Applied Energy 363 (2024) 123061

Contents lists available at ScienceDirect

Applied Energy

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

Sustainable and self-sufficient social home through a combined PV-hydrogen pilot

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HIGHLIGHTS

- Hybrid PV-hydrogen system for electricity decarbonization in social housing.
- First real design and implementation of a PVHyP in the SUDOE region.
- Remote operation and continuous monitoring of the PVHyP for 22 months.
- 100% reduction of CO_2 emissions and bills in the social home throughout the year.
- Sustainable power system for vulnerable tenants in risk of energy poverty.

ARTICLE INFO

Keywords:
Social dwelling
Electric energy pilot plant
PV energy
Green hydrogen
Design
Real implementation

ABSTRACT

Utilizing surplus renewable energy to produce and store green hydrogen can help meet energy demands during periods of low renewable energy production, and thus contributing greatly to decarbonize emission-intensive sectors, such as the residential and building sector. In this context, this manuscript reports the design, construction and operation of a hybrid PV-hydrogen demonstrative pilot (PVHyP) for the 100% electrical self-sufficiency of a social housing in the town Novales (Spain). The work addresses i) the collection of real consumption data from the dwelling, ii) the design considering real characteristics and market availability of the devices, iii) final balance of plant implementation, and iv) the energy management strategy followed. The implemented control system allows the facility to be tracked and operated remotely. Besides, this flagship implementation in the SUDOE region (Spain, Portugal and southwest of France) has achieved the electrical independence from the grid under diverse climate conditions, eliminating 2260 kg of CO_2 emissions associated to electricity consumption, saving almost 15,200 kWh of primary energy during two years of monitoring. Thus, around 1170 € where avoided in electricity bills (100% savings), resulting on multiple benefits for social dwellers in risk of energy poverty.

1. Introduction

The deployment of renewable energy sources (RES) has been continuously growing since the early 2000s to fight back the harmful effects of fossil fuels to the atmosphere [1]. Thus, the global RES capacity as per 2022 amounts to almost 3400 GW, meaning a 116% increase in the last decade driven by the required energy transition [2] [3]. In the case of EU, the ambitious target of 42.5% of final energy consumption coming from RES [4] has led to a drastic decrease on the levelized cost of energy (LCOE) associated to each renewable technology, with onshore wind energy and photovoltaic (PV) presenting the biggest reduction [5].

However, the intermittent and variable characteristics of RES require their integration with dispatchable backup power generation or energy storage systems (ESS) for the purpose of emulating baseload and load-following power supply profiles. In this context, various ESS technologies have been developed and subjected to extensive testing over the years [6]. Although certain conventional ESS solutions have reached a high level of maturity and cost competitiveness, they are penalized by various limitations, including substantial land area requirements, adverse environmental consequences, material scarcity concerns, and others [7].

Hydrogen holds the potential to enhance the flexibility of the energy system by aligning energy supply with demand profiles [8], thereby mitigating the prevailing disparities resulting from the intermittency of

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https://doi.org/10.1016/j.apenergy.2024.123061
Received 8 January 2024; Received in revised form 21 February 2024; Accepted 16 March 2024
Available online 26 March 2024

Nomenclature

AC	Alternate Current
AEMEC	Anion Exchange Membrane Electrolyzer
Bat	Battery
Bio	Biomass
Boi	Boiler
CAPEX	Capital Expenditures
DC	Direct Current
DG	Diesel Generator
DH	District Heating
DRY	Dryer
$E_{bat,c}$	Battery charge energy, kWh
$E_{bat,d}$	Battery discharge energy, kWh
E_{EL}	Electrolyzer energy consumption, kWh
E_{Excess}	Energy exported to the grid, kWh
E_{FC}	Fuel Cell energy production, kWh
EL	Electrolyzer
E_{LOAD}	Home energy consumption, kWh
$E_{UNCOVERED}$	Energy not covered by the pilot plant
EMS	Energy Management Strategy
E_{RES}	Renewable energy production, kWh
ESS	Energy Storage System
EV	Electrovalves
FC	Fuel Cell
HD	Hydro Energy
HP	Heat Pump
KPI	Key Performance Indicator
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
LOHC	Liquid Organic Hydrogen Carriers
LPSP	Loss of Power Supply Probability
mCHP FC	Micro-Combined Heat and Power Fuel Cell
NPC	Net Present Cost
OPEX	Operational Expenditures
PFD	Process Flow Diagram
PHCA	Pumped Hydro and Compressed Air
PLC	Programmable Logic Controller
PT	Pressure Transducer
PV	Photovoltaic
PVHyP	Hybrid PV-hydrogen pilot
RC	Ranking Cycle
Ref	Reformer
RES	Renewable Energy Sources
R-FC	Reversible Fuel Cell
RHS	Renewable Hydrogen-based System
SC	Supercapacitor
SCADA	Supervisory Control And Data Acquisition
SMP	Smart Power Meter
SOC_{Bat}	Battery state of charge, %
SOC_{H2}	Hydrogen tank state of charge, %
SSR	Self-Sufficiency Ratio, %
STC	Solar Thermal Collector
TES	Thermal Energy Storage
WT	Wind Turbine

wind and solar resources [9]. Currently, green hydrogen produced from RES and water electrolysis is the most extended alternative to produce carbon-free hydrogen. Nevertheless, there are other novel and innovative methods based on photo/electro/photolectro-catalysis with great potential [10–12] Hydrogen exhibits versatility in its adaptability to various temporal and geographical requirements, accommodating storage needs spanning from daily to seasonal durations and facilitating both local and global distribution [13,14]. Furthermore, its applicability extends beyond electricity generation [15], enabling the coupling of sectors, which, in turn, facilitates the conversion of generated power into diverse usable forms [16]. Thus, hydrogen has positioned itself as one of the alternatives with significant potential for decarbonizing not only hard-to-abate sectors such as industry [17] and transportation [18–20] but also others like the residential and building sector, which accounts for 40% of the final energy consumption in Europe [21,22]. Besides, hydrogen can be blended with natural gas to take advantage of the existing infrastructure, and thus, reduce the environmental impact of heat generation [23] or it can be retrieved from industrial waste streams with high hydrogen content [24–26].

Consequently, hydrogen-based technologies emerge as a sustainable and versatile alternative for energy storage, demonstrating adaptability and feasibility for both large-scale energy storage applications and small backup systems, while allowing for long seasonal energy storage without degradation concerns. Nevertheless, hydrogen-based technologies need to overcome significant challenges concerning safe handling, efficient storage and economic feasibility to ensure a broad deployment and uptake as ESS [27,28]. Moreover, the scarcity of certain minerals is critical both for the deployment of the hydrogen economy and the large-scale implementation of RES technologies. Some of these critical raw materials are manganese, cobalt, rare earths or platinum group metals [29]. In the particular case of hydrogen, different actions are being conducted to substitute catalysts based on noble metals by cheaper materials based on nickel, iron or zinc [30]. Therefore, further investigation and research activities are required to drastically cut down the costs associated to this technology and to achieve safe and efficient operation of hydrogen-based ESS.

Under this framework, multiple studies have been conducted addressing the potential hybridization of RES and hydrogen technologies to mitigate the emissions associated to energy use in different stationary applications [31,32]. Therefore, Table 1 provides a short overview of recently published research articles addressing the sizing, simulation and optimization of different hybrid configurations and energy management strategies (EMS) focused on any building type. Furthermore, the major accomplishments and limitations reflected by these publications are detailed.

These works propose multiple solutions based on the combination of RES and hydrogen as ESS to meet the demand of a wide variety of buildings, being most of them analyzed in a standalone configuration. Nevertheless, the interaction of these hybrid renewable hydrogen-based systems (RHS) with the grid has also raised great interest in taking advantage of periods with lower electricity fees and maximum RES production [44,52]. Multiple software and programming tools have been employed to address the design and optimization of these theoretical studies. Some of them have used HOMER Pro software to optimize the dimensioning and configuration of RHS with minimum net present cost (NPC) as objective function. This user-friendly tool allows to simulate multiple off-grid hybrid systems containing one, two or more RES technologies, including both electrical and thermal energy demands [33,40]. Besides, it allows the coupling with different software codes to further include specific technologies in the assessment that are not contained within the tool. In this sense, this is one of the main limitations of HOMER Pro, together with the need to develop a more precise hydrogen package.

Conversely, different software codes such as MATLAB, TRNSYS or GAMS are employed to define diverse objective functions, allowing to optimize the technical performance and replicate transient behaviors of the RHS. Besides, multi-objective optimization studies can be conducted addressing not only the minimization of life-cycle costs (LCC) or the

Table 1
Hybrid renewable hydrogen-based systems for stationary applications.

Optimal Configuration	Application	Location	Objective function	Software	Main outcomes	Limitations	Ref.
PV/WT/EL/FC/Bat/Boi/HP	Residential	Croatia	Minimize NPC	HOMER Pro/Excel	Electricity, thermal and cooling needs covered with H_2, batteries and heat pump. Detailed EMS included	Lack of LCOE assessment	[33]
PV/WT/FC/EL	Residential /Mall	Iran	Minimize NPC and LPSP	MATLAB	Minimal load interruption probability of 1% obtained. Faster new optimization algorithm developed	Hybrid system not self-sufficient. Lack of LCOE assessment.	[34]
PV/WT/FC/EL/DH	City	Various countries	Minimize CAPEX and OPEX, optimization tool comparison	Gurobi/CPLEX /Mosek with Python and GAMS	Mixed-integer linear programming applied to 12 cities worldwide. Hybrid system reduces up to 60% OPEX, with 100% carbon emissions reduction	Lack of NPC and LCOE assessment	[35]
PV/FC/EL/Bat/Grid	Residential community	Italy	Minimize OPEX and LCOE	*E*-OPT	The integration of 3 buildings increases the overall self-sufficiency. Doubling the storage capacity slight reduces OPEX but it does not justify the CAPEX increase	Hybrid system not self-sufficient. Lack of LCOE assessment.	[36]
PV/R-FC/Bat/HP	Residential community	Italy	Maximize overall efficiency and minimize payback period	TRNSYS	Primary energy savings of 83% with the hybrid system, 65% of self-produced electricity and payback period of 4.4 years	Hybrid system not self-sufficient.	[37]
STC/RC/FC/EL/TES/PHCA	Hybrid power system	China	Technical optimization	MATLAB /Aspen-HYSYS	Novel configuration to cover both electricity and heat demands	Lack of economic assessment	[38]
PV/FC/EL/Bat/Grid/STC/TES	Residential	Morocco	Techno-economic and environmental optimization	EnergyPlus/ PVsyst /SketchUp	Comparison of three different cities to cover thermal and electricity needs, 3D model of the building included	Hybrid system not self-sufficient. Hydrogen-based system not economically viable	[39]
PV/WT/Bio/EL/Grid	Residential community	Italy	Minimize NPC, AEMEC performance optimization	HOMER Pro /Aspen Plus	Hybrid system with competitive LCOE of 0.084 €/kWh and hydrogen production with AEMEC	Hybrid system not self-sufficient, fuel cell not included	[40]
PV/WT/EL	Country	Uruguay	Minimize LCOH	GNU Octave	Compressed pipelines are cost-optimal for large quantities, compressed trucks for low demands. LOHCs are optimal for medium demand and large distances	Lack of geo-spatial evaluation for hydrogen supply chain	[41]
PV/WT/EL/Bat/TES	Residential community	China	Minimize LCOE and CO_2 emissions	Gurobi	Advanced optimization modeling to integrate different technologies and grid scheduling, carbon taxes included	Hybrid system not self-sufficient. Lack of LCOE assessment	[42]
PV/WT/FC/EL/DG/Bat	Microgrid	South Korea	Maximize economic profits	GAMS/CPLEX	Annual profits over $5000 obtained for the hybrid system covering electrical and thermal needs	Hybrid system not self-sufficient. Lack of LCOE assessment	[43]
PV/WT/FC/EL/Grid/TES	Microgrid	China	Minimize operation and emission costs	GAMS/CPLEX	Hybrid system reduces OPEX in 4.2% and emissions in 3%	Hybrid system not self-sufficient. Lack of NPC and LCOE assessment	[44]
PV/WT/FC/EL/Grid/Bio	City	Various countries	Maximize hydrogen production	RETscreen Expert	Higher hydrogen production potential in Denmark than in the other analyzed cities.	Hybrid system not self-sufficient. Lack of NPC and LCOH assessment, fuel cell not included	[45]
PV/FC/EL	Remote Area	China	Minimize LCC and LPSP	MATLAB	Modified optimization algorithm to supply a grid-independent building	Lack of LCOE assessment	[46]
PV/WT/FC/EL/Bat/HP	Residential community	Finland	Minimize LCC and maximize overall efficiency	MATLAB /Excel	Off-grid configuration with heat recovery from hydrogen energy storage system	Thermal needs not fully covered	[47]
PV/FC/EL	Street lighting /Desalination	Egypt	Minimize LCOE and payback time	MATLAB Simulink	Off-grid street lighting system based on hydrogen technologies attached to a barometric desalination unit	System not cost competitive compared to grid prices.	[48]
PV/FC/EL/Bat	Residential	Finland	Technical optimization	MATLAB	Preliminary design of a stand-alone single-family home with PV panels already mounted	Lack of economic assessment	[49]
PV/FC/EL/Bat	Residential	Algeria	Technical optimization	MATLAB Simulink	EMS optimization to maximize the overall efficiency of an off-grid home	Lack of economic assessment	[50]
PV/FC/EL/Bat/TES	Residential	Iran	Technical optimization	MATLAB /TRNSYS	Off-grid buildings in two locations with energy and thermal needs covered	Lack of economic assessment	[51]
Grid/FC/EL/TES	Residential	China	Minimize LCOE and scheduling strategy	Gurobi	Prediction horizon of 20 h allows for a greater hydrogen production and higher RES penetration	Hybrid system connected to the grid	[52]

