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Optimal multi-stack scheduling strategy for large-scale electrolysis: Integration with renewable energy and multi-market electricity

Natalia Naval [a,*], Ander Martinez Alonso [b], Guillermo Matute [c], Jose M. Yusta [a]

[a] Department of Electrical Engineering, University of Zaragoza, María de Luna, 3, 50018 Zaragoza, Spain
[b] Electrotechnical Engineering and Energy Technology, MOBI Research Group, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[c] DNV, Edificio Trovador, Plaza Antonio Beltrán Martínez, 50002 Zaragoza, Spain

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ABSTRACT

The production of renewable hydrogen through the electrolysis of water has grown with the advancement of renewable energies. Power purchase agreements (PPAs) are essential to ensure a steady and affordable supply of renewable energy at hydrogen production plants, allowing green hydrogen to be truly sustainable and competitive in the energy market. The aim of this paper is to propose an optimal hourly techno-economic dispatch model of a multi-stack hydrogen production system with two PPAs, photovoltaic (on-site) and wind (off-site) to meet hydrogen production in the defined calculation window and minimize operating costs. The model allows purchasing energy in the wholesale market if the PPAs do not meet all the hydrogen demand and selling surpluses when the energy purchased through PPAs exceeds the demand of the electrolysis plant. A mixed-integer nonlinear programming model is formulated to optimize the technical and economic management of the proposed system. The problem is applied to a Spanish case where pioneering projects are being carried out through the provision of PPAs. The increase in wind PPA capacity enables a significant reduction in energy imports from the grid, with decreases ranging from roughly 50% to 80% and a higher profitability. It is essential to achieve a balanced wind-solar mix to ensure efficient electrolysis demand coverage and reduce export losses.

1. Introduction

1.1. Context

Hydrogen is becoming a key technology for a decarbonized economy, offering a sustainable alternative to fossil fuels. Global green hydrogen production capacity was approximately 8 GW in 2023 and is expected to reach 428 GW by 2030 [1]. Production is planned to increase from 0.7 Mt in 2022 to 20 Mt in 2030 and 523 Mt by 2050.

Nowadays, more than 30 countries are developing their national hydrogen strategies, mainly focusing on electrolysis of water from renewable sources. Hydrogen can be stored and transported efficiently and has diverse applications in energy, transportation, and industry [2].

Power Purchase Agreements (PPAs) are crucial to ensuring the supply of renewable electricity for hydrogen production, reducing price volatility and improving financial planning. However, factors like agreement type and plant size can impact project feasibility [2].

The Delegated Act on RFNBOs (Renewable Fuels of Non-Biological Origin) is part of the implementation of the European Union's Renewable Energy Directive (RED) and defines rules for hydrogen (and other fuels) produced from renewable electricity to be recognized as "renewable" for the purposes of targets and certification. It mainly establishes three conditions for hydrogen to be considered renewable: additionally, temporal correlation, and geographical correlation. In this context, PPAs are key tools to ensure green hydrogen [3].

Regarding additionally, this can be reached when fuel producers have signed PPAs, either direct or through intermediaries, to purchase from renewable electricity producers an amount at least equal to the electricity declared as renewable [3].

The temporal correlation will be met if the renewable fuel is produced during the same month in which the electricity was produced by the renewable plant with which it has a PPA contract. From 2030, this temporal correlation will become hourly [3].

Finally, the geographical correlation is fulfilled if the renewable electricity comes from the same area as the electrolyzer or from an interconnected area that meets the interconnection and price conditions [3].

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

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Nomenclature

Indexes

h	index for number of hours
j	index for number of electrolyzers

Data

TW	calculation window
$N_{cold_{start}}$	number of cold starts allowed in the selected calculation window
n_{ely}	number of electrolysis systems that make up the hydrogen production plant
$P_{ely,j}$	nominal power of each electrolyzer of the hydrogen production plant (kW)
η_j	efficiency of each electrolyzer $\left(\frac{\text{kWh}}{kg}\right)$
MPL	minimum partial load allowed for each electrolyzer (% of power with respect to nominal power)
$P_{H_2}^{TW}$	hydrogen production in the calculation window (kg)
$E_{consPPApv}^{h}$	hourly photovoltaic production (kWh)
$E_{consPPAw,total}^{h}$	total hourly wind power production (kWh)
$E_{standby,j}^{h}$	hourly electricity consumption of each electrolyzer in stand-by mode (kWh)
ρ_{PPAw}^{h}	hourly price for electricity purchased from wind PPA $\left(\frac{€}{kWh}\right)$
ρ_{PPApv}^{h}	hourly price for electricity purchased from the photovoltaic PPA $\left(\frac{€}{kWh}\right)$
ρ_{exp}^{h}	hourly price for energy exported to the grid $\left(\frac{€}{kWh}\right)$
ρ_{imp}^{h}	hourly price for energy imported from the grid $\left(\frac{€}{kWh}\right)$
$\rho_{hydrogen}^{h}$	hydrogen sales price $\left(\frac{€}{kg}\right)$
$C_{a,j}^{h}$	costs of each electrolyzer in the idle state (€)
$C_{b,j}^{h}$	costs of each electrolyzer in production state (€)
$C_{c,j}^{h}$	costs of each electrolyzer in stand-by state (€)
$C_{ab,j}^{h}$	costs of the transition from shutdown to production of each electrolyzer *j* (€)
$C_{cb,j}^{h}$	costs of the transition from stand-by to production of each electrolyzer *j* (€)
$C_{SCR,j}^{h}$	cost of stack degradation $\left(\frac{€}{h}\right)$
ATR^{h}	network access tariff rate $\left(\frac{€}{kWh}\right)$
$C_{SL,j}^{h}$	lifetime of the stack (h)
$C_{SR,j}^{h}$	replacement cost (€)
$C_{WC,j}^{h}$	water consumption cost of each electrolyzer (€)
$C_{WCR,j}^{h}$	amount of water required for each electrolyzer $\left(\frac{\text{L}}{kg}\right)$
$C_{W,j}^{h}$	water cost $\left(\frac{\text{L}}{m^3}\right)$
$CSUT_j^{h}$	percentage of time required for cold start-up of each electrolyzer (%)
$HSUT_j^{h}$	percentage of time required for hot start-up of each electrolyzer (%)
ATR^{h}	access tariff rate

Variables

$\mathrm{E}_{\mathrm{exp,w}}^{\mathrm{h}}$	hourly energy exported to the grid from the wind PPA (kWh)
$\mathrm{E}_{\mathrm{imp,mkt,j}}^{\mathrm{h}}$	hourly energy imported from the grid per electrolyzer *j* (kWh)
$\mathrm{E}_{\mathrm{imp,mkt,total}}^{\mathrm{h}}$	total imported hourly energy from the grid (kWh)
$E_{consPPAw}^{h}$	hourly energy consumed for hydrogen production from the wind PPA (kWh)
$\mathrm{I}_{\mathrm{exp}}^{\mathrm{h}}$	binary variable equal to 1 if energy is exported to the grid, otherwise it will be equal to 0
$\mathrm{I}_{\mathrm{imp,mkt}}^{\mathrm{h}}$	binary variable equal to 1 if any of the electrolyzers *j* is consuming from the grid, otherwise it will be equal to 0
$\mathrm{I}_{\mathrm{imp,mkt,j}}^{\mathrm{h}}$	binary variable equal to 1 if an electrolyzer *j* imports energy from the grid, and otherwise it will be equal to 0
$\mathrm{I}_{\mathrm{imp,mkt,total}}^{\mathrm{h}}$	integer variable corresponding to the total number of electrolyzers consuming electricity from the grid
$\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}$	hourly load factor of each electrolyzer *j* in production mode
$\mathrm{a}_{\mathrm{j}}^{\mathrm{h}}$	binary variable equal to 1 if electrolyzer *j* is in the idle state, and otherwise it will be equal to 0
$\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}$	binary variable equal to 1 if electrolyzer *j* is in production state, and otherwise it will be equal to 0
$\mathrm{c}_{\mathrm{j}}^{\mathrm{h}}$	binary variable equal to 1 if electrolyzer *j* is in stand-by state, and otherwise it is equal to 0

1.2. Electrolysis technologies and their challenges

Water electrolysis is a key method for green hydrogen production, using electricity to separate water into hydrogen and oxygen. Studies [4]-[5] focus on the different electrolysis technologies, their operating principles and challenges.

