakers, M. Stocks, T.N. Do, Low-cost, low-emission 100% renewable electricity in Southeast Asia supported by pumped hydro storage, Energy 236 (2021) 121387, https://doi.org/10.1016/j.energy.2021.121387.

[42] M. Child, D. Bogdanov, C. Breyer, The role of storage technologies for the transition to a 100% renewable energy system in Europe, Energy Procedia 155 (2018) 44–60, https://doi.org/10.1016/j.egypro.2018.11.067.

[43] OMIE. http://www.omie.es/inicio, 2023 (accessed February 10, 2023).

[44] I. Sârbu, I. Borza, Energetic optimization of water pumping in distribution systems, Period. Polytech. Ser. Mech. Eng. 42 (1998) 141–152.