*Abbreviations: PV (photovoltaic panels), WT (wind turbines), HD (Hydro energy), Bio (Biomass), STC (Solar Thermal Collector), FC (Fuel Cell), R-FC (Reversible-Fuel Cell), EL (Electrolyzer), Bat (Battery), SC (Supercapacitor), DG (Diesel Generator), HP (Heat Pump), TES (Thermal Energy Storage), PHCA (Pumped hydro and compressed air), DH (District Heating), Ref (Reformer), Boi (Boiler), mCHP FC (micro-combined heat and power fuel cell), RC (Rankine Cycle), NPC (Net Present Cost), KPI (Key Performance Indicator), EMS (Energy Management Strategy), LPSP (Loss of Power Supply Probability), CAPEX (Capital expenditures), OPEX (Operational expenditures), AEMEC (Anion Exchange Membrane Electrolyzer), LCOE (Levelized Cost of Energy), LCOH (Levelized Cost of Hydrogen), LCC (Life cycle cost), AEMEC (Anion Exchange Membrane Electrolyzer), LOHC (Liquid Organic Hydrogen Carriers).

levelized cost of energy (LCOE) such as the analysis reflected by Meriläinen et al. [47], but also including some uncertainty variables like loss of power supply probability (LPSP) reported by Jahannoosh et al. and Lu et al. respectively [34,46]. Moreover, performing environmental-based optimization by including CO_2 penalties [42], or designing a developed scheduling strategy to leverage low electricity rates for extra hydrogen generation [52] can be conducted through tailor-made codes implemented in these tools. Finally, the optimization of the EMS and technical performance of the configuration [51], the selection of the best optimization algorithm [35], or the possibilities of hybridization with different thermal energy storage (TES) devices [42] has also been the subject of study in recent years.

Following the large number of simulations and theoretical assessments of RHS, it is required to develop experimental setups and pilot plants to further advance the knowledge through experience and face unpredicted problems and phenomena. Thus, meeting different energy demands and achieving diverse self-sufficiency ratios (SSR) and overall efficiencies are among the main objectives [53]. Yunez-Cano et al. [54] implemented a system consisting of PV panels, fuel cell (FC) and electrolyzer to store hydrogen on a metal hydride tank to meet the electricity demand of a mobile house. Bartolucci et al. and Cordiner et al. [55,56] analyzed several telecom stations situated across various regions in Italy that incorporate a PV/FC system combined with batteries for practical testing in the field. These systems employ diverse energy management approaches to assess the optimal utilization factor of PV, hydrogen production, and FC energy flow tailored to each specific location. These setups encompass a container to store the hydrogen generated via water electrolysis at 30 bars of pressure (with electrolyzers present only in 4 out of 9 locations). Additionally, a cluster of tanks is refilled externally at 200 bars to prevent electricity shortages and ensure continuous supply of power in all instances. Carbone et al. [57] examined various load situations to verify and authenticate an experimental photovoltaic/fuel cell system designed for illuminating the university campus. Consequently, the illumination, represented as a consistent load, functions based on two modes: day-time usage (activated from sunrise to sunset) and night-time usage (operating from sunset to sunrise). A 93% SSR was achieved under the first operation mode, while SSR was reduced to 80% during night. On the other hand, Endo et al. [58] investigated a moderate-sized containerized setup utilizing TiFe-based metal hydrides for storage in Japan. This study successfully achieved a notable reduction, up to 99%, in the thermal management operations associated with the metal hydride tanks. Likewise, Segawa et al. [59,60] developed a pilot plant named after Hydro Q-Bic® consisting of 64.75 kW of PV panels, 5 Nm^3/h water electrolyzer, 40 Nm^3 of metal hydride hydrogen storage, 14-kW FC, and 20-kW/20-kWh Li-ion batteries. The authors conducted uninterrupted 24-h experiments under various weather conditions, also examining their interaction with the electrical grid. This system achieved a reduction in the building's CO_2 emissions of over 50%, surpassing what would be achieved solely by the use of PV panels.

On top of that, the REMOTE project focuses on decarbonizing diverse microgrids in Norway, Spain, and Greece. This initiative integrates various RES technologies, components of the hydrogen chain, and diesel-fueled generators (DG). While these setups render the microgrids autonomous from the main grid, they rely on DG backup. Consequently, they can attain a SSR of over 95% through RHS, leading to nearly complete decarbonization of the microgrid [61–63]. In Sweden, an intriguing application was executed at a private residence. The villa incorporated PV and geothermal energy, hydrogen production, and fuel cell systems. It had 144 kWh lithium-ion batteries for short-term storage and 324 kg of hydrogen for seasonal storage, resulting in near-complete independence from the grid [64]. Likewise, the HYDROGEN HOUSE PROJECT encompasses a 40 kW PV facility paired with 20 kW of hydrogen FC and batteries. Originated as a private initiative in New Jersey (USA), it has since transitioned into a public partnership with a primary emphasis on education [65]. Finally, these solutions have been also implemented in remote mountain huts [66,67] or in different microgrids to power several buildings [68].

The evaluation of the different studies and real implementations shows a wide range of applications in different locations, looking for a system as optimized as possible from the techno-economic point of view. In particular, the models allow to simulate the behavior of systems detached from the grid as well as their interaction with it and the energy flows between different equipment. On the other hand, the real systems show difficulties in achieving high degrees of self-sufficiency due to the current state of development of hydrogen technologies, as well as not reporting data on the monitoring of the implemented systems for long periods. In this context, it has been detected the lack of implementations in the sector of buildings and public and social housing that could improve their energy efficiency [69]. Moreover, the actual configurations do not show the energy management strategies followed and do not provide details on the equipment needed to complete the balance of plant.

Therefore, this work presents the fundamental results reported after two years of monitoring a pilot plant in the town of Novales (Cantabria, Spain). This plant combines PV panels and hydrogen (PVHyP) as a method of seasonal energy storage, achieving the ambitious target of accomplishing an electrically self-sufficient social housing unit throughout the year. To achieve this goal, a tailor-made energy management strategy (EMS) has been developed based on the state of charge of the battery pack and the energy flow within the PVHyP, ensuring that the electrical consumption of the home is always covered either through PV panels, fuel cell or battery pack. This installation not only demonstrates the technical feasibility of applying renewable hydrogen in the residential sector, but also presents a 100% sustainable and decarbonized alternative to combat energy poverty among the most economically vulnerable inhabitants, proposing an advanced energy storage system integrated in buildings of rural areas to boost RES penetration. Furthermore, the proposed configuration presents a detailed balance of plant (BoP) that is modular and easily scalable, together with 3D modeling of the layout, pictures of the final components on place and the results derived from the remote operation of the PVHyP. Thus, this pioneering pilot plant fosters the utilization of sustainable energy systems in the domestic sector, bridging the existing gap between theoretical research and real implementation and serving as case study to provide key insights for the scale up and further decision making in the implementation of the solution in either residential communities or even different industries with high electricity consumption.

2. Materials and methods

Traditionally, passive renovation and refurbishment has been the main alternative to improve the energy performance certification and the efficiency in aged buildings. However, the development of more sustainable energy supply technologies is opening a new path to ensure more efficient and integrated building energy management. Under this framework, the design, development and implementation of a demonstrative PVHyP for seasonal energy storage has been adopted to guarantee 100% electrically self-sufficient and decarbonized social dwelling.

2.1. Social dwelling description

To demonstrate the feasibility and benefits of the PVHyP in the residential sector, a prototype has been developed in a social house in a small village called Novales that is located in the Autonomous Community of Cantabria (Spain, 43°22′48.0“ North - 4°11'06.5” West). In this location there are two social buildings that were built in 2015. Thus, one social dwelling from these buildings has been selected for the connection with the pilot plant, with this social house having around 80 m^2. Besides, the electricity consumption of this home has been obtained from bills collected during a year and through the data harvested in the smart power meter of the utility grid company, totalling 2513 kWh/year with and average daily consumption of 6.88 kWh. Thus, the daily demand profile of the single house is represented in Fig. 1a, along with the seasonal average electricity consumption. Moreover, Fig. 1b represents the climatic conditions of Novales, including horizontal irradiance, maximum and minimum average temperatures per month [70]. It should be noted that heating requirements, supplied by a propane boiler, ventilation or air-conditioning systems inside the house have not been included in this study.

As it can be noticed, the electricity consumption increases slightly during fall and wintertime compared to summer as inhabitants spend more time at home, with average consumption over 7.3 kWh/day in both seasons. Given the characteristics of the consumption, the use of PV panels to supply electricity to the home results in a great excess of energy during summertime due to the low demand, averaging a consumption of 5.88 kWh/day, which represents a decrease of 1 kWh/day compared to the annual average. Therefore, we have selected hydrogen technologies to store seasonal energy surplus during the year and meet the demand during the winter when solar energy is scarce.

2.2. Pilot plant sizing and definition

This PVHyP aims at achieving energy self-sufficiency in the house without the need of electricity from the grid or fossil fuel-based ancillary gensets like diesel generators. The primary source of the system is PV energy. To combat PV intermittency and take advantage of the periods with energy surplus, lithium-ion batteries are installed for day-to-day energy storage and hydrogen-based technologies for seasonal energy accumulation. All the methodological framework followed from the input data consisting of meteorological characteristics of Novales and load consumption of the social dwelling to the final pilot plant design is exposed in Fig. 2.