Alkaline Electrolysis (AWE) is a mature, cost-effective and commercially available large-scale technology. However, it has lower efficiency and a slow response to variable renewable energy loads [4,6]. Proton Exchange Membrane Electrolysis (PEMEL) offers higher efficiency and flexibility. However, the investment cost is higher due to the use of noble metal catalysts, and lower components durability [6]. Anion Exchange Membrane (AEM) electrolysis is an emerging technology that combines advantages of AWE and PEMEL, such as metal-free catalysts and alkaline operation, though challenges remain in membrane durability [5].

Paper [7] analyzes the electrification of hydrogen using proton exchange membrane fuel cells, which are commercially suitable for automotive applications. Furthermore, it also addresses several challenges, such as high costs, infrastructure limitations, market development, and data gaps on resource availability and sustainability for green hydrogen production.

1.3. Electrolysis with renewable generation

The optimal operation for hydrogen production with renewable energy focuses on maximizing hydrogen production efficiency, minimizing costs, and addressing the intermittent nature of renewable energy sources. Various strategies and techniques have been explored to achieve these objectives, adapting to the specific characteristics of different types of electrolyzers and the renewable energy sources used.

Optimization algorithms (linear, nonlinear, mixed-integer) are implemented to determine the optimal energy dispatch to the electrolyzers, considering factors such as electrolyzer efficiency, electricity costs, hydrogen demand, and the state of energy storage systems (batteries, hydrogen tanks) [8–17]. On the other hand, other works use heuristic methods to solve optimization problems in hydrogen production systems [18–21]. They can provide faster solutions compared to exact optimization techniques, especially for complex, large-scale systems where finding an optimal solution may be time-consuming. Nevertheless, a significant drawback is that heuristic methods do not guarantee an optimal solution. The quality of the solution can be highly dependent on the specific heuristic used and its parameters, meaning results might vary significantly across different scenarios.

The literature includes articles proposing optimal operation strategies for hydrogen production systems with the integration of photovoltaic and wind plants, [10–13,17]. Paper [10] presents an optimal dispatch model for self-consumption photovoltaic plants with electrolysis system to reduce operating costs. In addition, the authors of [11] include in the modeling the possibility of generating polarization curves and calculating the efficiency under different operating conditions. Work [12] assesses the daily scheduling strategy and capacity configuration of a wind-solar hydrogen production system. Paper [13] presents a multi-stack operation model with different power levels for hydrogen production using alkaline technology with integration of off-grid wind plants. The authors of [17] address the optimal management of both distributed and centralized electrolysis-based hydrogen generation and storage systems. An optimization model is proposed to maximize net profit by selling hydrogen and participating in grid ancillary services.

The integration of batteries with photovoltaic (PV) systems and electrolyzers enables a more continuous and stable power supply to the electrolyzers, improving their capacity factor and reducing dependence on the intermittent energy directly from the renewable source [11,15,16,19–21]. The authors of [15] include photovoltaics with battery storage to meet electrical and hydrogen demands to minimize costs. Similarly, article [16] studies participation in energy markets and ancillary services to obtain the optimal operation. Paper [19] obtains the optimal scheduling of a hybrid renewable energy system with hydrogen storage, electrolytic cell, hydrogen gas turbine and including demand response. Work [20] assesses the daily scheduling strategy and capacity configuration of a wind-solar hydrogen production system. The authors of [21] analyze different energy management systems for microgrids based on hydrogen technologies, such as the main optimization techniques, simulation tools, challenges, etc. The authors of [14] economically assess the use of pumped hydro storage, photovoltaics and hydrogen storage.

Some articles include the management of the three main operating states—production, standby, and idle—to minimize energy consumption when hydrogen is not being produced and to reduce startup times. This approach helps improve overall system efficiency by optimizing the transition between states, reducing unnecessary power usage, and extending the lifespan of electrolyzers [8,9]. The authors of [8] study the operating characteristics and states of each type of electrolyzers. In addition, article [9] focuses on modeling three operating states of electrolyzers, shutdown, production and standby. On the other hand, some models consider the variable efficiency of electrolyzers based on load and operating temperature to optimize energy consumption [18].

1.4. Economic assessment and project feasibility

Other studies analyze the economic feasibility of hydrogen production systems using specific indicators and models. The Levelized Cost of Hydrogen (LCOH) assesses the competitiveness of produced hydrogen and varies significantly depending on the location, technology, project scale, and economic conditions [22]. For projects that integrate renewable energy production to power electrolysis, the Levelized Cost of Energy (LCOE) of these energy sources (such as photovoltaic solar, wind, and concentrated solar power) is a determining factor in the final cost of hydrogen. The hybridization of different renewable sources can lead to higher efficiency and higher capacity factors, which potentially reduces the LCOE and, consequently, the LCOH [23]. In more complex systems with multiple components (such as different types of photovoltaic panels and electrolyzers), the goal is to minimize the Total Annualized Cost (TAC) , as proposed by the authors of [24].

On the other hand, Power Purchase Agreements (PPA) enhance feasibility by stabilizing prices and reducing risks. The authors of [25] develop a techno-economic mathematical model applied to the economic feasibility study of hydrogen projects with the incorporation of on-site solar PPA. In addition, the economic viability is sensitive to several parameters. Works have explored the sensitivity of LCOH/LCOE to factors such as the price of PPAs [25], capital costs (CAPEX) [26], operational costs (OPEX) [27], electricity prices [27], hydrogen demand [25], location and availability of renewable resources [26]. Article [26] focuses on the planning of a renewable energy park for the production of green hydrogen in different locations and renewable systems. Work [27] analyzes the economic feasibility of wind, photovoltaic, biogas energy system to meet residential and commercial electricity demand.

1.5 Research gaps

Although optimal economic dispatch models in energy systems have been widely proposed in the reviewed literature, there are still gaps that need to be addressed.

- Insufficient focus on operational optimization: Few studies realistically address the optimal operation of hydrogen production plants in conjunction with PV and wind generation plants, leaving a gap in strategies for maximizing economic and technical performance under variable renewable generation.
- The lack of integration of on-site and off-site Power Purchase Agreements: previous studies do not propose mathematical models that integrate both on-site and off-site PPAs in order to obtain the optimal operation of hydrogen production plants. In addition to proposing models that participate in the wholesale electricity market, to consider price arbitrage opportunities and optimize operational profit.
- Absence of large-scale multi-stack electrolysis considerations: Current research overlooks the inclusion of multi-stack electrolysis systems, which are crucial for enhancing the flexibility and efficiency of hydrogen production plants.
- Limited practical application: The majority of reviewed articles focus on theoretical frameworks or simplified case studies, with scarce application to actual projects, leading to models that may not reflect the operational complexities of real hydrogen production facilities.

In summary, the literature reveals significant gaps in the modeling and optimization of hydrogen production systems. Specifically, there is a clear need for comprehensive mathematical models that integrate both on-site and off-site PPAs, incorporate multi-stack electrolysis configurations, and are applicable to real-world projects. Addressing these gaps is essential to provide more realistic, flexible, and efficient strategies for the optimal operation of hydrogen plants integrated with renewable energy sources.

1.6 Research objectives and contributions

In this context, the research question is: How can the efficient integration of on-site and off-site renewable PPAs, multi-stack electrolysis, and market dynamics enhance the operation and sustainability of green hydrogen production?

