International Journal of Sustainable Development and Planning
Vol. 19, No. 11, November, 2024, pp. 4109-4114
Journal homepage: http://iieta.org/journals/ijsdp

# Solid-State Hydrogen as an Energy Storage Strategy in the Building Sector for Sustainable Development

Aminhossein Jahanbin*, Umberto Berardi

Department of Architecture, Construction and Design, Politecnico di Bari, Bari 70125, Italy

Corresponding Author Email: aminhossein.jahanbin@poliba.it



https://doi.org/10.18280/ijsdp.191101

**Received:** 18 September 2024
**Revised:** 25 October 2024
**Accepted:** 31 October 2024
**Available online:** 28 November 2024

***Keywords:***
*green hydrogen, energy storage, hybrid storage systems, solid-state hydrogen, off-grid buildings, techno-economic optimization, dynamic simulation*

**ABSTRACT**

This study investigates the technical and economic feasibility of implementing a combined energy storage strategy for PV-driven buildings, incorporating solid-state hydrogen energy storage. A coupled EnergyPlus-TRNSYS model is developed to evaluate the dynamic performance of the hybrid system. Targeting a net-zero energy building, the optimal component sizing of the hybrid system is achieved through a statistical optimization model. A subsequent comparative techno-economic analysis of the optimal scenario highlights its benefits and limitations. The results suggest that off-grid operation of the building leads to an annual $CO_2$ reduction of 11.8 tons $CO_2$/yr. The findings show that direct PV electricity supply accounts for 58.9% of the building energy demand, while the fuel cell and battery contribute 23.4% and 17.7%, corresponding to 7.4 and 5.6 MWh, respectively. The economic analysis indicates LCOE and LCOH values of 0.379 \$/kWh and 6.14 \$/kg.

## 1. INTRODUCTION

In light of the global commitment to carbon neutrality and decarbonization targets for sustainable development, the upcoming decade is pivotal for charting a path toward net-zero emissions by 2050 and limiting global warming to 1.5℃, as outlined in the Paris Agreement [1]. Achieving these objectives underscores the urgency of a comprehensive energy transition, marked by the gradual decommissioning of coal and fossil fuel-based power plants and the accelerated adoption of renewable energy sources (RES). RES are broadly regarded as the most practical and impactful means to reduce greenhouse gas emissions while providing a sustainable energy supply to meet the growing global demand.

As the world grapples with the escalating impacts of climate change, the development and deployment of innovative strategies to harness RES across multiple sectors become imperative [2]. Recognizing that the building sector is a major energy consumer, the European Union aims to achieve low-carbon, sustainable growth by reducing greenhouse gas emissions by at least 40% by 2030, and has therefore established several short- and long-term targets to enhance energy efficiency and decrease energy consumption within this sector [3]. Within the building sector, efforts to leverage renewable sources, coupled with the electrification of end-use sectors, are critical steps in this transition. Solar energy adoption has gained considerable momentum; however, a notable gap often persists between solar energy generation and the energy consumption patterns of buildings. This disparity highlights the vital role of efficient energy storage systems in optimizing the use of solar energy, ensuring a stable and reliable energy supply [4].

One potential solution to mitigate greenhouse gas emissions and achieve carbon neutrality is the implementation of hybrid systems, which represent a practical strategy in energy management [5]. Within these systems, the energy storage system (ESS) plays a pivotal role in decoupling energy generation from end-use, thereby promoting the increased adoption of RES [6]. In the building sector, battery energy storage system(s) (BESS) are widely utilized for short-term energy storage, benefiting from high round-trip efficiency and rapid response times [7]. Despite these advantages, BESS present challenges such as sensitivity to elevated temperatures, high self-discharge rates, and limited lifespan, which restrict their feasibility for long-term storage applications [8].

As a promising alternative, hydrogen storage technologies provide longer lifespans, resilience to high temperatures, and minimal self-discharge [9]. These attributes have accelerated interest in hydrogen energy storage systems as a sustainable solution for renewable energy integration and as a key driver for achieving energy sector decarbonization by 2050 [10]. Hydrogen storage serves as a promising RES-based storage option for subsequent electricity generation through fuel cells within the building sector.

This strategy seeks to establish a balance between energy supply and demand; during off-peak periods, excess electrical power can be converted to hydrogen, which is stored for later utilization. Conversely, the stored hydrogen can be reconverted into electrical power during peak demand periods [11]. In addition, integrating BESS into hydrogen-based ESSs has been proposed in the literature as an effective solution to improve the overall performance of hydrogen-based systems in microgrids, while also maximizing the lifespan of hybrid system components.

Hydrogen storage methods are broadly divided into physical and chemical approaches. Physical storage includes compressing hydrogen gas in cylinders or liquefying it in cryogenic tanks, while chemical storage relies on solid-state storage within metal hydride storage (MHS). Although high-pressure and cryogenic tanks offer straightforward accessibility for commercial use, they generally provide lower energy density and pose greater safety concerns compared to the solid-state storage of hydrogen within materials. Metal hydrides (MH) have been a major focus in research on solid-state hydrogen storage materials, owing to their high hydrogen volumetric capacity, stability, and reversibility. MHS systems provide key advantages for long-term hydrogen storage, operating effectively across a broad range of temperatures [12].