HOMER Pro software is employed to optimize the dimensions of the RHS, based on the solar irradiation available in the location of Novales and the aforementioned consumption profile to minimize the required capacity per component and the resulting NPC and LCOE. Thus, the electricity demand previously defined in Fig. 1, the climate conditions of Novales and the costs and characteristics of the main equipment are entered in the HOMER Pro software. These costs and characteristics have been collected from international agencies and organisms and these are gathered in Table 2. It should be noted that the selected costs for simulation correspond to the mean values from the CAPEX ranges.

Once the configuration is sized, a recalculation is conducted based on the analysis of the market carried out to search for actual equipment that closely matched the most realistic dimensions reported by the software and taking into account their characteristics, hydrogen storage pressure and considering extra energy requirements such as the hydrogen compressor consumption or the demand of the control system and monitoring devices. These adjustments are defined thanks to a tailor-made program developed in a spreadsheet. Hence, this program quantifies the periods of energy surplus and deficit, considering the real characteristics of the fuel cell, electrolyzer, compressor and batteries, dimensioning these elements to meet the energy demanded by the social dwelling during the whole year. This energy balance between generation and consumption is done in an hourly basis, ensuring that the electricity demanded by the social house is always covered either by the PV panels, the batteries or the fuel cell. The addition of these ancillary components results in a higher electricity demand of the PVHyP.

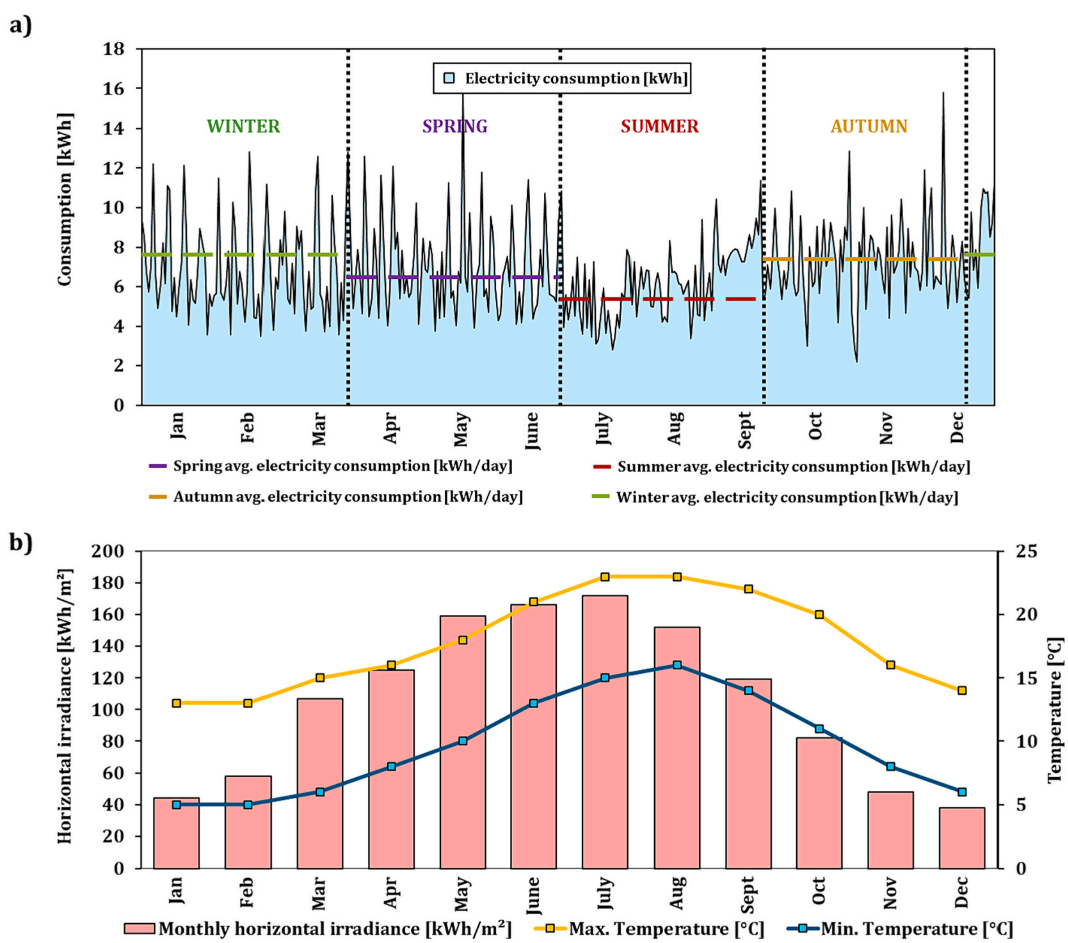

Fig. 1. a) Daily and seasonal average electricity consumption for the social dwelling of Novales; b) Monthly horizontal irradiance, average maximum and minimum temperatures.

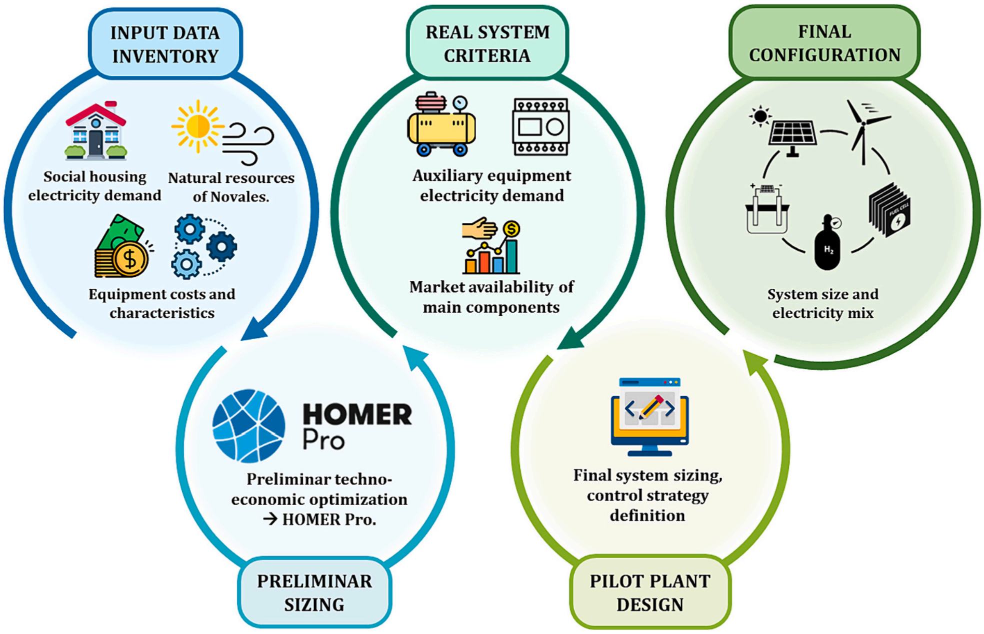

Fig. 2. Methodology used for the pilot plant design.

Table 2
Summary of CAPEX, OPEX, and replacement costs for the main components of PVHyP.

Component	CAPEX [US$/kW]	Replacement [US$/kW]	OPEX [US$/kW]	Characteristics	Reference
PV panels	250–1050	50% CAPEX	5% CAPEX	Lifetime: 25 years. Derating factor: 85%	[71–74]
Fuel Cell	1600–6000	40% CAPEX	5% CAPEX	Lifetime: 30,000 h. Efficiency: 54%.	[75–79]
Electrolyzer	500–5600	30% CAPEX	2% CAPEX	Lifetime: 20 years. Efficiency: 50 kWh/kg.	[9,76,77,80]
Hydrogen tank	700–1000 US$/kg	85% CAPEX	1% CAPEX	Lifetime: 25 years.	[77,81,82]
Inverter	300–900	85% CAPEX	5% CAPEX	Lifetime: 25 years. Efficiency: 95%	[71,83]
Battery	500–1000 US$/kWh	100% CAPEX	1% CAPEX	Lifetime: 15 years. Roundtrip efficiency: 90%	[84]

Finally, several key performance indicators (KPI) have been defined in Eqs. (1–5) to assess the performance of the pilot plant in terms of efficiency, primary energy savings, CO_{2eq} emissions avoided, and economic savings. Besides, the LCOE obtained from a previous techno-economic assessment conducted by the authors will be included together with these KPIs [85]. It should be noted that primary energy and CO_{2eq} emissions savings have been obtained from the Spanish Regulation of Thermal Installations in Buildings [86], while the utility grid price corresponds to the one reported for the second quarter of 2023 in Spain [87]:

$$E_{useful,n} = \sum \left(E_{load} + E_{excess,year\ n}\right) \quad (1)$$

$$\mu_{RHS,year\ n} = \sum \left(E_{useful,n}\right) \Big/ \left(E_{PV}\right) \quad (2)$$

$$Primary\ energy\ savings, year\ n = 2.403 \cdot \sum \left(E_{useful,n}\right) \quad (3)$$

$$CO_2\ emissions\ avoided, year\ n = 0.357[kg\ CO_2/kWh] \cdot \sum \left(E_{useful,n}\right) \quad (4)$$

$$Economic\ savings = 0.373[€/kWh] \cdot \sum \left(E_{PV-load}\right) \quad (5)$$

Where "n" is the year, $\mu_{RHS,year\ n}$ is the efficiency of the system in year "n", $E_{useful,n}$ is the total useful energy (consumed by the load and injectable into the grid) in kWh, E_{load} is the total energy consumed by the home in kWh, $E_{excess,year\ n}$ is the total load injectable to the grid in year "n" in kWh, and $E_{PV-load}$ is the energy generated by PV panels directly consumed by the social home.

Subsequently, to further assess the overall performance of the PVHyP, both the energy and exergy efficiencies of the PV panels, the electrolyzer and the fuel cell have been evaluated as long as they are the main equipment of the power system [88]:

$$\eta_{ex,PV} = \frac{P_{PV}}{\dot{E}x_{solar}} \quad (6)$$

$$\eta_{en,EL} = \frac{\dot{m}_{H_2,prod} \cdot LHV_{H_2}}{P_{EL}} \quad (7)$$

$$\eta_{ex,EL} = \frac{\dot{m}_{H_2,prod} \cdot ex_{H_2}}{P_{EL}} \quad (8)$$

$$\eta_{en,FC} = \frac{P_{FC}}{\dot{m}_{H_2,cons} \cdot LHV_{H_2}} \quad (9)$$

$$\eta_{ex,FC} = \frac{P_{FC}}{\dot{m}_{H_2,cons} \cdot ex_{H_2}} \quad (10)$$

Where $\eta_{ex,PV}$ is the exergy efficiency of the PV panels, P_{PV} is the power generated by the PV array in W and $\dot{E}x_{solar}$ is the exergy of the solar radiation incident on them per unit time measured in W. Likewise, $\eta_{en,EL}$ is the energy efficiency of the electrolyzer and $\eta_{ex,EL}$ its exergy efficiency, with $\dot{m}_{H_2,prod}$ being the mass flow rate of hydrogen produced in kg/s, LHV_{H_2} the lower heating value of hydrogen of 120 MJ/kg, ex_{H_2} the specific exergy of hydrogen and P_{EL} its power consumption in W. Finally,

$\eta_{en,FC}$ is the energy efficiency of the fuel cell and $\eta_{ex,FC}$ its exergy efficiency, $\dot{m}_{H_2,cons}$ is the mass flow rate of hydrogen consumed in kg/s, and P_{FC} its power production in W.