In order to overcome these gaps, this article aims to develop an optimal hourly techno-economic scheduling model of a multi-stack electrolysis system for hydrogen production with the integration of an on-site PV PPA and an off-site wind PPA in addition to participating in the wholesale electricity market to minimize operating costs. Furthermore, real generation and electrolysis system data are used to validate the proposed model and lead to realistic technical and economic feasibility studies.

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

- An hourly optimization model is proposed for the operation of a large-scale multi-stack electrolysis system, considering technical and economic factors. The proposed model is non-linear mixed integer.
- Combination of the wholesale electricity market as well as an on-site solar PPA and an off-site wind PPA.
- This approach uses data from actual projects, ensuring a more accurate analysis of operating conditions.

It is analyzed how a renewable hybrid supply scheme can improve the sustainability and profitability of hydrogen production. The model can serve as a reference for future renewable energy optimized electrolysis strategies.

The rest of the article is structured as follows: Section 2 defines the objective and assumptions of the proposed mathematical model. Section 3 formulates the mathematical model. Section 4 indicates the case study and the scenarios defined for the validation of the model. Section 5 analyzes the results obtained. Finally, Section 6 summarizes the main conclusions.

2. Description of the model and assumptions

The model proposed in this research consists of a hydrogen production plant, whose demand will be met from photovoltaic generation agreed at a PPA price, wind production supplied at a PPA price, and purchase from the grid at hourly electricity market price together with fees and charges. Furthermore, as the wind PPA is financial, the existing surplus could be resold to the electricity market. It should be noted that the hydrogen production plant will consist of the electrolysis facility, in addition to the compression and storage equipment. The distribution chain is outside the scope of this model, as this part is usually handled by another actor. The model aims to minimize operating costs and produce the required hydrogen demand by managing the available resources (see Fig. 1).

The proposed model considers the following assumptions.

In relation to the energy exchange process of the system in the OMIE day-ahead electricity market:

- The model is grid-connected to take advantage of opportunities to purchase and sell energy with the electricity market through an indexed contract with a trader.
- It is possible to accurately estimate wholesale electricity market prices in the model, as these prices are generally available the day before consumption.

According to the PPAs:

- ON-SITE PV PPA, all production is consumed in the operation of the system's electrolyzers. The resale of solar PPA is not allowed.
- OFF-SITE wind PPA, pay as produced, therefore, it is possible to resell the energy not consumed at market price minus 7% sales tax of the production.
- By integrating an on-site solar PPA and an off-site wind PPA, hybrid hydrogen projects can guarantee not only the stability and reliability of energy production, but also the ability to resell excess electricity without incurring losses, optimizing both hydrogen production and project profitability through proper management of surplus energy.

Regarding the hydrogen production plant:

- The electrolyzer presents three operating states:
  - Production mode: the electrolyzer produces hydrogen. The production varies between a minimum value and full load operation (nominal power).
  - Stand-by mode: the electrolysis system does not produce hydrogen, but the stack is maintained with the appropriate pressure and temperature conditions because it is planned to produce hydrogen again in a short period of time. In this mode, the electrolyzer consumption is low.
  - Idle mode: the electrolyzer is completely off and has no consumption.
- The load factor of the electrolyzer expresses the percentage of power demand in relation to the rated power of the electrolyzer for each hour of production. Each individual electrolyzer unit varies between a minimum partial load value, in this case 0.1, and 1 for the production state, while its value will be 0 in the idle and stand-by states.
- The electrolysis system has different types of start-ups.
  - Cold start: the electrolyzer switches from idle mode to production. The response time is several minutes.
  - Hot start: the electrolyzer transitions from stand-by mode to production. This transition has a response time of several seconds.
  - The transitions from production to stand-by and from production to shutdown are assumed to be an immediate transition.

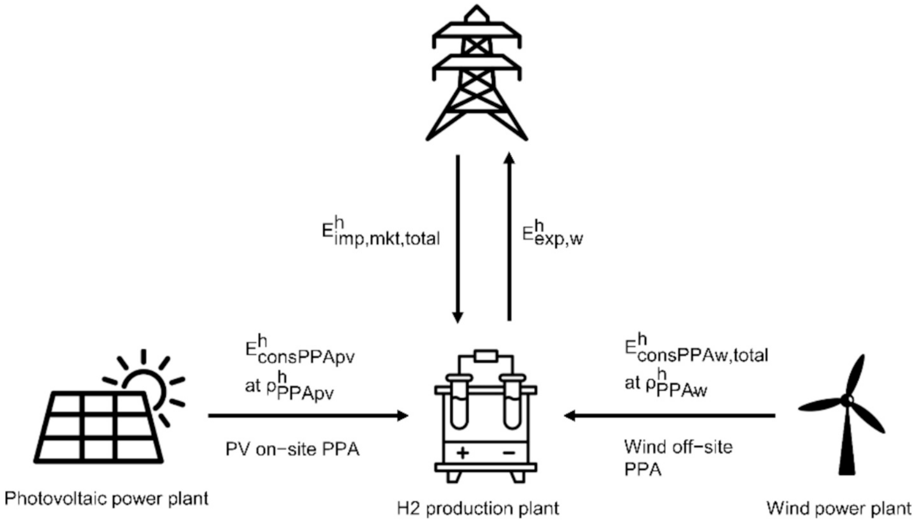

Fig. 1. Proposed model scheme

- The model includes a maximum number of cold starts for each electrolyzer to reduce degradation. In this paper, the maximum number is 3 every 72 hours.
- The system consists of ten electrolyzers connected in parallel.
- The calculation window is considered to be 3 days. This time window allows the operator to meet hydrogen demand during maintenance tasks, in addition to anticipating PV and wind generation and electricity prices in the wholesale market.
- This article has assumed constant electrolyzer efficiency to avoid increasing the computational complexity of the model. However, under real operating conditions, efficiency may vary, so this simplification can lead to deviations for hydrogen produced [26]. As further work, the incorporation of this variable efficiency behavior should be studied to obtain more accurate results.
- The model assumes a hydrogen storage buffer at the electrolyzer output, enough to meet a 3-day demand, as storage capacity is not explicitly modeled.

3. Mathematical formulation

The objective of this problem is to develop an optimal hourly mathematical model of techno-economic dispatch of an electrolysis plant composed of several electrolyzers and two wind and photovoltaic PPAs to meet a required hydrogen production in the chosen calculation window at minimum cost. In addition, the system is connected to the electrical grid to have the possibility of purchasing energy in the OMIE day-ahead market, in case the production cannot be covered with the supply of the two PPAs, or selling the wind generated surpluses in the electricity market.

The main hourly optimization variables are the operating states of each of the electrolyzers (idle, $\mathrm{a}_{\mathrm{j}}^{\mathrm{h}}$, production, $\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}$, o stand-by, $\mathrm{c}_{\mathrm{j}}^{\mathrm{h}}$), the load factor of each of them ($\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}$), the energy consumed by each electrolyzer from the grid ($E_{imp,mkt,j}^{h}$), and the energy sold in the wholesale market to obtain additional income ($E_{exp,w}^{h}$), among others.

