

Optimisation of Multi-Energy Systems and Power-to-X Technologies: A Hydrogen-based Industrial Case Study

Mikel Fernández-Allende, Amaia González-Garrido

TECNALIA, Basque Research and Technology Alliance (BRTA)
Astondo Bidea, Building 700, 48160 Derio, Spain
mikel.fernandezallende@tecnalia.com

Esther Torres-Iglesias

Department of Electrical Engineering,
University of the Basque Country (UPV/EHU)
Ingeniero Torres Quevedo Plaza, 1, 48013 Bilbao, Spain

Abstract—This study presents a daily cost optimization for a hybrid renewable energy system, hydrogen and battery storage, for PtX technology implementation. Using mixed-integer linear programming, this paper aims at minimising total system cost, subject to technical system constraints. This paper is focused on the modelling and optimisation of a hydrogen-based industrial case study comparing the operating strategy between a typical summer and winter day. Although RES generation is not sufficient to fully meet the energy needs of the industry, the system operation aims to reduce the daily cost. The results show a clear priority for the direct use of hydrogen over its conversion into electricity, due to its low efficiency and cost. The system successfully manages hydrogen generation, battery and production, depending on prices, while ensuring a stable industrial supply. Hydrogen storage fluctuates and tends to reduce system cost, which requires accurate management to avoid hydrogen shortages during peak demand.

Index Terms—Green Hydrogen, Multi-Energy Systems, Optimisation, Power-to-X, Sector Coupling.

I. INTRODUCTION

Nowadays, Energy Communities (EC) allow an open and fair participation, enabling members to exchange energy from different resources like Photovoltaic (PV), Wind Turbine (WT) and Hydroelectric (HY) power plant and Battery Energy Storage Systems (BESS) [1]. This energy exchange, either in a physical or virtual way, generates economic, environmental and social benefits. On the path to full decarbonisation, further step is the combination of Renewable Energy Resources (RES) with Power-to-X (PtX) technologies. Indeed, PtX technology is being proposed with the aim of increasing efficiency in power systems, by enabling the sector coupling through the usage of Hydrogen (H_2), named as Multi-Energy System (MES) [2]. For the optimal operation of the MES, it is necessary to apply advanced optimisation techniques [3], in order to, i.e., optimise industrial processes or facilitate the integration of RES [4], contributing to EU's climate targets.

The interdependencies and proper sizing of technologies in MES operation are critical, which should be analysed in depth to minimize the whole system cost, being subjected to technical constraints [5]. For example, both hydroelectric power plants and Electrolysers (EL) are restricted by the availability of

water, which lead to interdependencies among carriers. The effective deployment and operation of these technologies faces several challenges, including the RES uncertainty, the European common market framework, and efficient energy conversion in complex multi-carrier systems. Authors in [6] propose a scenario for efficient resource management through ECs, which allow the usage and management of RES in such a way that energy that is not consumed can be stored in BESS or H_2 tanks.

Both daily, weekly and seasonal flexibility are expected to increase significantly in the coming decade [7], leading to a greater necessity of short-term and long-term storage solutions, due to the RES fluctuations. In this sense, [8] proposes a seasonal storage of surplus renewable energy for storage in BESS, H_2 system storage (H_2SS) and thermal storage, this will make it possible to use this energy at times of low generation in the residential sector. In contrast, authors in [9] address H_2SS in salt caverns for long term, being H_2SS more suitable for storing PV compared to the higher volatility of WT. Combining short-term storage in BESS with long-term storage in H_2SS emission are reduced, as they address the diverse dynamics of the generation-demand mismatch. Similarly, [10] found that H_2SS shows strong seasonality and is ideal for managing long-term fluctuations in RES, while BESS balances daily energy. Sensitivity analysis reveals that higher RES capacity and H_2 storage increases self-sufficiency of ECs. All previous studies analyse different sizing and configuration of diverse storages.