Furthermore, the power consumed/produced by these devices and their corresponding exergy rates are compared. Hence, Eqs. (11–13) have been followed to evaluate all these parameters [89]:

$$\dot{E}x_{solar} = A \cdot G \cdot \left[1 - \frac{4}{3}\left(\frac{T_0}{T_S}\right) + \frac{1}{3}\left(\frac{T_0}{T_S}\right)^4\right] \quad (11)$$

$$ex_{H_2} = ex_{chem} + ex_{phy} \quad (12)$$

$$ex_{phy} = C_p \cdot T_0 \cdot \left[\frac{T_0}{T_S} - 1 - ln\left(\frac{T_0}{T_S}\right) + ln\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right] \quad (13)$$

Where A is the area of the PV array in m^2, G the global irradiance in W/ m^2, T_0 and T_S the ambient and sun temperatures respectively in K, ex_{chem} the specific chemical exergy of hydrogen (117,113 kJ/kg), and ex_{phy} the specific physical exergy of hydrogen measured in kJ/kg. Finally, C_p is the heat capacity of hydrogen (14.89 kJ/kg·K), p the pressure of hydrogen in bar, p_0 the ambient pressure in bar, and γ the coefficient of adiabatic expansion.

2.3. Operation and control strategy

To properly manage the energy flows within the PVHyP, and thus, achieve an optimal performance of the power system, an accurate control strategy is fundamental. These strategies must ensure the correct supply of electricity to cover the demand, as well as an efficient energy storage. This avoids the oversizing of certain components and the installation of redundant equipment. Fig. 3 depicts schematically the main equipment of the pilot plant and the energy flows throughout the system and the EMS employed. Thus, the following sequence of operation of the system has been proposed:

1- PV panels are the primary energy source and will supply the load meanwhile solar irradiation is sufficient.
2- When there is excess PV generation, surplus energy is stored in the batteries in the first stage for day-to-day accumulation.
3- The surplus energy that cannot be stored in the batteries is stored in the form of hydrogen generated by means of the electrolyzer.
4- The hydrogen produced is saved in a first stage in a buffer tank with an intermediate pressure. When the buffer is full, the compressor is activated and the hydrogen will be stored in the high-pressure tank.
5- When the solar irradiation is insufficient to cover the demand of the house, the batteries supply the necessary energy to the dwelling.
6- If the batteries are discharged, the fuel cell generates electricity to charge the batteries from the stored hydrogen. As far as possible, the hydrogen stored in the buffer is used first, to avoid the compression stage, thus increasing energy efficiency.
7- The system and the house are connected to the grid on a self-consumption basis to sell-back to the grid all the excess energy that

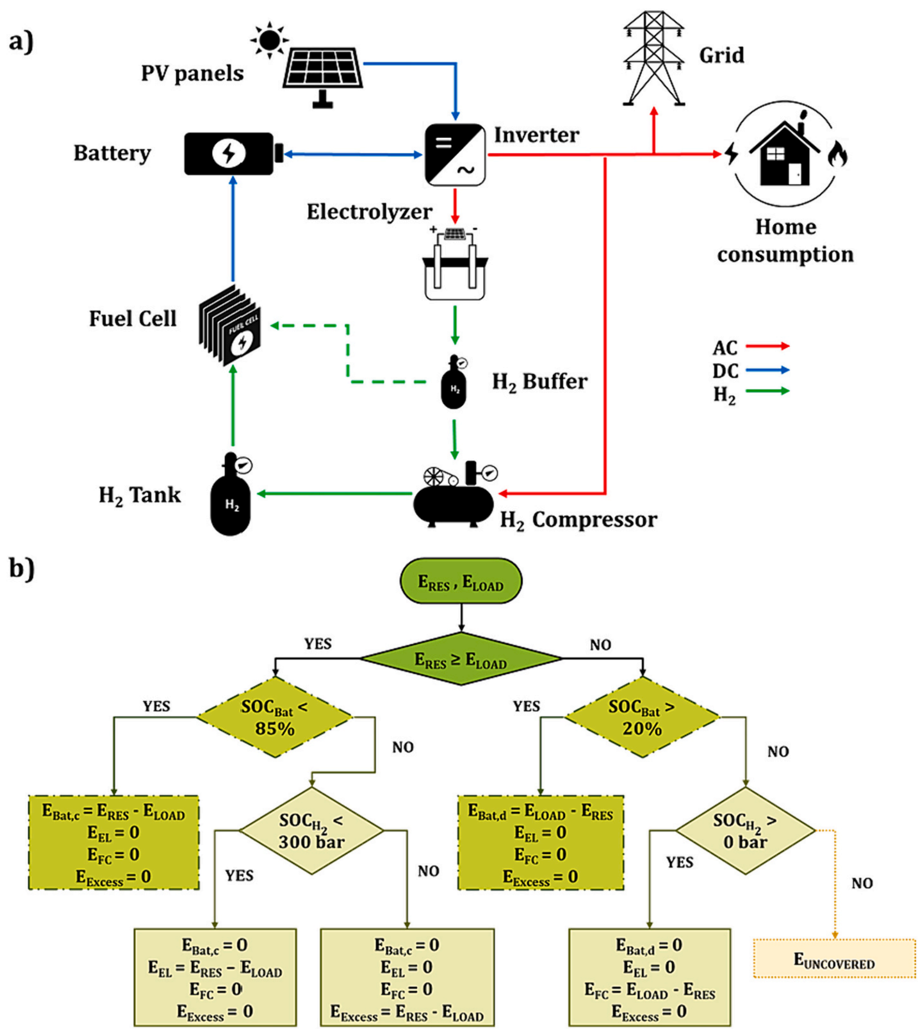

Fig. 3. a) Schematic diagram and b) EMS of the hybrid RHS implemented in Novales (Spain).

the system is not able to assimilate, obtaining some revenues in compliance with the price defined in the contract with the utility company.

This procedure is controlled and programmed in the programmable logic controller (PLC), which harvests and classifies all the data collected from the different components continuously, tracking the desired parameters to ensure the planned automatized sequence of operation. Thus, the equipment controlled by the PLC and the thresholds for their start/stop are exposed below:

1- Inverter: this device converts the direct current (DC) generated either by PV panels and/or batteries into alternate current (AC) consumed by the home. It also tracks the power generated by PV panels, the battery state of charge (SOC) as well as their charge and discharge power and energy, the power and energy imported and exported to the grid, the home power and energy consumption, and the power generated by the fuel cell. The inverter communicates with the PLC through the RS232 communication protocol. Thus, all the variables are saved in a register with a number. The PLC reads the number and position of each desired variable. In our case, the parameters are read by the PLC to drive the hydrogen supply chain.
2- Electrolyzer: the PLC monitors the SOC of batteries and starts the electrolyzer once SOC $\geq$ 85% AND excess power $>$ 0 W, this means that the battery pack is being charged and there is still energy surplus that can be accumulated. The water purification system operates automatically until the water tank is full and the latter pumps water into the electrolyzer during its operation. Conversely, the electrolyzer is stopped given one of the following circumstances: a) batteries SOC $\leq$ 60%, b) battery discharge power $>$ PV panels power AND home power consumption $\geq$500 W, c) buffer tank pressure $\geq$ 35 bar AND high-pressure tank inlet pressure (PT4) $\geq$ 300 bar. The PLC communicates with the electrolyzer using MODBUS TCP interface.
3- Compressor: based on a reciprocating electrically driven piston, it has two different compartments: low pressure chamber and high-pressure chamber. In this regard, the compressor registers H_2 pressure at the inlet (equal to the pressure of the buffer tank) and the outlet (high-pressure tank). The compressor starts when buffer tank pressure $\geq$ 34 bar AND high-pressure tank pressure $<$ 300 bar and stops when high-pressure tank pressure $\geq$ 300 bar OR buffer tank pressure $\leq$ 28 bar.
4- Fuel cell: it starts producing electricity in two different cases: 1) SOC $\leq$ 20%, or 2) battery discharge power $>$ 2500 W AND home power consumption – battery discharge power $>$ 0 W. If the fuel cell is started because SOC $\leq$ 20%, it will stop when SOC $\geq$ 35%. In contrast, if the fuel cell is activated because the battery cannot supply the home demand, the fuel cell stops 5 min after the home power consumption is $<$2500 W. This time is defined to avoid possible transient energy flows that can induce multiple start/stop cycles to the fuel cell and thus, damage the device. The PLC opens and closes the different electrovalves according to the pressure levels of both the buffer and the high-pressure tank. The PLC controls the operation of the fuel cell using CANBUS communication language.

Furthermore, the different screens available with the parameters tracked by the PLC are presented subsequently. Thus, these screens are integrated into the Supervisory Control and Data Acquisition system (SCADA), enabling a remote control and monitoring of the pilot plant:

- Manual/automatic: it includes a button to operate the plant either manually or automatically. In this screen the electrovalves, the compressor, the fuel cell and the light of the installation hut are operated.
- Electrolyzer: including the monitoring of the status, the total hydrogen generated, the actual hydrogen flow rate, stack voltage and current, electrolyte temperature, as well as both dryer inlet and outlet pressure.
- Pressure transducers: this screen tracks the hydrogen pressure in different points of the gas network such as fuel cell inlet, high-pressure tank outlet, compressor outlet, both buffer bottles and buffer outlet stream.
- PV panels: all the variables concerning PV subsystem are monitored in this screen. The main parameters controlled here are battery SOC, battery charge/discharge power and energy, grid exported/imported power and energy, generated PV power and energy, home power and energy consumption.
- Diagram: the main process diagram integrates red/green indicators in the components mentioned in the manual/automatic screen, as well as the pressure in each point of the gas network, the battery SOC, the home power consumption, and the hydrogen flow rate in the mass flow controller.
- Fuel cell: the power and energy generated by the fuel cell, the stack current, the voltage, and the anode pressure are included in this screen.
- Graphs: all the variables previously defined and mentioned can be represented thanks to the SCADA, with a minimum data resolution of 1 s.

3. Results and discussion

This section addresses the demonstration of the robustness and resilience of the implemented PVHyP to ensure the electrical self-sufficiency of the social dwelling. Hence, the collected results display the final dimensions of the pilot plant and the interaction among the various equipment, the temporal evolution of the monitored variables (demonstrating the proper compliance with the specified control sequence), and the values obtained for each of the defined KPIs.

3.1. PVHyP characteristics

The final design of the PVHyP considers the market analysis that has been performed to assess the availability of the real equipment (dimensions and characteristics), also considering the budgetary constraints to execute the implementation and accounting relevant aspects such as the outlet pressure of the electrolyzer, the hydrogen storage pressure, or the energetic requirements of an auxiliary compressor. Hence, Table 3 contains the bill of materials and equipment that form the pilot plant, including their main characteristics. Apart from the listed components, piping, tubing, wires, gas connections and joints are required. Finally, Fig. 4 presents a Process Flow Diagram (PFD) that depicts the balance of plant (BoP) of the prototype system.

The final BoP of the designed system collects diverse components necessary for the appropriate operation of the PVHyP. Regarding the hydrogen supply chain, it is produced from tap water. To ensure a proper quality, a water pre-treatment system is included to reduce the water conductivity and a water tank to store the purified water to be fed into the electrolyzer. Besides, a hydrogen dryer employing pressure swing adsorption and temperature swing adsorption is incorporated to enhance hydrogen purity and fuel cell longevity, together with a buffer tank consisting of two steel bottles of 50 L to avoid multiple start/stop cycles of the hydrogen compressor. Finally, multiple pressure transducers (PT), electrovalves (EV), check valves, a pressure regulator, a mass flow controller and a smart power meter is included to complete the BoP. Conversely, the PV subsystem includes a battery charge regulator, a PLC and a smart power meter to ensure a proper voltage/current supplied to the inverter and battery pack, to control the system and to measure the consumption of the dwelling respectively.