3.1. Objective function

The objective function (Equation (1)) minimizes the operating costs of an electrolysis system with several electrolyzers connected to the grid, and two PPAs wind and photovoltaic, to meet a hydrogen demand in the considered calculation window. Regarding system costs, cold start-up costs ($C_{ab,j}^{h}\cdot\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{a}_{\mathrm{j}}^{\mathrm{h-1}}$) are included, hot start ($C_{cb,j}^{h}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{c}_{\mathrm{j}}^{\mathrm{h-1}}$), stacks degradation ($C_{SCR,j}^{h}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}$), electricity purchase in the electricity market in production mode $\left(E_{imp,mkt,j}^{h}\cdot(\rho_{imp}^{h}+ATR^{h})\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\right)$ and stand-by $\left(E_{imp,mkt,j}^{h}\cdot(\rho_{imp}^{h}+ATR^{h})\cdot\mathrm{c}_{\mathrm{j}}^{\mathrm{h}}\right)$, as well as the energy consumed from the wind PPA ($E_{consPPAw}^{h}\cdot\left[\rho_{PPAw}^{h}+ATR^{h}\right]$). The hourly energy cost corresponds to the sum of the electricity market price, ρ_{imp}^{h}, and the network access tariff rate, ATR^{h}. Access tariff rates are regulated charges incorporated into electricity supply agreements. On the other hand, according to the system income, those due from hydrogen production $\left(C_{b,j}^{h}\cdot\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\right)$ and the sale of surplus produced from the wind plant ($\left[\rho_{PPAw}^{h}-\rho_{exp}^{h}\right]\cdot E_{exp,w}^{h}$) are considered. In the same way, the hourly energy cost from wind PPA should include both the fixed PPA price and the access tariff rate.

The fourth term of the objective equation ($C_{cb,j}^{h}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{c}_{\mathrm{j}}^{\mathrm{h-1}}$) is associated with the cost of transition from stand-by mode, where the electrolyzer does not produce hydrogen, to production mode. In stand-by mode, the electrolyzer consumes a low amount of energy to remain warm and pressurized and reach production state with a fast response.

$$min\sum_{h=1}^{TW}\left[\sum_{j=1}^{n_{ely}}\left(C_{b,j}^{h}\bullet\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}\bullet\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\right)+C_{SCR,j}^{h}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}+\left(C_{ab,j}^{h}\bullet\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}\bullet\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\bullet\mathrm{a}_{\mathrm{j}}^{\mathrm{h-1}}\right)+\left(C_{cb,j}^{h}\bullet\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\bullet\mathrm{c}_{\mathrm{j}}^{\mathrm{h-1}}\right)+\left(E_{imp,mkt,j}^{h}\bullet(\rho_{imp}^{h}+ATR^{h})\bullet\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\right)+\left(E_{imp,mkt,j}^{h}\bullet(\rho_{imp}^{h}+ATR^{h})\bullet\mathrm{c}_{\mathrm{j}}^{\mathrm{h}}\right)\right]+\sum_{h=1}^{TW}\left[\rho_{PPAw}^{h}-\rho_{exp}^{h}\right]\bullet E_{exp,w}^{h}+\sum_{h=1}^{TW}E_{consPPAw}^{h}\bullet\left[\rho_{PPAw}^{h}+ATR^{h}\right] \tag{1}$$

Equation (2) indicates the production costs of each electrolyzer. It is obtained as the difference between the hourly water consumption of each electrolyzer ($C_{WC,j}^{h}$) and the amount of hydrogen obtained each hour multiplied by the selling price of hydrogen ($\frac{P_{ely,j}}{\eta_j}\cdot\rho_{hydrogen}^{h}$).

Equation (3) calculates the water consumption, which is obtained by the product of the water cost ($C_{W,j}^{h}$), the amount of water required ($C_{WCR,j}^{h}$) and the amount of hydrogen produced ($\frac{P_{ely,j}}{\eta_j}$).

Equation (4) obtains the stack degradation cost by the quotient of the stack replacement cost ($C_{SR,j}^{h}$) and the expected stack lifetime ($C_{SL,j}^{h}$).

Equation (5) indicates the calculation of the transition cost from shutdown to production of each electrolyzer equal to the product of the percentage of time required for start-up ($CSUT_j^h$) and the lost remuneration due to not producing hydrogen ($\frac{P_{ely,j}}{\eta_j}\cdot\rho_{hydrogen}^{h}$).

Equation (6) shows the stand-by to production transition calculation for each electrolyzer equal to the product of the percentage of time required for start-up ($HSUT_j^h$) and the remuneration loss due to not producing hydrogen ($\frac{P_{ely,j}}{\eta_j}\cdot\rho_{hydrogen}^{h}$).

$$C_{b,j}^{h}=C_{WC,j}^{h}-\frac{P_{ely,j}}{\eta_j}\cdot\rho_{hydrogen}^{h} \tag{2}$$

$$C_{WC,j}^{h}=C_{W,j}^{h}\cdot C_{WCR,j}^{h}\cdot\frac{P_{ely,j}}{\eta_j} \tag{3}$$

$$C_{SCR,j}^{h}=\frac{C_{SR,j}^{h}}{C_{SL,j}^{h}} \tag{4}$$

$$C_{ab,j}^{h}=CSUT_j^h\cdot\frac{P_{ely,j}}{\eta_j}\cdot\rho_{hydrogen}^{h} \tag{5}$$

$$C_{cb,j}^{h}=HSUT_j^h\cdot\frac{P_{ely,j}}{\eta_j}\cdot\rho_{hydrogen}^{h} \tag{6}$$

3.2. Constraints

3.2.1. Hydrogen production

Equation (7) imposes the required hydrogen production within the defined calculation window ($P_{H_2}^{TW}$).

$$\sum_{h=1}^{TW}\left[\sum_{j=1}^{n_{ely}}\frac{P_{ely,j}}{\eta_j}\cdot\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}\right]=P_{H_2}^{TW} \tag{7}$$

3.3.2.2. Energy balance. Equation (8) shows the energy balance in each hour. The consumption of the electrolyzers in production mode ($\frac{P_{ely,j}}{\eta_j}\cdot\mathrm{r}_{\mathrm{j}}^{\mathrm{h}}\cdot\mathrm{b}_{\mathrm{j}}^{\mathrm{h}}$) and stand-by ($E_{standby,j}^{h}\cdot\mathrm{c}_{\mathrm{j}}^{\mathrm{h}}$) must be equal to the sum of the consumption from the wind ($E_{consPPAw}^{h}$) and photovoltaic ($E_{consPPApv}^{h}$) PPAs, and the energy purchased in the day-ahead electricity market ($E_{imp,mkt,j}^{h}$).

$$E^h_{consPPApv} + E^h_{consPPAw} + \left[\sum_{j=1}^{n_{ely}} E^h_{imp,mkt,j} - \frac{P_{ely,j}}{\eta_j}\cdot \mathrm{r}^h_j\cdot \mathrm{b}^h_j - E^h_{standby,j}\cdot \mathrm{c}^h_j\right] = 0 \qquad (8)$$

Since this is an off-site, pay as produced wind PPA, the total wind production ($E^h_{consPPAw,total}$) corresponds to the sum of the energy consumed for hydrogen production ($E^h_{consPPAw}$) and the energy sold in the electricity market ($\mathrm{E}^h_{exp,w}$), as shown in Equation (9).

$$E^h_{consPPAw,total} = E^h_{consPPAw} + \mathrm{E}^h_{exp,w} \qquad (9)$$

3.3.2.3. Energy exchange with the grid. Equations (10)-(15) indicate the restrictions associated with the energy exchange in the OMIE electricity market.

Equation (10) limits the energy sold in the electricity market ($\mathrm{E}^h_{exp,w}$), considering the wind energy generated in each hour ($\mathrm{I}^h_{exp}\cdot E^h_{consPPAw,total}$).

Equation (11) calculates the total energy consumed from the grid ($E^h_{imp,mkt,total}$). The limits of the hourly imported energy of each electrolyzer ($E^h_{imp,mkt,j}$) are imposed in Equation (12), taking into account the rated power of the electrolyzer ($\mathrm{I}^h_{imp,mkt,j}\frac{P_{ely,j}}{\eta_j}\cdot \mathrm{r}^h_j\cdot \mathrm{b}^h_j$) and the stand-by consumption ($E^h_{standby,j}\cdot \mathrm{c}^h_j$).