Despite these benefits, MHS systems face challenges, notably their relatively high cost compared to other storage options. This cost factor can hinder their widespread adoption in various applications, necessitating further research and development efforts to enhance cost-effectiveness [13].

The economic viability of MHS-based systems within microgrids is heavily influenced by design optimization, precise component sizing, and the associated costs of deployment. These factors underscore the critical need for comprehensive studies that can reveal strategies for reducing costs and enhancing system efficiency. Such research can play a pivotal role in making MHS-based solutions more competitive, positioning them as viable alternatives for sustainable microgrid applications. Optimizing these parameters facilitates the integration of MHS technology into RES systems, thereby advancing broader goals of energy resilience and decarbonization.

To this end, this study assesses the techno-economic feasibility of off-grid electrification in the building sector using a PV-driven hybrid BESS-MHS system, targeting net-zero energy operation. Optimal component sizing of the hybrid system is investigated through a statistical optimization framework. A coupled EnergyPlus-TRNSYS model is developed to assess the system's dynamic performance in detail. Following optimization, a techno-economic analysis is conducted to highlight the advantages and limitations of the proposed solution.

## 2. METHODOLOGY

Targeting off-grid electrification, this study proposes an ESS powered by PV panels, featuring a hybrid BESS-MHS configuration. The primary components of this hybrid system include PV solar panels, a water electrolysis unit, an MHS tank with integrated heating/cooling, a fuel cell unit, BESS, inverters and converters, and a master control unit for energy distribution management. Figure 1 provides a schematic of the proposed hybrid system, detailing the connections between key components for efficient power generation and energy storage.

The building under study is located in the Mediterranean region of Apulia, Italy, and is classified within the Cfa climate zone as per the Köppen climate classification system [14], corresponding to Zone 5A in the ASHRAE climate zones [15]. The 3D model of the office building under study is generated using the OpenStudio-EnergyPlus plugin to simulate the building hourly load. This model incorporates the thermophysical characteristics of the envelope as well as data regarding the internal activities within the office. The building technical features are designed according to the ANSI/ASHRAE/IES Standard 90.1 specifications [16]. Furthermore, the thermal transmittance from the building envelope, as well as the windows (U-value), are regarded following the limited allowable values prescribed by the national regulations for new buildings in Italy (climate zone C) [17].

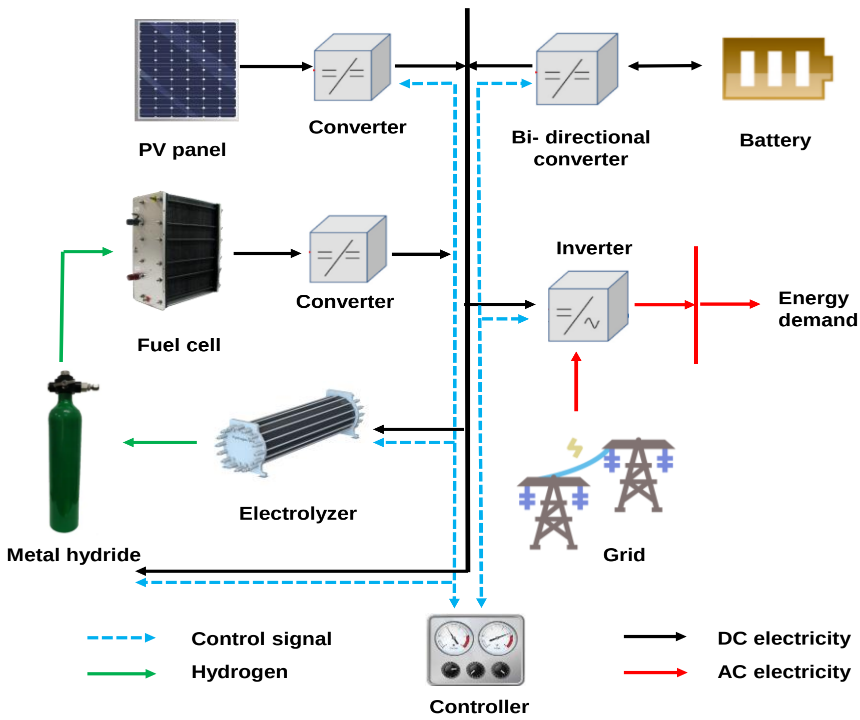


**Figure 1.** Schematic of the proposed hybrid system

Using simulated load, a dynamic simulation model is established in TRNSYS to address the transient comportment of the hybrid system during one-year operation. In the dynamic simulation model, the master control unit acts as a central component, overseeing the interaction between various system elements. This involves managing the charge status of both the hydrogen storage systems and the BESS, as well as controlling the activation of the fuel cell and electrolyzer. A Fortran code is developed and integrated into the TRNSYS library to serve as the MHS component, enabling dynamic simulations of the hydrogen storage unit during its absorption and desorption processes. Magnesium hydride ($MgH_2$) is chosen as the hydride for hydrogen storage which is considered one of the most promising options because of its cycling stability, abundance, and non-toxic properties [18]. Additional details on the dynamic simulation model and MHS characteristics can be found in [19].