On the one hand, it is important to find optimal configurations for various types and sizes of technologies. Most of studies use Mixed Integer Linear Programming (MILP) to address the sizing problem. For example, in [11], total annual cost is minimised, guaranteeing energy supply according to variable demand. In contrast, [12] optimises both the system investment and their interconnections in a flexible EC, with RES and grid access, but they conclude that BESS is not economically viable for the specific case study. Authors in [13] aim to reduce costs and improve H_2 integration in a residential neighbourhood. Reduced EL and Fuel Cell (FC) model with constant efficiencies and no system dynamics are proposed, which have significant impacts significantly impact the costs and feasibility of the integrated system. Moreover, [14] defines the optimal configurations in types and sizes of technologies in

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an off-grid insular ECs, in which H₂ storage technologies improves economic viability by reducing the need for BESS and maximising the use of RES.

On the other hand, the optimal operation should be also sought. For example, [15] optimises economic dispatch and operational efficiency, minimising daily costs in a residential area. However, it does not address optimal configurations of technologies or long-term storage. Other authors in [16] minimize the total expected net energy and CO₂ emission cost of the LEC, while meeting given day-ahead demand of community's users. Similarly, [17] focuses on the management and trading of energy in EC through auctions, achieving cost reductions. However, the previous articles address optimisation of the day-ahead system operation, they do not cover optimal configurations of technologies, long-term storage or hydrogen integration.

As can be concluded from the brief literature review, previous studies are focused on the optimisation of residential energy communities. While some of them addressed the sizing [11]-[14], hydrogen interaction with other storage technologies [7]-[10]; others are focused on day-ahead operation [15]-[17]. No previous studies have addressed the generation and operation of H₂-based systems applied to the industrial sector.

Therefore, this paper is focused on the modelling and optimisation of an industrial case study, composed by PV, WT, HY, multiple storage technologies (BESS and H₂SS), EL, and FC. The optimisation problem is modelled using MILP, including the technical and operational system constraints, and the energy exchange flows across multiple carriers.

The objective of the proposed optimisation is to minimise the daily operation cost of the system, related to buying or purchasing electricity from/to the external grid, guaranteeing energy supply, applied in a summer and winter typical days. The daily performance of H₂ technologies is discussed and compared during both typical days in presence of variable grid prices and the level of grid self-sufficiency is evaluated.

Section II describes the methodology, Section III presents the results, and Section IV outlines the main conclusions.

II. METHODOLOGY

Section II presents the mathematical optimisation model of MES, focused on industrial applications. The optimisation problem is modelled using MILP, including the technical and operational system constraints, and the energy exchange flows across multiple energy carriers.

A. Objective function

The objective function is to minimise daily operation cost of the system, which is the cost of buying electricity from the grid, as indicated in eq. (1), where P_t^{grid} represents the electricity exchange to or from the grid, it has negative values when electricity is being taken from the grid and positive values when is injected to the grid the electricity taken from the grid.

$$\min OPEX = \min [\sum_t -P_t^{grid} \cdot \lambda_t^{grid}] \Delta t \quad (1)$$

B. System modelling and constraints

The PV output power (P_t^{PV}), expressed in kW, is defined in eq. (2), where μ^{PV} is the efficiency of the PV panel (%), A^{PV} is the surface area of the PV panels (m²), and G_t is the solar irradiance at any given time (t) (in kW/m²).

$$P_t^{PV} = \mu^{PV} \cdot A^{PV} \cdot G_t \quad (2)$$

The available WT power (P_t^{Wav}), expressed in kW, is a function of actual wind speed (v_t) at each t and the rated power of wind farm (P^{wr}), as expressed in eq. (3).

$$P_t^{Wav} = \begin{cases} 0 & v_t \leq v^i; v_t > v^0 \\ P^{wr} \cdot \left(\frac{v_t - v^i}{v^r - v^i} \right) & v^i < v_t \leq v^r \\ P^{wr} & v^r < v_t \leq v^0 \end{cases} \quad (3)$$

where v^r is the rated wind speed (m/s), v^i is the cut-in wind speed (m/s), and v^0 is the cut-out wind speed (m/s).