Equation (13) shows the total number of electrolyzers that are importing energy from the grid in each hour ($\mathrm{I}^h_{imp,mkt,total}$).

Equation (14) allows to control by means of a binary variable, when any of the electrolyzers of the system is importing energy from the grid ($\mathrm{I}^h_{imp,mkt}$).

Equation (15) prevents the purchase ($\mathrm{I}^h_{imp,mkt}$) and sale (I^h_{exp}) of energy in the electricity market from occurring simultaneously in the same hour.

$$0 \le \mathrm{E}^h_{exp,w} \le \mathrm{I}^h_{exp}\cdot E^h_{consPPAw,total} \qquad (10)$$

$$E^h_{imp,mkt,total} = \sum_{j=1}^{n_{ely}} E^h_{imp,mkt,j} \qquad (11)$$

$$0 \le E^h_{imp,mkt,j} \le \mathrm{I}^h_{imp,mkt,j}\frac{P_{ely,j}}{\eta_j}\cdot \mathrm{r}^h_j\cdot \mathrm{b}^h_j + E^h_{standby,j}\cdot \mathrm{c}^h_j \qquad (12)$$

$$\mathrm{I}^h_{imp,mkt,total} = \sum_{j=1}^{n_{ely}} \mathrm{I}^h_{imp,mkt,j} \qquad (13)$$

$$-n_{ely}\cdot\left(1-\mathrm{I}^h_{imp,mkt}\right) \le \mathrm{I}^h_{imp,mkt,total} \le n_{ely}\cdot \mathrm{I}^h_{imp,mkt} \qquad (14)$$

$$\mathrm{I}^h_{imp,mkt} + \mathrm{I}^h_{exp} \le 1 \qquad (15)$$

3.3.2.4. Operating states of the electrolysis system. Regarding the operating states of the electrolysis system, Equation (16) restricts the operation of each electrolyzer to a single state in each hour (idle, a^h_j, production, b^h_j, or stand-by, c^h_j). Equations (17) and (18) prevent the transition from idle to stand-by, and vice versa, respectively.

$$\mathrm{a}^h_j + \mathrm{b}^h_j + \mathrm{c}^h_j = 1 \qquad (16)$$

$$\mathrm{c}^h_j\cdot \mathrm{a}^{h\text{-}1}_j = 0 \qquad (17)$$

$$\mathrm{c}^{h\text{-}1}_j\cdot \mathrm{a}^h_j = 0 \qquad (18)$$

Equations (19)-(21) show the limits of the load factor of each electrolyzer in each hour (r^h_j) between the minimum load value in production mode (*MPL*) and 1, while if the electrolyzer is idle or stand-by, the value will be 0.

$$\mathrm{r}^h_j - \mathrm{b}^h_j \le 0 \qquad (19)$$

$$-\mathrm{r}^h_j + MPL\cdot \mathrm{b}^h_j \le 0 \qquad (20)$$

$$0 \le \mathrm{r}^h_j \le 1 \qquad (21)$$

Equation (22) limits the number of cold starts of each electrolyzer within the defined calculation window ($N_{cold_{start}}$).

$$\sum_{h=1}^{TW} \mathrm{b}^h_j\cdot \mathrm{a}^{h\text{-}1}_j \le N_{cold_{start}} \qquad (22)$$

Based on the objective function and the constraints of the optimization problem formulated, the model is of a non-linear mixed-integer type, since there are integer decision variables corresponding to the import/export of electricity and the operating states of the electrolyzers (idle, production and stand-by), in addition to continuous variables (energy consumed and exported to the grid, among others). In order to efficiently model and optimize the proposed mathematical problem, the GAMS® (General Algebraic Modeling System) software is used since this software provides multiple solvers available. In this paper, SCIP (Solving Constraint Integer Programs) is used as a solver to obtain the optimal solution. SCIP employs branching and cutting techniques that allow the original model to be divided into subproblems for its resolution. It is a solver suitable for efficiently solving mixed-integer programming (MIP) and mixed-integer nonlinear programming (MINLP) models.

4. Case study

To validate the proposed model, it is applied to a Spanish case study that includes an infrastructure domain with a PV plant supplying the on-site PPA, a wind plant supplying the off-site PPA, pay as produced, and the hydrogen production plant (electrolysis, compression and storage of sufficient hydrogen to meet the demand in a defined calculation window).

Table 1 shows the data for photovoltaic and wind PPAs, along with grid access. In hydrogen production projects with PPAs, a flatter generation profile is needed, and less risk of having to resell the PPA at a loss, so a ratio of 2 (wind): 1 (solar) is being chosen for hybridized projects.

Table 2 indicates the main technical and economic parameters of the multi-stack electrolysis system required for the optimization of the proposed model.

Table 3 shows the scenarios for analyzing the behavior of the model.

For each scenario, the optimization is performed in consecutive 3-day windows. In other words, the system proposed is optimized sequentially each 3-day period, and it is repeated until all days of the month are completed.

Table 1
Solar and wind PPA data and grid access.

Parameter	Value
Photovoltaic PPA Agreement	On-site
Photovoltaic PPA price	30 €/MWh
Photovoltaic peak power	100 MW
Wind PPA Agreement	Off-site, pay as produced
Wind PPA price	40 €/MWh
Wind power	200 MW
Electricity supply contract	Pass-through contract indexed to the wholesale electricity market
Energy sales	Excess wind PPA electricity sold at hourly electricity market prices minus 7% tax on electricity generation

Table 2
Electrolysis plant technical and economic data

Parameter	Value/Description
Technology	Alkaline
Components in the container	MV/LV transformer, rectifier, stack, BOP
CAPEX	800 €/kW
Stack replacement cost	30% of CAPEX
Stack replacement lifetime	80,000 hours
Water cost	3.8 €/m^3
Water consumption to produce hydrogen	15 L/kg
Total plant power	100 MW
Number of electrolyzers	10
Power of each electrolyzer	10 MW
Minimum partial load of each electrolyzer	10%
Overall system efficiency	50 kWh/kg
Stand-by consumption	2% of rated electrolyzer power
Cold start-up time	20 min
Hot start-up time	30 s
Maximum number of cold starts in the defined calculation window	3
Time window	3 days
Hydrogen demand in the calculation window	9863 kg
Hydrogen sales price	5 €/kg

5. Results and discussion

This section presents the results obtained after applying the model to the scenarios proposed in Table 3.

5.1. Hourly energy results

First, the hourly behavior during 72 hours is illustrated for scenario 6, as shown in Fig. 2. In this case, the wind power is double the photovoltaic and electrolysis power, which is what, is happening in large hydrogen projects. This occurs due to the need to have a flat power profile, where there are fewer moments of generation above the electrolysis consumption, to avoid the risk of reselling the PPA at a loss (in recent years electricity prices are much lower in solar hours), even though the cost of a wind PPA is more expensive than a PV one.

The electrolysis plant operator can use generation from the photovoltaic and wind PPAs in addition to the purchase of power from the grid to maintain the required hydrogen production within the 72-hour calculation window. All of the production associated with the on-site photovoltaic PPA is consumed in the production of hydrogen with the electrolyzers, with no export capacity, while the off-site wind PPA allows the financial operation of reselling excess production to the wholesale electricity market.

Importing from the grid occurs at times when wholesale electricity market prices are lower, mainly at night, to meet the demanded amount of hydrogen. In addition, if in a given hour the wholesale market price is lower than the fixed price agreed in the wind PPA (40 €/MWh), it may be more economical to consume directly from the grid instead of considering the energy from the wind PPA.

Regarding export to the grid, at times when production from PPAs is higher than the total electrolysis power, and at times when the hourly market price is higher than the wind PPA price (above 40 €/MWh), the option is taken to resell the wind PPA and obtain a profit margin. For example, as can be seen in Fig. 2, in hours 9 and 10 the surplus of the wind PPA is resold. Being a day in July, there is a large generation of renewables (44 MWh of PV and 62 MW wind), so the electrolyzers operate at nominal load to produce hydrogen, and the excess is sold to the electricity market at a price of 51 €/MWh, higher than the purchase price of the wind PPA. In this way, income from the electrolysis system is maximized.