Concerning the operation of the PVHyP, PV panels harvest the generated energy that is sent to an inverter for distribution within the home. Surplus energy is allocated towards battery charging, with any remaining excess stored in the form of hydrogen through electrolysis of

Table 3
Pilot plant equipment description and characteristics.

Subsystem	Component	Characteristics and description
PV subsystem	PV panels	Rated power: 400 Wp × 20 units, 8 kWp Module efficiency: 20.17%.
	Inverter	Rated power: 6 kW. Maximum power: 8 kWp. Inverter efficiency: 97.7%.
	Batteries	Nominal capacity: 2.4 kWh × 4 units, 9.6 kWh Useful capacity: 2.2 kWh × 4 units, 8.8 kWh Rated voltage: 48 V DC.
	Battery charge regulator	Maximum voltage/current: 150 V DC/60 A. Efficiency: 98%.
Hydrogen supply chain	Anion Exchange Membrane Electrolyzer	Power consumption: 4.8 kWh/Nm^3, 2.4 kW. Water consumption: 0.4 L/h. Water conductivity required: $<$ 20 μS/cm. Production rate: 500 NL/h. Outlet pressure: 35 bar. Hydrogen purity: 99.9%.
	Dryer	Power consumption: 200 W. Hydrogen output purity: 99.999%. Nominal consumption: 0.045 kWh/Nm^3. Hydrogen drying rate: 2.5 Nm^3/h.
	Water tank module	Power consumption: 50 W. Capacity: 35 L. Maximum water flow rate: 3.8 L/min.
	Water purification system	Power consumption: 80 W. Water production rate: 1.3 L/min. Water output conductivity: $<$ 20 μS/cm.
	Proton Exchange Membrane Fuel Cell	Maximum power output: 2.5 kW. Operating voltage: 48 V DC Hydrogen consumption: $<$ 0.065 kg/kWh
	Compressor	Power consumption: 1.5 kW. Minimum inlet pressure: 30 bar. Maximum outlet pressure: 350 bar. Hydrogen flow rate: 120 L/min at 70 bar.
	Hydrogen storage tank	Storage capacity: 600 L. Working pressure: 300 bar. Outlet pressure: 0–3 bar regulated.
	Hydrogen buffer tank	Storage capacity: 100 L, 2 × 50 L steel bottles. Working pressure: 200 bar.
Instrumentation	PLC	–
	SCADA	–
	Pressure transducers (PT)	Pressure ranges: 4 bar (x3), 40 bar (x2), and 400 bar (x1).
	Electrovalves (EV)	Pressure range: 4 bar.
	Pressure regulator	Outlet pressure: 0–3 bar regulated.
	Hydrogen volumetric detector	Reading range: 0–100% LFL (Lower Flammability Level). Alarm limit: 20% LFL.
	Mass flow controller	Pressure range: 0–5 bar. Flow range: 1–50 NL/min.
	Smart Power Meter (SMP)	Voltage, current: 230 V AC, 50 Hz.

pre-treated water. Hydrogen is then generated in the electrolyzer and purified. Subsequently, the purified hydrogen is stored in a buffer tank until reaching a pressure of 35 bar, followed by compression and storage in high-pressure bottles up to 300 bar. During periods of insufficient solar radiation and battery reserves, the fuel cell starts its operation, utilizing the hydrogen stored at the buffer and high-pressure tanks. It should be noted that the FC is firstly activated with the hydrogen reserves of the buffer tank. This is aimed at increasing the overall efficiency of the system due to a reduction of compression requirements. A charge regulator links the fuel cell to both charge the batteries and/or provide electricity to the social dwelling via the inverter. Furthermore, the PLC integrates data from all equipment, instrumentation, and control devices to ensure automated and efficient process operations. Finally, a grid connection facilitates the sale of surplus electricity that exceeds storage capacity while guaranteeing continuous household power supply during maintenance and/or system malfunctions.

3.2. PVHyP implementation

Prior to the implementation of the PVHyP and the placement of the equipment in its final location, it is required to provide the installation with the necessary civil infrastructure. In this regard, the European and Spanish legislative framework concerning self-consumption facilities [90], hydrogen storage [91] and acoustic standards inside the different rooms of the home [92] have been examined. Besides, the specific regulations identified by the Subworking Group of Hydrogen Technologies of the Spanish Ministry of Industry, Commerce and Tourism, have been followed, which are applicable in the case of this pilot plant were followed [93]. Finally, the standards for fuel cells and water electrolyzers have been reviewed to identify safety requirements, volumetric gas detectors, explosive atmospheres, zoning of venting areas and purging of residual gases during operation, iconography, and creation of manuals for both operation and maintenance of the equipment and for its use.

Considering all the constraints derived from the review of the regulatory framework, it was decided to locate the PV panels on the roof of the building and the remaining components of the plant inside an installation hut placed in a neighbouring land plot. Fig. 5a displays the preliminary 3D design with the internal layout of the PVHyP, while Fig. 5b reflects the final placement of the installations hut next to the social dwelling to be supplied. The different parts of the shed can be appreciated, with an acoustic ventilation screen to ensure an appropriate ventilation flow in the inside, and a separate cage that contains

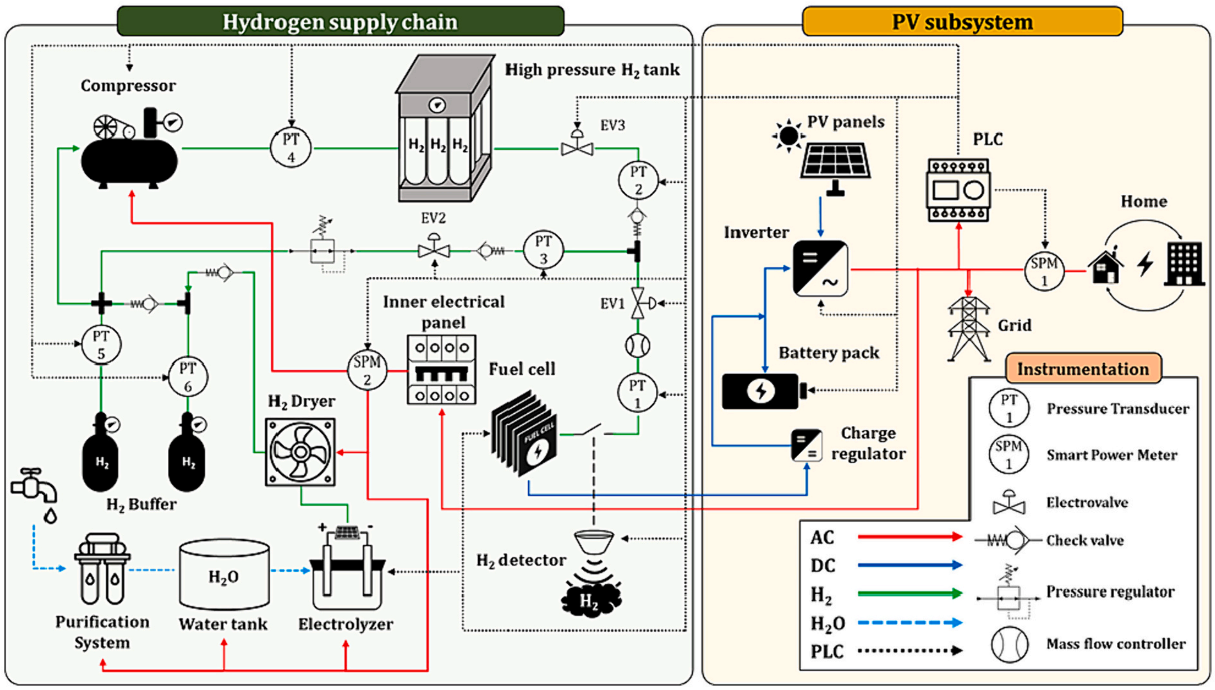

Fig. 4. PFD of the PVHyP connected to the social house of Novales.

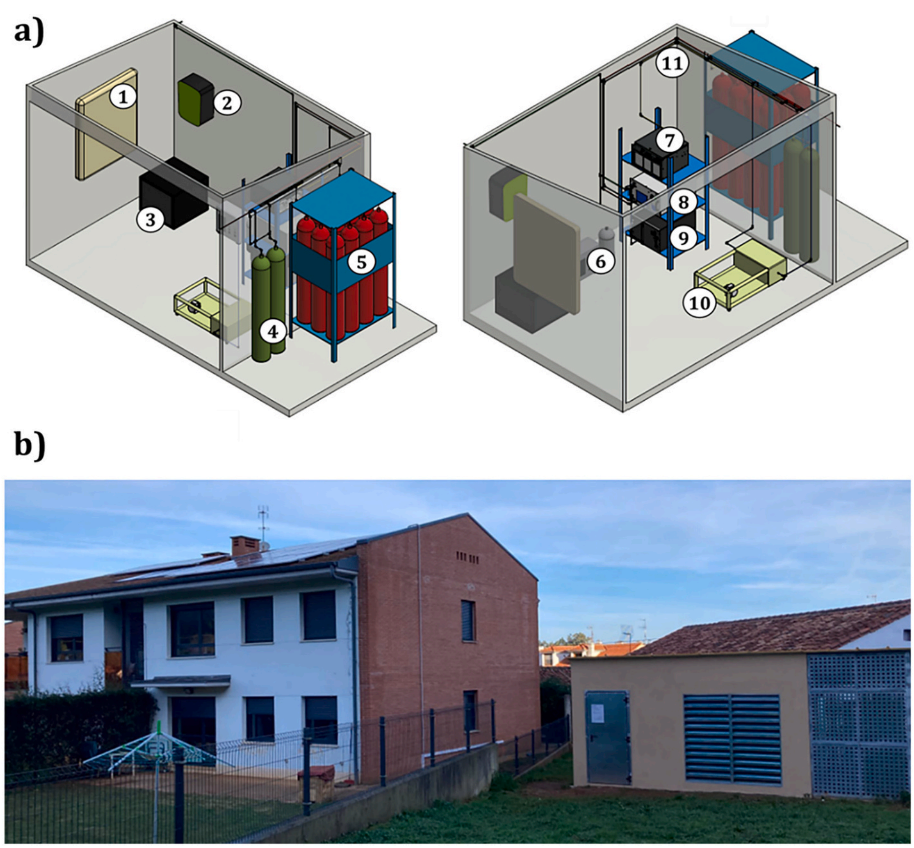

Fig. 5. a) Schematic 3D design and layout of the PVHyP: electrical panel and PLC (1), inverter (2), battery pack (3), buffer tank (4), high-pressure tank (5), water purification system (6), fuel cell (7), electrolyzer and dryer (8), water tank (9), compressor (10), piping and instrumentation (11); b) social home and installations hut containing the pilot plant.

both the buffer and the high-pressure storage tank. All the hut is acoustically isolated to ensure the internal comfort of the inhabitants.