The HY output power (P_{HY}) [5] in eq. (4), in kW, depends on the water density (ρ), the acceleration of gravity (g), the effective pressure head water across the turbine (H^{HY}) in m, and the water flow rate (Q) in m³/s, and the overall efficiency (η^{HY}).

$$P_t^{HY} = \frac{Q \cdot H^{HY} \cdot g \cdot \rho}{\eta^{HY}} \quad (4)$$

For simplicity of the problem modelling, the total renewable power generation (P_t^{RES}) can be expressed as the sum of the individual contributions (P_t^{PV} , P_t^{WT} , P_t^{HY}), as defined in eq. (5):

$$P_t^{RES} = P_t^{PV} + P_t^{WT} + P_t^{HY} \quad (5)$$

Regarding the BESS modelling, the net BESS power considering the efficiencies ($P_t^{BESS,in}$) is defined in eq. (6):

$$P_t^{BESS,in} = P_t^{BESS,ch} \cdot \eta^{BESS,ch} - \frac{P_t^{BESS,dch}}{\eta^{BESS,dch}} \quad (6)$$

where $P_t^{BESS,ch}$ is the output charging power, $P_t^{BESS,dch}$ is the output discharging power; $\eta^{BESS,ch}$ and $\eta^{BESS,dch}$ are the charging and discharging efficiency, respectively.

Additionally, it is considered that the BESS does not allow simultaneous charging and discharging, as modelled in eq. (7) and eq. (8), by means of the binary variable u_t .

$$P_t^{BESS,dch} - P_t^{conv} \cdot u_t \leq 0; u_t = \{0(ch), 1(dch)\} \quad (7)$$

$$P_t^{BESS,ch} - P_t^{conv} \cdot u_t \leq 0; u_t = \{0(ch), 1(dch)\} \quad (8)$$

Finally, the State of Charge (SOC_t) in the BESS at any given time (t) is modelled as expressed in eq. (9):

$$SOC_t = SOC_{t-1} + P_t^{BESS,in} \cdot \Delta t / C^{BESS} \quad (9)$$

where SOC_{t-1} is the state of charge at previous time (t-1), $P_t^{BESS,in}$ is the input power to the BESS at time t, Δt is the time interval, and C^{BESS} the nominal capacity of the BESS in kWh.

Regarding the PtX technologies, the hydrogen mass flow is modelled. Firstly, the total mass of H₂ produced by the EL ($m_t^{EL,H2}$) over a specific time interval (Δt), expressed in kg, is defined as eq. (10), as a function of the EL input power (P_t^{EL}).

$$m_t^{EL,H2} = \frac{P_t^{EL} \cdot \Delta t \cdot \eta^{EL}}{LHV^{EL,H2}} \quad (10)$$

where η^{EL} is the efficiency of the EL, and the $LHV^{EL,H2}$ is the Lower Heating Value (LHV) of H₂. It can be noted out that the P_t^{EL} cannot exceed its rated power of the EL.

Secondly, the mass of H₂ stored in the H₂SS ($m_t^{H2SS,H2}$) is modelled as in eq. (11). The $m_t^{H2SS,H2}$ at any time t cannot exceed a maximum value, being constrained by the internal pressure of the tank (P_r^{H2SS}) in bar, within its operating range.

$$m_t^{H2SS,H2} = \frac{P_r^{H2SS} \cdot V^{H2SS}}{R \cdot T^{H2SS}} \quad (11)$$

where V^{H2SS} the volume of the storage tank in m³, R is the universal gas constant (8.314 J/mol·K), and T^{H2SS} is the temperature in K inside the H₂SS.

Thirdly, FC generates electricity and heat by using the stored H₂ in H₂SS, as can be observed in (12):

$$P_t^{FC} = m_t^{FC,H2} \cdot HHV^{FC,H2} \cdot \eta^{FC} \quad (12)$$

$$Q_t^{FC} = m_t^{FC,H2} \cdot HHV^{FC,H2} \cdot (1 - \eta^{FC}) \quad (13)$$

where P_t^{FC} is the electrical power generated between the product of $m_t^{FC,H2}$ is H₂ produced, $HHV^{FC,H2}$ is the Higher Heating Value (HHV) of H₂ applied to the FC and its efficiency.