In general, the purchase prices agreed in the PPA contracts are usually lower and more stable over the hours than the prices in the wholesale electricity market, which are subject to variations and increase depending on demand, weather conditions and generation costs in the grid, among others. As a result, the tendency of the model is to self-consume as much generation as possible from the PPAs to minimize the operating costs of the electrolysis plant and meet the required hydrogen demand.

5.2. Electrolyzers operation

On the other hand, the operation of the system's electrolyzers during 72 hours is illustrated for scenario 6, as shown in Fig. 3.

It can be seen how in the hours with the lowest wholesale market price, all the electrolyzers operate at full load (100% of their rated power) to produce hydrogen and meet the required demand (hours 6-20, 50-53 in Fig. 3). Conversely, when market prices are high, the electrolyzers adjust their load factor according to the generation available in those hours.

Regarding stand-by operation, it is mainly used during night hours, without photovoltaic generation (hours 4-5, 48-49 in Fig. 3). The system decides to adjust the consumption of the electrolyzers, turning off some of them and putting others in stand-by mode to avoid the high costs of cold start-up when the electrolyzers are expected to switch to production mode in the following hours.

Fig. 4 represents the operational behavior of each electrolyzer that make up the system for a 3-day period in July. As can be seen, the operation of the electrolyzers is associated with the high intermittency and variability of photovoltaic or/and wind power generation over the 72 hours. The electrolyzers dynamically adjust their load factor to adapt to the availability of renewable resources. Consequently, the operation of the system is based on maximizing hydrogen production during the hours the highest renewable generation.

5.3. Energy results for all study cases

Table 4 shows the overall energy results for the study scenarios.

First, the impact of wind PPA capacity on grid power imports is assessed. As the wind PPA capacity increases from 100 MW (scenarios 1-3) to 300 MW (scenarios 7-9), a significant decrease in the purchase of power in the wholesale electricity market is seen. For example, for January it decreases by 65%, for April by 48%, and for July by 79%.

Table 3
Study scenarios

Scenario	Wind power (MW)	Wind capacity factor (%)	Photovoltaic power (MW)	Photovoltaic capacity factor (%)	OMIE average energy price (€/MWh) [28]	Month
1	100	28.77	100	12.30	49.98	January
2	100	15.79	100	20.77	42.67	April
3	100	19.79	100	22.89	61.88	July
4	200	28.77	100	12.30	49.98	January
5	200	15.79	100	20.77	42.67	April
6	200	19.79	100	22.89	61.88	July
7	300	28.77	100	12.30	49.98	January
8	300	15.79	100	20.77	42.67	April
9	300	19.79	100	22.89	61.88	July

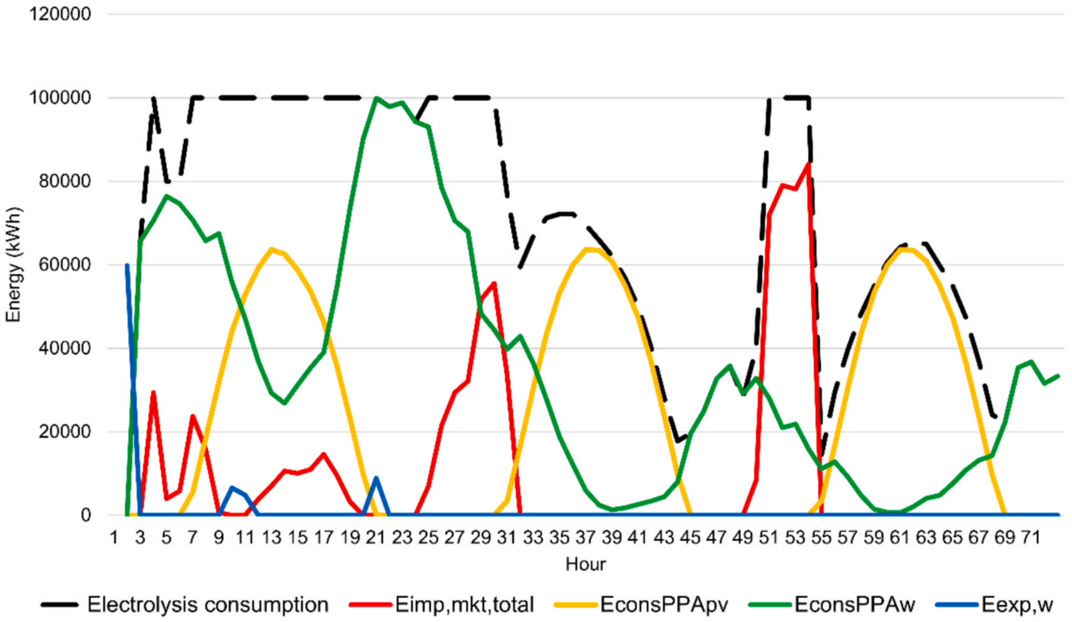

Fig. 2. Results of optimal dispatch in 72 hours of July

Therefore, as the size of the wind PPA increases, dependence on the grid is reduced, allowing a high percentage of the electrolysis demand to be met by renewable generation.

Comparing the monthly results in the amount of energy imported from the grid, this is higher in April than in January and July since wind power production and the OMIE electricity market price are lower, making it more attractive to use the grid to meet demand, as can be seen in Table 3.

Regarding seasonal variation and consumption from the PV PPA, it can be seen that the April and July scenarios (scenarios 2-3, 5-6 and 8-9) reflect a higher participation of PV PPA compared to January. This is consistent with the increased availability of solar radiation in the spring and summer months, which increases the coverage of electrolysis demand by photovoltaic PPA. For example, in scenario 9, associated with the month of July, PV PPA consumption reaches 17,028,604 kWh, while in January (scenario 7) photovoltaic consumption is considerably lower at 9,147,987 kWh, i.e., a reduction of 46%. This increase in PV contribution implies a decrease in grid dependence as discussed above.

On the other hand, in relation to the export of energy to the grid, the results reflect that the scenarios with high wind capacity tend to produce greater energy surpluses, especially in the winter months, when the demand for electrolysis does not consume all the available generation. For example, in scenario 7, energy export in January reaches 30,646,520 kWh, as a consequence of the overcapacity of the 300 MW wind PPA.

There must be a balance between wind and photovoltaic capacity to improve profitability by harnessing generation from both technologies