Furthermore, several images from the main equipment composing the pilot plant are subsequently displayed. Fig. 6a contains the components of the PV subsystem, as well as the electrical panel with the PLC, and the devices of the entire hydrogen supply chain; while Fig. 6b

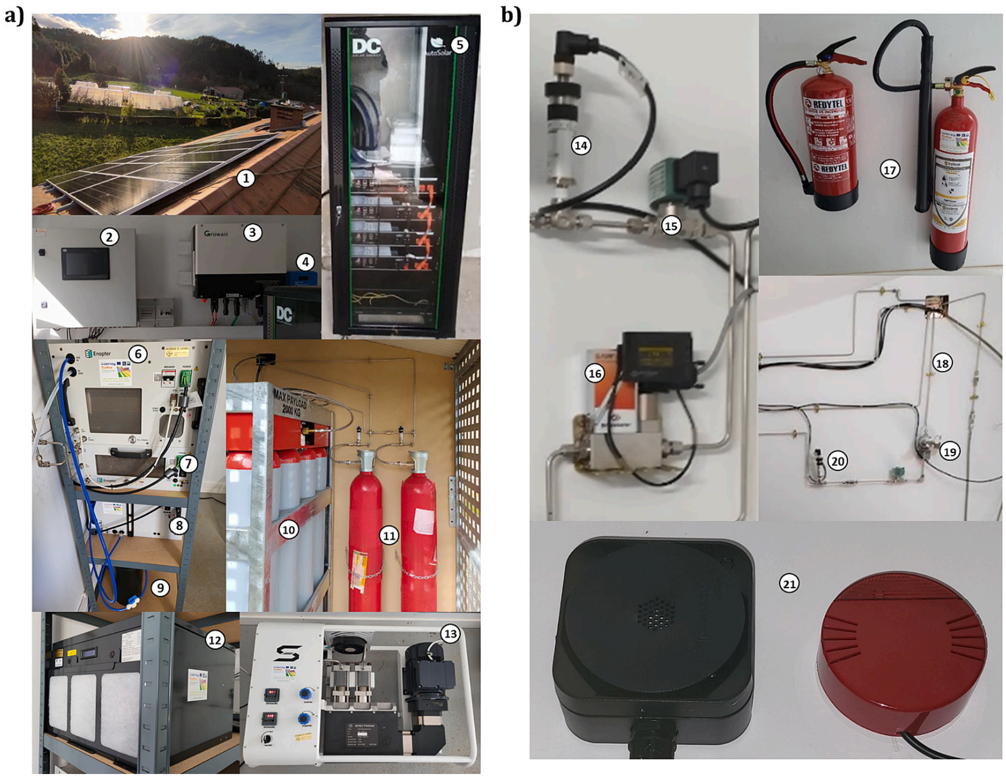

Fig. 6. a) PV panels (1), PLC and electrical panel (2), inverter (3), battery charge regulator (4) and battery pack (5), electrolyzer (6), dryer (7), water tank module (8), water purification system (9), high-pressure hydrogen tank (10), hydrogen buffer tank (11), PEM fuel cell (12) and hydrogen compressor (13); b) instrumentation, control and safety devices: pressure transducer (14), electrovalve (15), mass flow controller (16), fire extinguishers (17), stainless steel piping (18), pressure regulator (19), check valve (20), hydrogen detector and alarm (21).

displays different instrumentation, control and safety devices located inside the installation huts to properly manage the hydrogen flows within the system. In this regard, the hydrogen detector shuts down the electrical supply to prevent the potential creation of explosive atmospheres due to hydrogen accumulation. Ultimately, fire extinguishers would be employed to putting out the fires if these are formed.

3.3. Monitoring and techno-economic assessment

After defining the control strategy of the power system and deploying the PVHyP, it is necessary to track the performance and behavior of the standalone configuration. The pilot plant was installed sequentially after commissioning and testing the devices at the facilities of the University of Cantabria. Firstly, the PV subsystem started operating with the battery pack as only storage method. Then, after finishing the civil work inside the installation hut, all the equipment required for the generation, compression and storage of hydrogen was installed and automatized. Lastly, the fuel cell was commissioned and automatized in parallel with the implementation of the instrumentation, safety and control equipment to conclude the BoP.

The major outcomes derived from the operation of the PVHyP previously described are presented hereafter. To visualize the correct operation of the equipment during the year, examples of several days under different conditions of home consumption and PV generation are shown. Thus, it is verified that both the hydrogen generation and the compression, storage, and reconversion into electricity on demand work according to the defined control parameters, complying with the premise of self-sufficient operation of the social housing. Therefore, the energy balance between generation (PV panels, fuel cell, battery discharge) and consumption (social home, electrolyzer, compressor, purifier, ancillary equipment, and battery charge) must be secured. To this end, Fig. 7 and Fig. 8 display the difference between total generation and consumption throughout the day in a continuous way with a data resolution of 1 min, the battery SOC evolution and the energy contribution per hour and component. Both figures represent six consecutive days of operation of the PVHyP that have been taken as representative because all the constituent elements of the system come into operation, diverse weather conditions occur (day 1 with low solar radiation, days 2 and 3 with high PV production or days 4 and 5 with variations throughout the day), and there are varied demands from the social home. In this case, generators (PV panels, batteries in discharge mode and fuel cell) are plotted in the positive side of Y-axis, while the consumers (home, electrolyzer, compressor, and dryer) are presented in negative and being symmetric with respect to X-axis. If the difference between generation and consumption is positive, we have extra electricity to be exported and sold back to the utility grid. Otherwise, if this difference is negative, it means that the system is not self-sufficient and needs the grid as a backup. It should be noted that battery in charge mode and the energy exported to the grid are considered as consumers as they do not contribute to meet the energy demanded by the home and the remaining equipment.

In view of both Fig. 7 and Fig. 8, it can be appreciated that the PVHyP is capable of covering all the electricity demand of the social dwelling and even generate energy surpluses (generation – consumption profile always positive) that can be retrieved to obtain further incomes when these are sold to the utility grid company. Moreover, this occurs in days with different climate conditions: day 1 corresponds to a cloudy/rainy day, while days 2 and 3 represent sunny days, respectively. The SOC of the battery rapidly grows in the second and third represented days, as PV generation is higher than the load consumption. Thus, the extra energy is employed for hydrogen generation, purification, compression, and storage during the mid-hours of the day, with the electrolyzer being the major energy consumer among the equipment composing the hydrogen value chain.

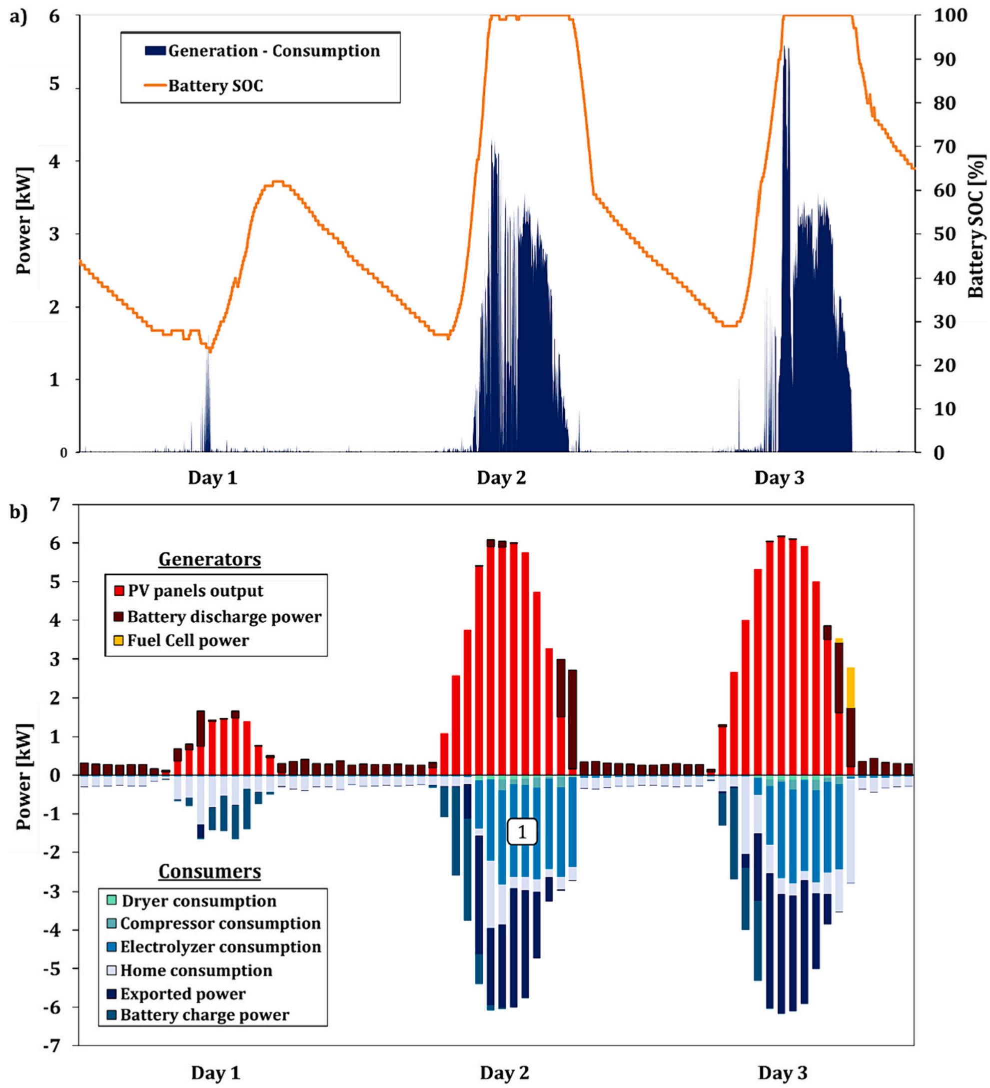

Fig. 7. a) Difference between generation - consumption profiles (dark blue) and battery SOC evolution (orange). b) Power supply and demand/energy storage in three consecutive days. Note: (1) electrolyzer, compressor and dryer operation during 9 h. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Besides, in periods with great home consumption (day 4 in the morning or days 3, 4 and 5 in the afternoon/evening), the fuel cell starts operating to meet the demand that the battery pack is not able to fulfil. The production, purification and compression of hydrogen highlighted with the number (1) in Fig. 7 is displayed in detail in Fig. 9, whereas hydrogen retrieval for electricity generation in the fuel cell and its interaction with the electricity demand and the battery pack emphasized with number 2 in Fig. 8 is explained in Fig. 10.

Fig. 9a displays the operation of the electrolyzer, compressor and dryer during a day with remarkable solar irradiation. Hence, the consumption of the electrolyzer, compressor and dryer are given on the primary Y-axis on the left, while battery SOC is given on the primary Y-axis on the right. Buffer tank pressure is represented on the secondary left Y-axis and high-pressure tank evolution on the secondary right Y-axis. Start/stop of both electrolyzer and dryer are marked with a green/red diamond respectively, highlighting the battery SOC in each point; and compressor start/stop cycles are represented with green/red squares and expose the start/stop pressures of the buffer. Finally, the increase on the level of the high-pressure tank per compression cycle is highlighted in green.

The electrolyzer was working during >9 h without interruption. Four different regions can be appreciated: activation, ramp up, nominal operation, and shut down. The activation lasts 5 min, heating up the electrolyte constantly when the battery SOC reaches 85%. At the same time, the hydrogen dryer is turned on. Once a minimum temperature of around 25 °C is achieved, the electrolyzer starts generating hydrogen within a two-stage ramp-up sequence with a small hydrogen purge in between. Then, hydrogen presents an average power consumption of 2.4 kW corresponding to the nominal operation, producing 500 NL/h under this regime. Ultimately, the electrolyzer and the dryer are turned off once the state of charge of the battery falls below 60%. As of December 31st 2023, the electrolyzer has been operated over 700 h, reporting a degradation rate of 5 μV/h. The low degradation of the stack is related with the expected lifetime of the electrolyzer (over 30,000 h) [94].