In eq. (13), the waste of heat Q_t^{FC} is the product between $m_t^{FC,H2}$, $HHV^{FC,H2}$, and one minus the efficiency. Steady state energy balance requires that the same energy input is the energy output, either as electrical energy or as heat, and that the sum of the two is equal to the input.), so the net output power is divided into the electrical power and the heat power of the FC.

Additionally, the H₂SS should maintain the balance of the mass entering and exiting the H₂ storage, considering the produced by the EL, consumed by the FC, and the direct consumption by the industry ($m_t^{ind,H2}$), as expressed in (14)

$$m_t^{H2SS,H2} = m_t^{EL,H2} - m_t^{FC,H2} + m_t^{ind,H2} \quad (14)$$

Finally, it is required to include an energy balance across the electrical carrier, as expressed in eq. (15), including all technologies linked to the electrical carrier, in which P_t^{ind} represents the power demanded from the industry at a given t .

$$\begin{aligned} P_t^{RES} + P_t^{BESS,dch} + P_t^{FC} \\ = P_t^{grid} + P_t^{BESS,ch} + P_t^{EL} + P_t^{ind} \end{aligned} \quad (15)$$

III. INDUSTRIAL CASE STUDY

Section III describes the industrial case study prepared to validate the daily optimization. Figure 1 illustrates all the technologies involved in the case study and interaction among energy carriers, in an industrial context, including a hybrid RES including PV, WT and HY technologies, storage systems such as the BESS and H₂SS. Additionally, PtX technologies are considered, like EL and FC. Table I indicates the main design parameters, as modelling of system components, such as RES, BESS and PtX technologies, need to ensure that the system can meet to a greater extend the required energy demands under

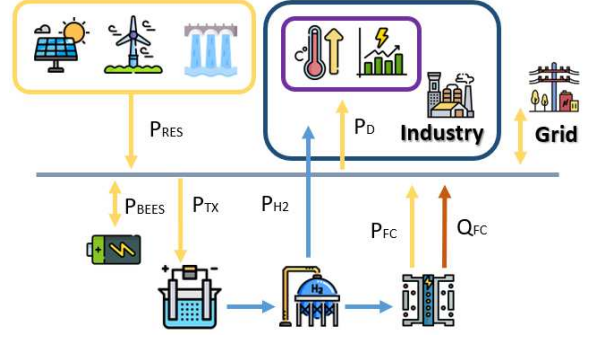


Figure 1. Industrial case study with all involved energy technologies.

TABLE I. DESIGN PARAMETERS

Parameter	Unit	Value
P_t^{PVmax}	kW	8000
A^{PV}	m ²	20000
μ^{PV}	p.u.	0.18
P_t^w	kW	5000
v^l	m/s	4.5
v^r	m/s	12
v^o	m/s	25
H^{HY}	m	5
ρ	kg/m ³	1000
η^{HY}	p.u.	0.80
$\eta^{BESS,ch}, \eta^{BESS,dch}$	p.u.	0.90
$SOC_{t=0}$	p.u.	0.50
p^{BESS}	kW	50
C^{BESS}	kWh	100
$LHV^{EL,H2}$	kW/kg	33.33
η^{EL}	p.u.	0.75
$m_{t=0}^{H2SS,H2}$	kg	0
$P_r^{H2SSmin}, P_r^{H2SSmax}$	bar	0 – 70
V^{H2SS}	m ³	5.27
T^{H2SS}	K	298
$HHV^{FC,H2}$	kW/kg	39.4
η^{FC}	p.u.	0.50

operating conditions. The PV system is designed with an installed PV power of 8000 kW and a PV area of 20,000 m². The wind turbine is designed with a rated power of 5000 kW. The hydroelectric power plant is dimensioned with a height of 5 metres to optimise the power generation, and water flow rate data are synthetic, but typical for a run-of-river HY. The BESS system and the H₂SS are dimensioned to store excess energy and provide backup power, with specific parameters such as pressure and temperature, as indicated in Table I. The EL is designed with a power output of 3500 kW with 75% and the FC with a power output of 3000 kW and 50% of efficiency convert and utilise H₂, ensuring the reliability and performance.