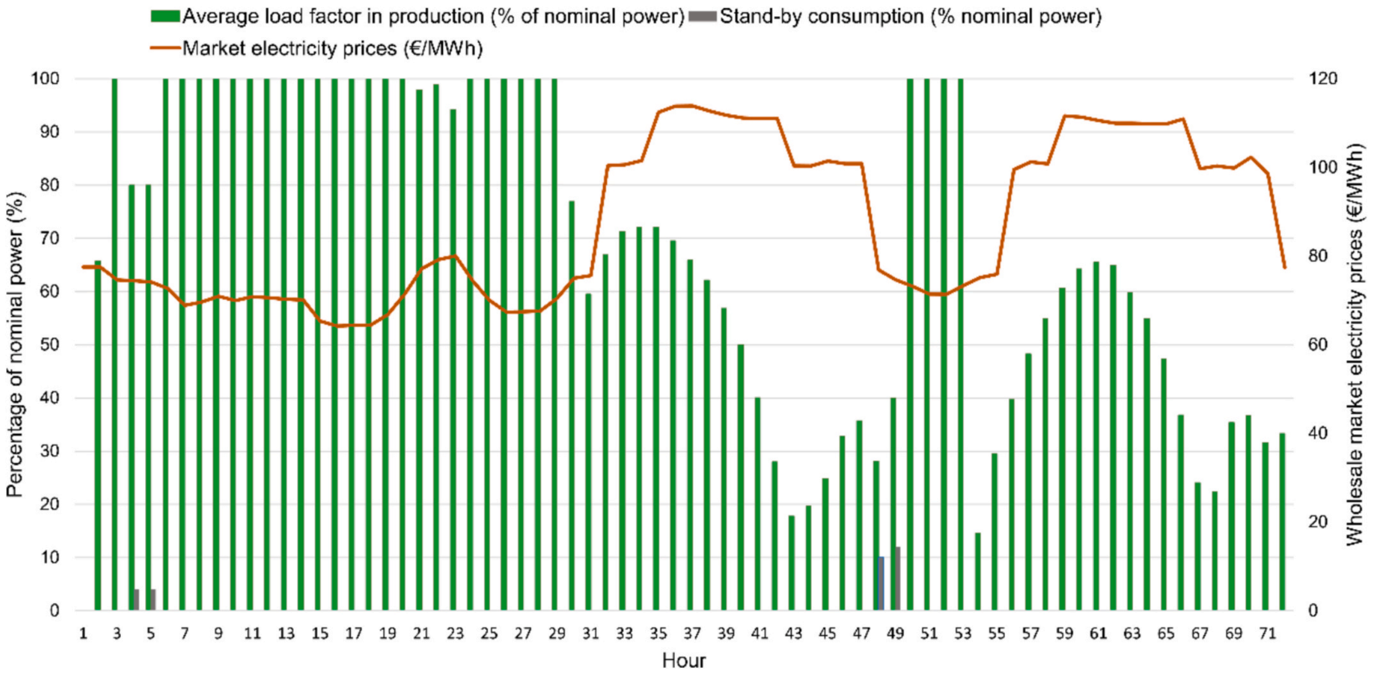

Fig. 3. Electrolyzer operation in 72 hours in July

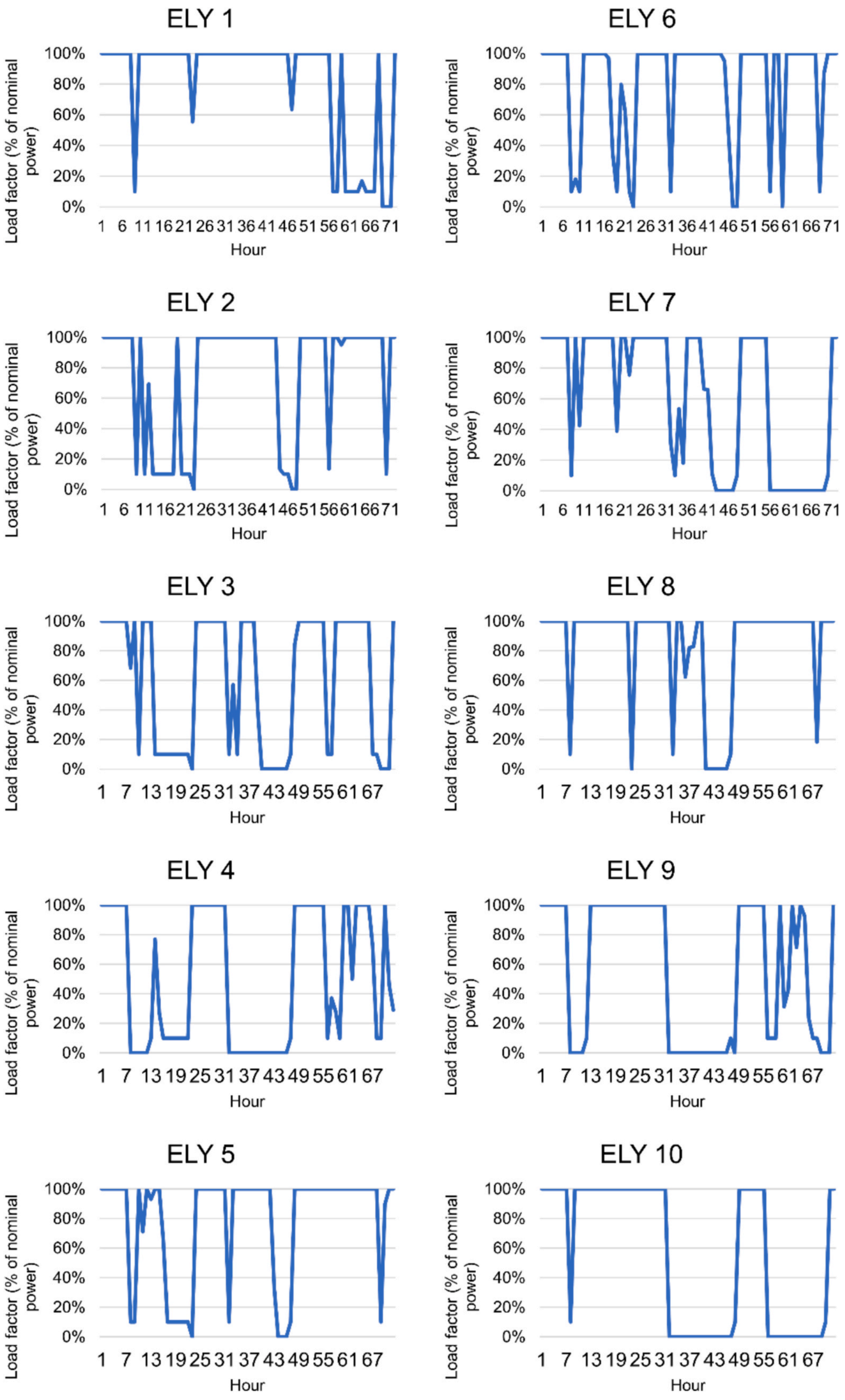

Fig. 4. Load factor of each electrolyzer in 3-day period in July

Table 4
Overall energy results for all study scenarios

Scenario	Total consumption of electrolyzers (kWh) $\sum_{j=1}^{n_{ely}} P_{ely,j} \cdot \mathrm{r}_{\mathrm{j}}^{\mathrm{h}} \bullet \mathrm{b}_{\mathrm{j}}^{\mathrm{h}}$	Energy imported from the grid (kWh) $E_{imp,mkt,total}^{h}$	Energy exported to the grid (kWh) $\mathrm{E}_{\mathrm{exp,w}}^{\mathrm{h}}$	Energy consumed PV PPA (kWh) $E_{consPPApv}^{h}$	Energy consumed wind PPA (kWh) $E_{consPPAw}^{h}$	Energy consumedstand-by (kWh) $\sum_{j=1}^{n_{ely}} E_{standby,j}^{h} \cdot \mathrm{c}_{\mathrm{j}}^{\mathrm{h}}$
1	49,315,050	19,233,515	439,577	9,147,987	20,962,748	29,200
2	49,315,050	24,103,070	1,061,955	14,955,885	10,306,095	50,000
3	49,315,050	17,744,860	149,264	17,028,604	14,572,186	30,600
4	49,315,050	8,889,240	11,484,226	9,147,987	31,320,424	42,601
5	49,315,050	17,521,960	5,849,694	14,955,885	16,886,406	49,201
6	49,315,050	7,635,581	4,756,635	17,028,604	24,686,265	35,400
7	49,315,050	6,661,608	30,646,520	9,147,987	33,560,455	55,000
8	49,315,050	12,500,952	12,186,937	14,955,885	21,917,213	59,000
9	49,315,050	3,667,698	15,488,602	17,028,604	28,675,748	57,000

at each time of year by maximizing coverage of electrolysis demand with these PPAs and minimizing energy wasted or exported at economic losses.

5.4. *Economic results for all study cases*

Table 5 shows the overall economic results for the study scenarios.