Regarding the compressor, it performs 4 start/stop cycles to increase the pressure of the stored hydrogen from almost 239 bar to 247.3 bar maximum, with a slight decrease after the last compression cycle due to the fall in ambient temperature. Each compression stage spans around 20 min, achieving a pressure increment of around 2 bars. It can be appreciated how the compressor is turned on every time the pressure transducer at the entry of the buffer tank (PT6) reaches 34 bar and stopped when the pressure is reduced to 28 bar. Furthermore, the compressor is a reciprocating piston compressor, resulting in fluctuating

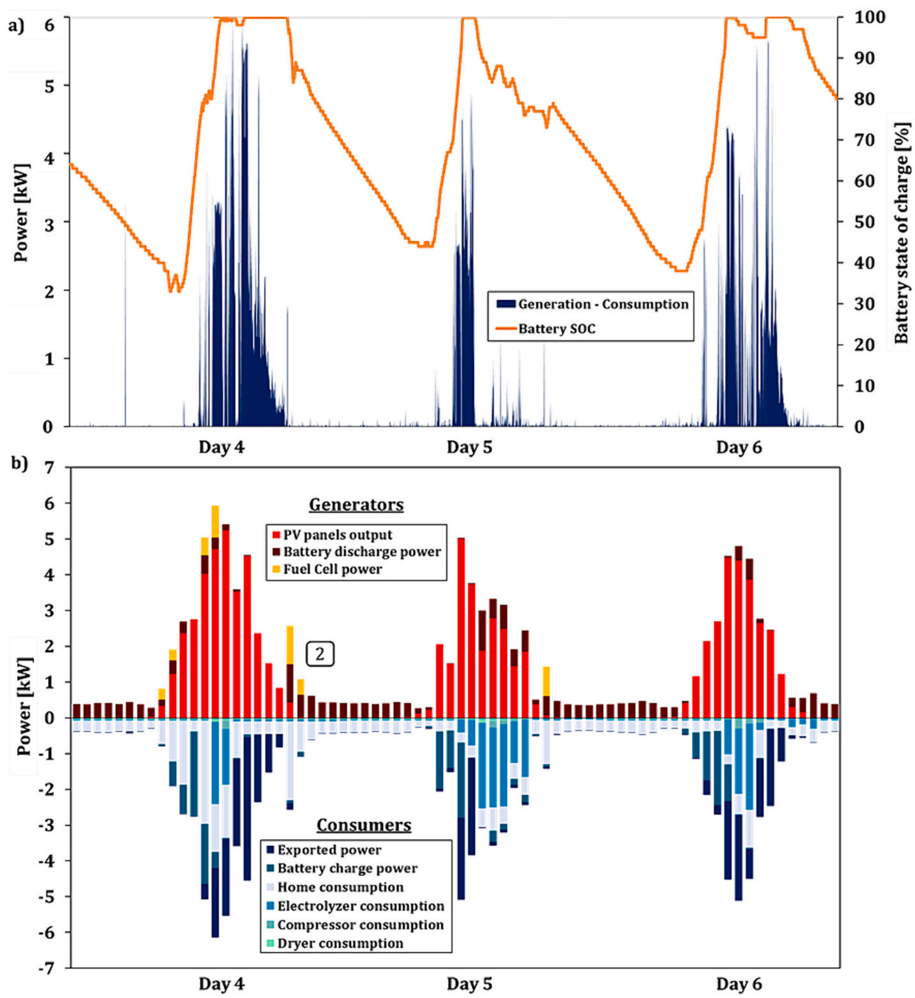

Fig. 8. a) Difference between generation - consumption profiles (dark blue) and battery SOC evolution (orange). b) Power supply and demand/energy storage in three consecutive days. Note: (2) fuel cell operation during night with high home consumption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

power consumption associated with the position of the piston stroke when the data is displayed. Finally, the dryer presents a first heating stage during electrolyzer ramp up and after that performs start/stop cycles to keep the target temperature of 125 °C to remove the traces of water in the hydrogen stream.

Conversely Fig. 9b depicts the energy and exergy content and performance of the electrolyzer during the same period of operation (>9 h). As it can be appreciated, the exergy efficiency of the electrolyzer exceeds the energy efficiency, achieving a maximum of 63.5% and 62.4% respectively during ramp up of the electrolyzer. The mean value of exergy efficiency during nominal operation is 58.8%, while the one for the energy efficiency is 57.8%. The exergy efficiency is always higher than the energy efficiency as the content of energy of hydrogen is lower than its exergy value [88]. Likewise, Fig. 9c reports the exergy content of the PV panels during the same period of operation. In this case, it can be seen that the exergy that would be obtained under an ideal, reversible thermodynamic process is much higher than the energy harvested by the PV array due to inefficiencies. In this case, the exergy efficiency has a maximum value of 18.8% with a mean value of 12.5%.

In Fig. 10a, the total power consumption including home demand and devices in standby and battery in charge mode are the main consumers, while PV panels, fuel cell and battery in discharge mode are the generator elements, all of them represented on the primary left Y-axis. Battery SOC is represented on the primary right Y-axis. Besides, the evolution of the pressure in the anode of the fuel cell is given on the secondary left Y-axis and the high-pressure tank level on the secondary right Y-axis. Start/stop thresholds for fuel cell are highlighted with green/red squares, with the stop of the fuel cell is represented with red diamonds. The aforementioned thresholds are based on the comparison between the total power consumption (P_{TOTAL}) and the maximum battery discharge power ($P_{DIS,\ BATmax}$). Particularly, the fuel cell represented in Fig. 10a, it starts operating once the load demand exceeds 3.3 kW, which is the maximum power that the batteries can deliver. At this time, the electrovalve located at the inlet of the fuel cell is opened and the anode pressure increases to almost 850 mbar (secondary left Y-axis). Then, it stabilizes in the range between 550 and 600 mbar. Finally, the fuel cell stops 5 min after the load consumption falls below the maximum discharge power of the batteries.

Likewise, the fuel cell is turned on again when the home demand ramps up. It can be noted that even with a consumption over 6 kW, the combination of the fuel cell and the battery can supply sufficient power for the tenants. For periods with high energetic demands, the fuel cell requires more hydrogen supply and thus, the anode pressure presents values around 650 mbar. Moreover, if the demand suddenly decreases, the extra energy generated by the fuel cell is employed to charge the batteries. It can be appreciated the reduction on the hydrogen stored in the tank, diminishing their pressure from 296.7 to 294.1 bar (secondary right Y-axis). Finally, the fuel cell presents a low degradation rate of 2.7 μV/h for >500 h of operation, being these values comparable to other works with a similar test duration [95–97]. It should be noted that the

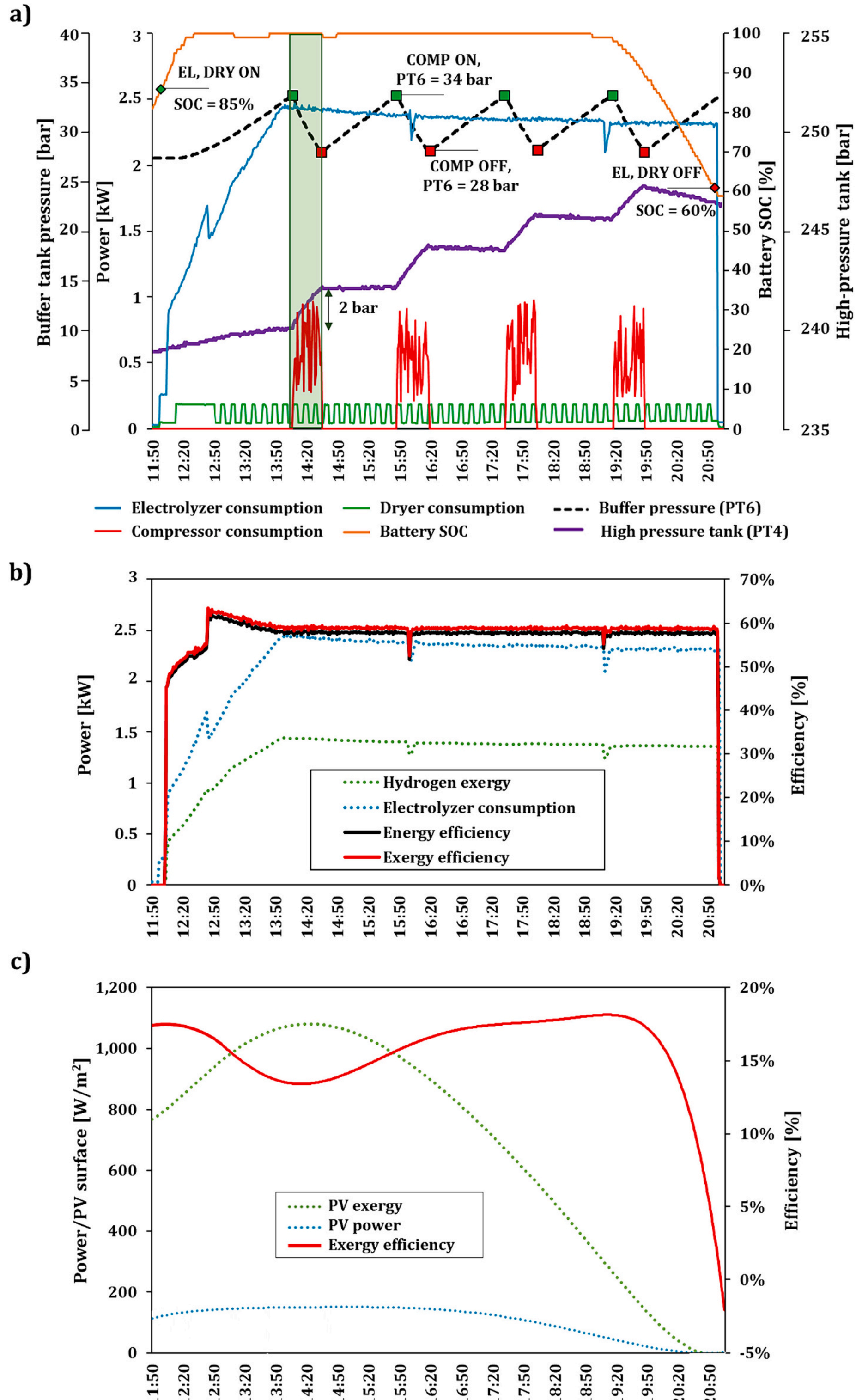

Fig. 9. a) Hydrogen generation, compression and purification during 9 h of operation. b) Electrolyzer consumption, hydrogen exergy and energy/exergy efficiencies of the electrolyzer. c) PV panels energy, exergy and exergy efficiency.

fuel cell is far from reaching its expected lifetime of 10,000 h, so further analysis needs to be done to assess the evolution of its degradation rate over time.

In Fig. 10b, the fuel cell output is presented along with the exergy content of hydrogen, the energy efficiency, and the exergy performance. Unlike the electrolyzer, the hydrogen exergy is higher than the output power delivered by the fuel cell with a very comparable energy/exergy efficiencies (62.4% maximum, 50.2% average during its operation).