Moreover, the daily profiles are extracted from various publicly available energy databases, industry reports and case studies on renewable energy systems. Solar irradiance and wind speed data were obtained from the PVGIS database [18], which provides hourly solar irradiance data profiles across Europe. A location in the northern region of Spain was selected, and the average hourly weather records for a summer and winter day were calculated. Finally, the hourly prices for the Iberian day-

ahead market in 2024 were selected, and the mean hourly prices for the summer and winter seasons were computed [19].

Industrial load follows the same daily pattern on both dates, subjected to a given industrial process, constant throughout the year. Hydrogen demand data for the industry are synthetic, due to the challenges in obtaining specific data from industrial processes. It allows to conduct a generic, but replicable, study.

IV. RESULTS AND DISCUSSION

Section IV presents the main results of two typical days for the H₂-based industry with optimal daily operation, focusing on energy generation, storage and conversion, in terms of cost and efficiency. The optimisation problem was coded in Python using *Pyomo* library for the optimisation modelling and CBC solver, in a PC with an Intel i5 processor and 8 GB of RAM.

Considering the generation profile of the RES, as observed in Figure 2, there are some differences between operation on a summer and winter day. On the summer day, PV generation predominates, reaching a maximum of 7900 kW at midday, while WT production is more moderate (typically between 1000 and 1500 kW) and split over several hours, while HY rises progressively until the afternoon. In contrast, the winter day shows that PV is minimal until 8:00 and gradually increases to a peak of about 2900 kW at midday. In contrast, WT is constant all day with peaks of 4000 kW. HY generation remains stable, but without reaching the maximum values of the summer day. Thanks to the high contribution of RES, energy surpluses are even exported to the grid at certain times of the winter day.

However, the low availability of WT and HY, and the shorter duration of solar irradiation make it necessary to import

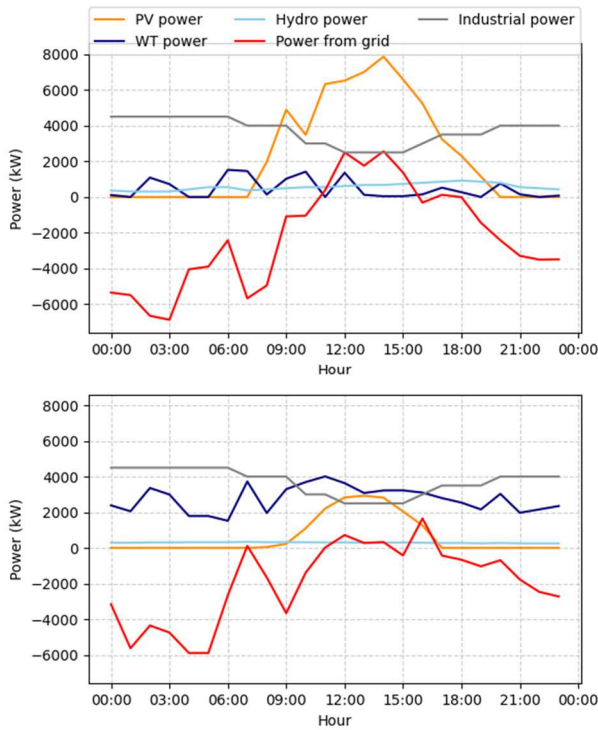


Figure 2. Power profile of RES generation, grid import/export power and industrial demand. (a) Summer day, and (b) Winter day.

TABLE II. SELF-CONSUMPTION INDICATORS AND ELECTRICITY COST.

	Summer	Winter
Daily self-consumption energy	81.37 MWh	88.56 MWh
Daily energy imported from grid	62.01 MWh	49.24 MWh
Self-consumption rate	56.8 %	64.3 %
Grid imported percentage	43.2 %	35.7 %
Daily electricity cost	4891.23 €	3257.18 €

electricity from the grid in the evening. It can be noted that the difference between the RES profiles and the hourly power imported from the grid is due to the power consumed by the electrolyser and the BESS output power. Overall, seasonality has a decisive influence on cost optimisation and the effective integration of clean energy. Table II presents the self-consumption rate and electricity cost, among other indicators.