Regarding energy purchase costs in the wholesale market in the production state, they reflect significant variations, depending on the power of the wind PPA and the time of year. In scenarios with higher wind generation, dependence on the grid to meet the amount of hydrogen demanded is reduced.

Regarding the income of the electrolysis system, on the one hand, income from hydrogen production is the same in all scenarios, since the model must always meet a hydrogen demand required every 72 hours. On the other hand, income from the sale of surplus wind power vary throughout the scenarios, taking positive and negative values. When the income from the sale of surpluses is negative, it means that the wholesale market price is higher than the PPA price, while if the income is positive, it corresponds to a market price below the PPA price. Therefore, in the latter case, selling surpluses in the wholesale electricity market is less economically favorable, since the spot price does not cover the agreed PPA price, generating losses when operating under these conditions. Seasonality and wind generation capacity are critical factors in the behavior of these revenues.

In general, scenarios with larger PPA size have the highest revenues, as a consequence of a higher wind production available to cover the demand of the electrolysis system and export a larger amount of surplus in the electricity market at more competitive prices.

According to wind PPA consumption costs, associated with energy consumption for hydrogen production under the wind PPA, vary depending on each scenario. In the cases of lower wind power and higher photovoltaic power participation, these costs are lower. Furthermore, rising PPA size increases these operating costs per consumption, reflecting intensive utilization of wind resources when more capacity is available.

Cold and hot start-up costs, associated with the operating costs of starting or maintaining the electrolyzers in operation, vary by month and are relevant to optimize operational continuity. Cold start-up costs are higher because initial start-up is more expensive in these systems.

In short, the energy purchase and consumption costs of the wind PPA are more sensitive to market conditions and represent one of the most variable and significant components in the total costs of each scenario. In addition, seasonality and wind generation capacity have an impact on obtaining a profit margin by selling the surplus to the grid and avoiding economic losses.

6. Conclusions

This paper proposes an optimal hourly mathematical model of techno-economic operation of multi-stack electrolysis systems for hydrogen production connected to the grid with the supply of photovoltaic and wind PPAs in order to minimize operation costs. Electricity is imported from the grid through a pass-through contract indexed to hourly electricity prices in the wholesale market, with a total 100 MW electrolysis plant consisting of 10 electrolyzers of 10 MW each, a compressor station and a hydrogen storage tank designed for three days of hydrogen production.

The proposed model successfully addresses the main objective of this study, which is to develop an optimal hourly techno-economic strategy for the operation of a multi-stack electrolysis system integrated with grid electricity, photovoltaic, and wind PPAs. By simulating various scenarios with different renewable capacities and analyzing the resulting impacts on energy imports, surplus exports, and overall system costs, the model demonstrates its capability to realistically capture the dynamic interactions between renewable supply, market conditions, and the hydrogen production demand. The conclusions drawn from the results confirm that the model effectively supports informed decision-making to enhance the profitability, efficiency, and sustainability of hydrogen production plants under varying market and renewable generation conditions.

From the results obtained from the application of the model, the following conclusions are summarized.

The increase in the capacity of the wind PPA allows a significant decrease in energy imports from the grid, between a range of almost 50%-80% depending on the size. This allows covering a higher proportion of the electrolysis demand with renewable generation, achieving a more grid-independent system. In addition, the higher contribution of the PV PPA in the months of high solar radiation also leads to further reducing the need to purchase electricity in the day-ahead electricity market.

In relation to the export of surpluses to the grid, the scenarios with greater wind capacity produce higher energy surpluses, especially in the winter months, when the demand for electrolysis does not consume all the available production. The highest value obtained of all the scenarios studied (30,646,520 kWh) corresponds to the month of January with a PPA of 300 MW wind as a consequence of wind overcapacity. Therefore, it is essential that there is an adequate balance between wind and solar capacity. This would lead to improved profitability by decreasing the volume of energy exported under unfavorable market price conditions.

It should be noted that income from the sale of surplus wind energy depend on the relationship between the wholesale market price and the agreed PPA price. When the market price is higher than the PPA price, additional income is obtained, while in the opposite case, economic losses are obtained. This effect highlights the importance of achieving optimal management of all available resources to take advantage of the most favorable market opportunities and minimize the operating costs of the electrolysis system.

The most influential system costs are the energy purchase costs in the day-ahead market and wind PPA consumption, which depend on electricity market fluctuations and the availability of wind generation. Therefore, maximizing the coverage of electrolysis demand with wind

Table 5
Overall economic results for all study scenarios (euros)

Scenario	Income from hydrogen production $C^h_{b,j} \bullet \mathrm{r}^\mathrm{h}_\mathrm{j} \bullet \mathrm{b}^\mathrm{h}_\mathrm{j}$	Income from sale of wind energy surplus $\sum_{h=1}^{TW} \left[\rho^h_{PPAw} - \rho^h_{exp}\right] \bullet E^h_{exp,w}$	Stack replacement costs $C^h_{SCR,j} \cdot \mathrm{b}^\mathrm{h}_\mathrm{j}$	Cold start-up costs $\left(C^h_{ab,j} \bullet \mathrm{r}^\mathrm{h}_\mathrm{j} \bullet \mathrm{b}^\mathrm{h}_\mathrm{j} \bullet \mathrm{a}^\mathrm{h\text{-}1}_\mathrm{j}\right)$	Hot start-up costs $\left(C^h_{cb,j} \bullet \mathrm{b}^\mathrm{h}_\mathrm{j} \bullet \mathrm{c}^\mathrm{h\text{-}1}_\mathrm{j}\right)$	Cost of purchasing energy in stand-by mode $\left(E^h_{imp,mkt,j} \bullet (\rho^h_{imp} + ATR^h) \bullet \mathrm{c}^\mathrm{h}_\mathrm{j}\right)$	Cost of purchasing energy in production mode $\left(E^h_{imp,mkt,j} \bullet (\rho^h_{imp} + ATR^h) \bullet \mathrm{b}^\mathrm{h}_\mathrm{j}\right)$	Wind PPA consumption costs $E^h_{consPPAw} \bullet \left[\rho^h_{PPAw} + ATR^h\right]$
1	4,875,286	-4,524	4,728	23,668	783	7	1,033,532	1,058,954
2	4,875,286	5,590	4,851	10,188	917	105	1,265,359	441,829
3	4,875,286	-2,692	4,876	19,586	650	0	1,314,803	736,839
4	4,875,286	-62,907	4,834	16,257	983	12	410,387	1,555,898
5	4,875,286	18,429	5,348	8,367	967	87	890,190	724,029
6	4,875,286	-85,915	4,800	10,656	717	0	553,207	1,232,018
7	4,875,286	-223,401	5,138	17,470	1,167	17	281,034	1,637,288
8	4,875,286	19,023	4,919	13,209	917	76	605,417	939,789
9	4,875,286	-278,454	5,321	8,431	1,067	0	264,712	1,408,776

and photovoltaic PPA leads to reduce losses at times when market prices are not competitive for the sale of surplus.

In conclusion, the model demonstrates that increasing wind capacity reduces grid dependence and increases profitability in surplus sales when market prices are competitive. In addition, a balanced mix of wind and solar generation optimizes the coverage of electrolysis demand and minimizes losses in the export of surpluses under unfavorable conditions.

The proposed model allows scheduling and coordinating the use of energy resources according to their availability and cost, in order to minimize operating costs for hydrogen production, and maximize its operational efficiency. In this way, decision making is facilitated to improve the feasibility and sustainability of the projects.

CRediT authorship contribution statement

Natalia Naval: Writing – original draft, Software, Investigation, Formal analysis, Writing – review & editing. **Ander Martinez Alonso:** Validation, Formal analysis. **Guillermo Matute:** Validation, Supervision, Formal analysis, Conceptualization. **Jose M. Yusta:** Validation, Formal analysis, Data curation.

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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