Lastly, the evolution of the hydrogen storage from October 1st 2022 to December 31st 2023 is exposed in Fig. 11, displaying a continuous decrease on the stored energy from October 2022 to mid-February 2023 coincident with the months of less solar irradiation. However, there is sufficient energy stored to meet the demand during the most restrictive period, being 9% the lowest value reported during the second week of

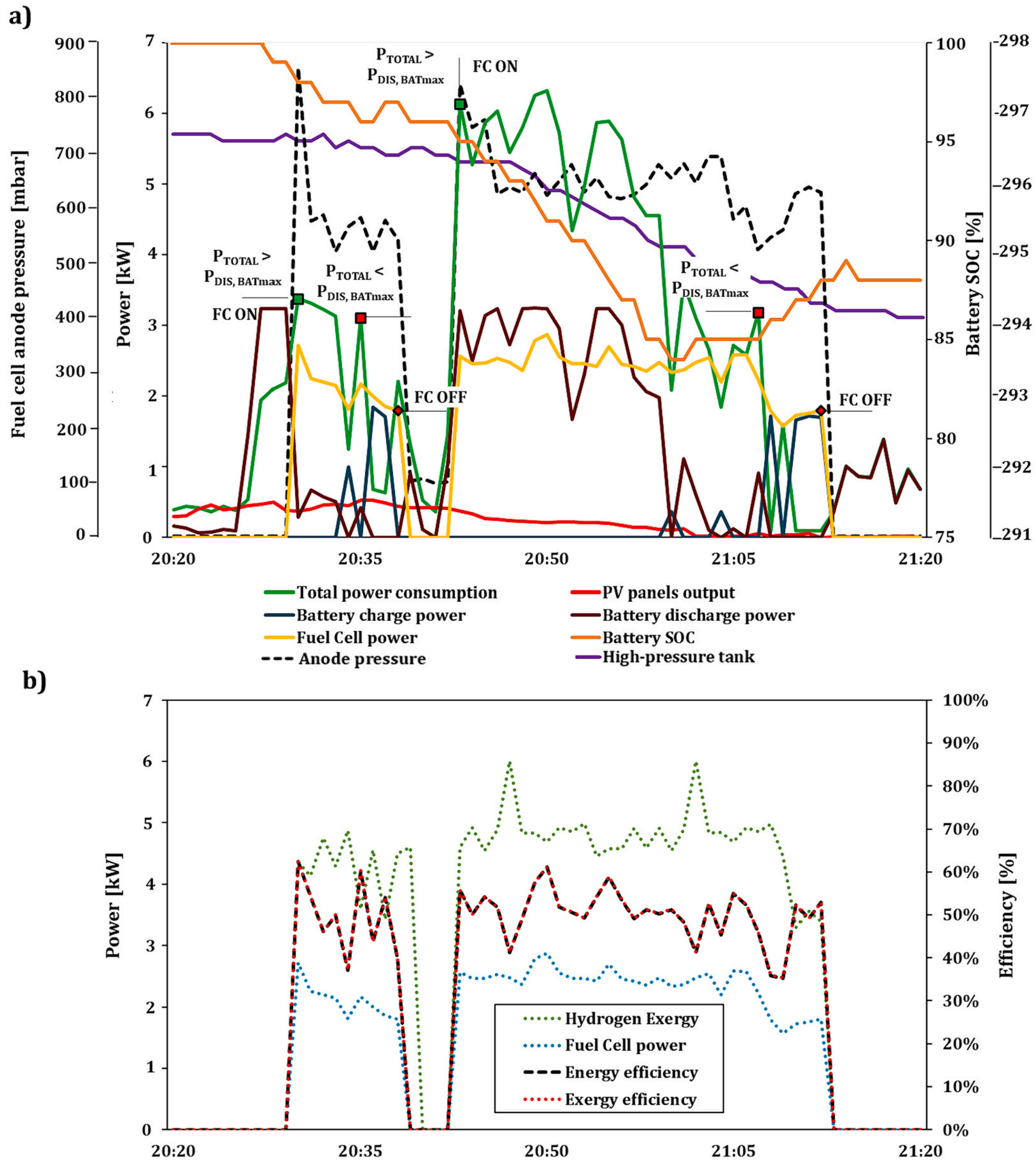

Fig. 10. a) Operation of the fuel cell at night with high home consumption, including generators, consumers, battery SOC curve, and evolution of fuel cell anode pressure and high-pressure tank level. b) Fuel cell power production, hydrogen exergy, and energy/exergy performance of the fuel cell.

February 2023. Then, hydrogen starts to be accumulated from mid-March 2023 onwards up to June 2023, when the tanks become full. There are occasional downturns during summer due to cloudy/rainy days, or periods of high energy consumption on the early or late hours of the day when the battery pack cannot to meet the demand in its own. Finally, hydrogen reserves decrease with the start of the autumn season, with the total stored autonomy at the end of 2023 being lower than at the end of 2022 (33% compared to 37%).

After having monitored the system for almost two years, some global KPIs are provided to assess the overall performance of the designed and implemented PVHyP. Thus, Table 4 summarizes the total energy consumed by the load, the energy generated by PV panels, the total amount of hydrogen produced, the overall efficiency, primary energy savings, CO_2 emissions avoided, and the economic savings since the deployment of the PV subsystem from January 2022 to December 2023.

So far, the performance of the pilot has been remarkable, achieving very promising results in terms of efficiency (comparable to the Spanish electricity grid), primary energy savings, emissions avoided, and economic savings. Thus, almost 15,200 kWh have been saved from fossil fuels (this value considers the inefficiencies of the electricity grid, from generated electricity to final electricity consumption, around 42%), which corresponds to approximately 2260 kg of CO_2. Furthermore, around 1170 € have been already saved by the tenants. This implies the complete electrical self-sufficiency of the social dwelling thanks to the system with a 100% reduction on the emissions related to the electrical consumption, resulting in the 100% elimination of the electricity bill. Moreover, as PV excesses are injected back to the grid, further users are benefited from a more sustainable electricity grid mix. This can be appreciated in the LCOE with and without energy sales, that lowers the energy price from 0.86 to 0.34 €/kWh. Therefore, the implementation of the renewable hydrogen-based PVHyP has contributed to reflect the technical feasibility of these technologies, ensuring uninterrupted electricity supply to the social home of Novales.

4. Conclusions

This work reports the implementation of a hybrid power system based on RES and hydrogen technologies to achieve the electrical self-sufficiency of a social housing in the town of Novales (Cantabria, Spain). In this regard, it has been possible to expand the existing

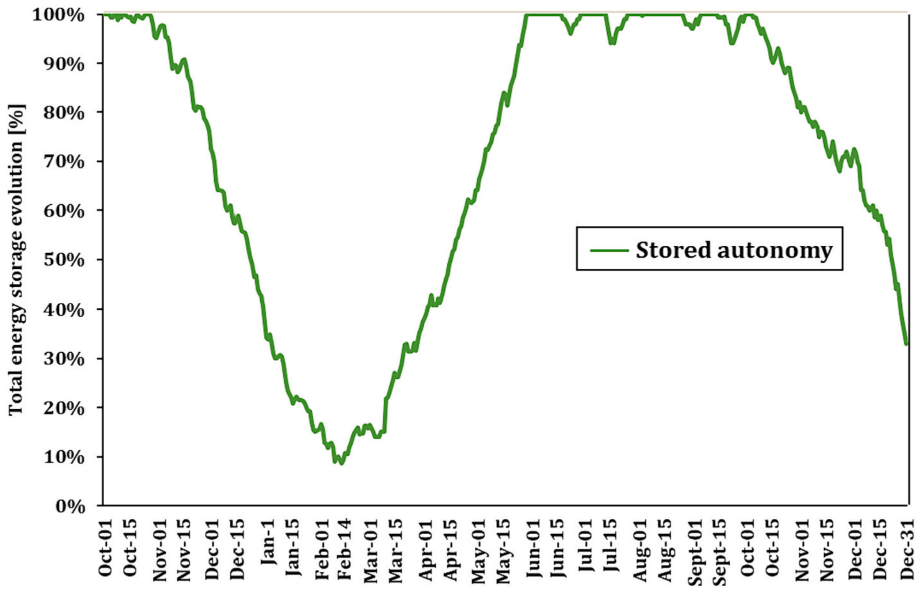

Fig. 11. RHS stored autonomy evolution from October 1st 2022 to December 31st 2023.

Table 4
KPIs of the PVHyP implemented in Novales (Spain) from January 2022 to December 2023.

KPI description	Result
Home energy consumption	6325 kWh
PV panels generation	13,327 kWh
Total produced hydrogen	271.72 Nm^3 / 24.5 kg of H_2
Overall efficiency	47.5%
Primary energy savings	15,199 kWh
CO_2 emissions avoided	2258 kg
Economic savings	1170 €
LCOE without sale of surplus energy	0.86 €/kWh
LCOE with sale of surplus energy	0.34 €/kWh

knowledge regarding these facilities not only from a theoretical point of view of design and simulation, but also from the reality of the current market, uninterrupted operation, automation, control, and continuous monitoring of the entire process. Thus, the possibilities provided by hydrogen as energy vector in the decarbonization of different stationary power applications, and more specifically, its hybridization with PV energy for sustainable supply in social housing, have been highlighted, and more specifically, its potential use for the decarbonization and increased energy efficiency in social housing.

The implementation of the real PVHyP required an adjusted redesign based on the specific characteristics of both the energy demand curve and the actual equipment that has been selected. In addition, it involves addressing a series of cross-cutting issues such as a systematic and exhaustive review of the legislative framework, the study of each equipment to be implemented and the definition of a control system and the energy management strategy that will allow a correct integration and interaction between them. In this way, the pilot plant of Novales (Spain) is a flagship implementation for social housing decarbonization. It has been proved that the control system performs as expected, with either the electrolyzer or the fuel cell being activated when there is surplus energy or when the battery pack and the PV panels cannot meet the energy demanded by the home. Furthermore, the continuous monitoring of multiple variables and parameters allows the operation of the PVHyP to be fully automatized and controlled from the University of Cantabria, which is 40 km far from the facility. Finally, a comprehensive analysis of the overall energy performance and the energy/exergy efficiency of the main components of the PVHyP has been carried out, reflecting values over 60% for both the electrolyzer and the fuel cell, with negligible degradation. Further assessment has to be done in the upcoming months to evaluate the evolution of all the parameters in terms of their performance and degradation.

This pioneering pilot plant in the SUDOE region (Spain, Portugal, and southwest France) has marked a step forward in the deployment of hydrogen technologies within the residential sector. It not only contributes to the decarbonization of household electricity use and improves their energy efficiency, but it also allows residents at risk of exclusion and energy poverty to access free and sustainable electricity. Thus, this pilot system represents a modular and scalable solution capable of meeting the electrical needs of isolated homes, remote residential communities, and critical infrastructures where uninterrupted power supply is crucial. Additionally, it enables actions to be carried out to electrify thermal demands, enabling hybridization with heat pumps, the use of electric radiators for meeting home heating needs, electric water heaters for supplying hot water or use in cogeneration systems. This implementation also adds value to properties, increasing their benefits for potential sales and presenting a competitive LCOE when extra electricity, that cannot be accumulated by the system, is sold to the utility grid company. Finally, thanks to the implemented PVHyP, almost 15,200 kWh of primary energy, 2.3 tons of CO_2, and around 1170 € (100% of electricity bill) have been already saved since the pilot plant started its operation back in January 2022. It should be noted that this pioneer power system continues its operation to date.

CRediT authorship contribution statement

V.M. Maestre: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **A. Ortiz:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **I. Ortiz:** Writing - review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgements

The research is currently receiving support from various sources. This research is being mainly supported by the Project ENERGY PUSH SOE3/P3/E0865, which is co-financed by the European Regional Development Fund (ERPF) in the framework of the INTERREG SUDOE program, as well as the project TED2021-129951B-C21, funded by the Spanish Ministry of Science and Innovation (MCIN/AEI/10.13039/501100011033). The authors want to extend their gratitude to the project "Plastic circularity through an efficient detection, collection, and valorization into Hydrogen and value-added products EAPA_0018/2022" within the framework of the INTERREG ATLANTIC program. The project PID2021-123120OB-I00 financed by MCIN/AEI/10.13039/501100011033 is also among the contributors. Additionally, the authors acknowledge the financial assistance provided by projects PLEC2021-007718 and the "Complementary Plan for Energy and Renewable Hydrogen" PRTR-C17.I1, financed by MCIN/AEI/10.13039/501100011033, the Regional Government of Cantabria, and Next GenerationEU/RTRP.

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