The State of Charge (SOC) profile of the battery is depicted in Figure 3, in comparison with the hourly prices. Comparing the two typical days, it is observed that the summer day starts with a SOC of 50 % at midnight and drops to 20 % in the first hour, then rises to 90 % at around 03:00, due to small price volatility. In contrast, the winter day follows a similar pattern to the beginning but reaches and maintains 90 % thanks to the off-peak prices and remains constant in the early morning, showing a longer high-value SOC during that interval. At morning peak prices period, during the summer day the SOC remains low until midday, while on the winter day it decreases less sharply, although it returns to 20 % around 08:00 to meet the demand.

The behaviour of prices also shows certain differences. Summer day shows very high values in the early morning, above 85 €/MWh, which drop significantly at midday, below 40 €/MWh, while the winter day starts has more moderate prices, around 60-70 €/MWh, although a profound valley price period at midday. At evening time on summer day, there is a pronounced peak at dusk that exceeds 110 €/MWh, while on the winter one, the price similarly rises above 100 €/MWh. This means that, on summer day, the differences between peaks and valley are more prominent, offering more spread of prices and arbitrage opportunities if the battery is managed appropriately.

Turning to the PtX technology, Figure 4 depicts the H₂ mass produced by the electrolyser, the stored at the H₂SS and the direct H₂ industrial demand. On the summer day, H₂ production in the electrolyser peaked at 78.76 kg between 2 h and 16 h, but dropped to zero during the early morning and next midnight (which aims to reduce the daily operating cost). These EL production intervals affect the internal storage at H₂SS, which peaked at 200 kg at around 16:00 h before reducing to meet demand (at peak prices), which increased from 30 to 75 kg between 0:00 and 13:00 h. In parallel, electricity prices ranged from approximately 85.83 €/MWh (midnight) to 37.31 €/MWh (afternoon), impacting on the operating costs of the EL.

The winter day shows a more uniform production regime 78.76 kg/h between 0:00 and 15:00 h (except the peak prices at sunrise time), followed by several periods with no production during the afternoon and evening. Consequently, storage reached 250 kg at 5:00 h and began to decrease as industrial demand, again between 30 and 75 kg, demanded a constant supply. This was compounded by a progressive increase in

electricity prices, which started from 68.37 €/MWh to 59.90 €/MWh between 0:00 and 3:00 h and exceeded 100 €/MWh in the evening, leading to a reduction in EL usage during those hours. Similar than the ESS usage, the EL tends to take advantage of midday hours during summer days and nighttime during winter days, which align with off-peak price periods.

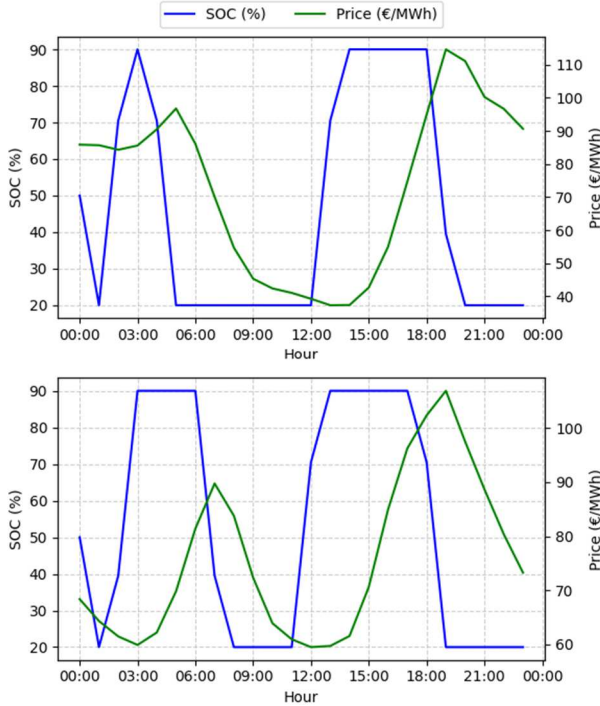


Figure 3. SOC and price. (a) Summer day, and (b) Winter day

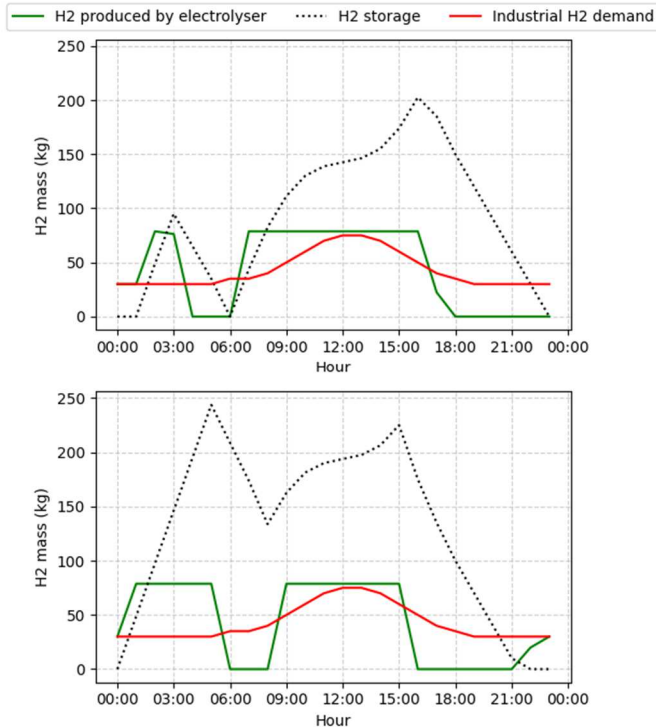


Figure 4. H2SS and H2 industrial demand. (a) Summer day, and (b) Winter day.

Therefore, comparing a summer with a winter day shows the importance of synchronizing the operation of the EL with peak and off-peak electricity prices to supply the daily demand curve, taking advantage of lower price periods to maximize production and fill storage. It can be concluded that, on winter days, the H₂SS is recharged more during nighttime, while on summer days, the optimization takes greater advantage of the longer valley prices at midday. Indeed, strategic management of H₂ reserves is essential to cover demand when generation is interrupted or insufficient, thus ensuring an optimal balance between costs and availability of the resource.

Finally, it can be noted out that the FC does not convert H₂ into electricity. That is, the optimisation leads to the direct utilization of the H₂ produced to meet the plant's demand, avoiding its conversion back to electricity through FC. This is due to low conversion efficiencies of PtX technologies, which do not result in a cost-effective scenario. Higher market revenues would not be obtained from the electricity produced by the FC and injected into the grid.

V. CONCLUSIONS

This study presents a daily cost of optimization of a hybrid renewable energy system that integrates photovoltaic, wind, and hydroelectric plants, hydrogen and battery storage, electrolyzers, and fuel cells, at two typical summer and winter day. An industry case study is included to demonstrate the application of this framework. Although RES with a 56.8% and 64.3% of self-generation is not sufficient to fully meet the energy needs of the industry, the system operation is optimized to reduce the daily electricity cost, managing RES production, BESS utilization, and H₂ generation to supply the daily demand.

Moreover, the BESS is charged at off-peak prices, while it is discharged at peak prices to satisfy the industrial demand and reduce the grid power. Similarly, the H₂ mass in the tank fluctuates to satisfy the direct industrial demand of hydrogen, without converting H₂ into electricity by the FC. However, stored H₂ reaching low levels during peak demand hours, which may pose operational risks of H₂ scarcity, while trying to maximize the operational cost. In addition, the system remains partially dependent on grid electricity, especially when RES production is low.

This suggests possible areas for improvement, such as increasing storage capacity, operating within safe limits, or integrating industrial demand-response strategies. It is important to evaluate multiple objectives, beyond just cost, for instance, ensuring safe operation under uncertainty or minimizing CO₂ emissions beyond a target. Future works aim to expand the analysis to an annual basis and explore different PtX sizing, while hybrid approaches with metaheuristic optimisation and artificial intelligence techniques would be implemented to solve more complex problems.

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