An optimization framework is developed to enable optimal sizing of the hybrid system components for achieving the off-grid electrification objective. The optimization strategy employs the Response Surface Methodology (RSM), a statistical technique that identifies the optimal combination of variables by evaluating the collective impact of multiple factors on system responses. The process begins with a Design of Experiments (DoE) approach, which minimizes the number of required experiments and identifies interactions among variables [20]. Each experiment includes controllable independent variables, known as factors, with their specific quantities or magnitudes defined as levels. In the present study, this process involves considering five key design factors: the PV cells surface, the rated power of the electrolyzer and fuel cell, the size of the metal hydride storage, and the energy capacity of the BESS.

Following the specified DoEs, a series of dynamic simulations are performed in TRNSYS. The RSM approach, utilizing the central composite design, analyzes the interactions among design variables and their impact on the response factor, specifically the required electricity from the grid. The response surface quadratic model is refined through analysis of variance to find the best-fit regression, leading to the identification of the optimal combination of design variables for the objective. Finally, a techno-economic analysis of the optimal solution is conducted using the metrics defined in detail in study of Abdolmaleki et al. [21]. Figure 2 shows details of the procedural steps followed in the present study.

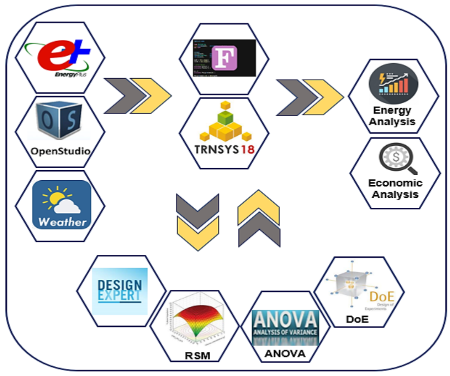


**Figure 2.** The procedural steps performed in the present study

## 3. RESULTS

Figure 3 (a and b) depicts the daily building load and PV energy output for a typical winter (a) and summer day (b). Based on Figure 3 (a), the PV system during the winter day falls short of meeting the building load requirements throughout the entire day. The PV system covers only 23.5% of the building load, leaving a deficit of 82.5 kWh of additional energy needed to fulfill the building demand. On the other hand, Figure 3 (b) shows that during summer, particularly between 11:00 and 16:00, the power generated by the PV system can fulfill the energy demands of the building. Notably, during this period, there is an excess of energy production by the PV system, amounting to 40.4 kWh. However, outside of this timespan, the PV output falls short of meeting the entire load demand of the building.

The PV system meets less than 25% of the building's load, resulting in a deficit of about 85 kWh to fully satisfy demand. In contrast, as shown in Figure 3 (b), the PV system generates sufficient power to meet the building's energy needs during the summer, particularly between 11:00 and 16:00. During this period, the PV system produces a surplus of 39.6 kWh. However, outside of these hours, PV output is insufficient to cover the building's total load requirements.

The results in Figure 3 highlight the critical need for integrating an efficient ESS into the building to achieve off-grid electrification. It is important to note that the PV power output reported here is based on a preliminary sizing of 40 PV panels. Additionally, simulation results show that the building under study requires an annual electricity demand of 31.7 MWh, resulting in $CO_2$ emissions of 11.8 tons per year.

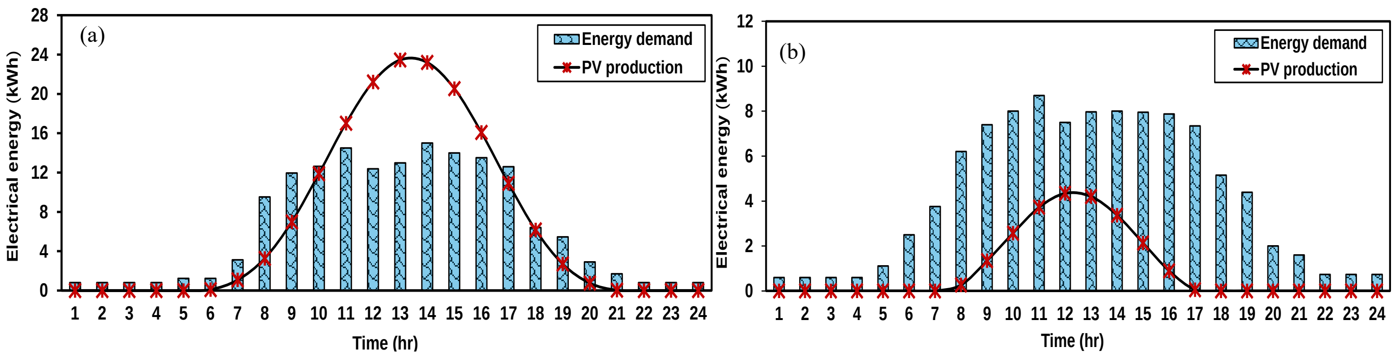


**Figure 3.** Daily building load and PV energy output for a typical winter (a) and summer day (b)

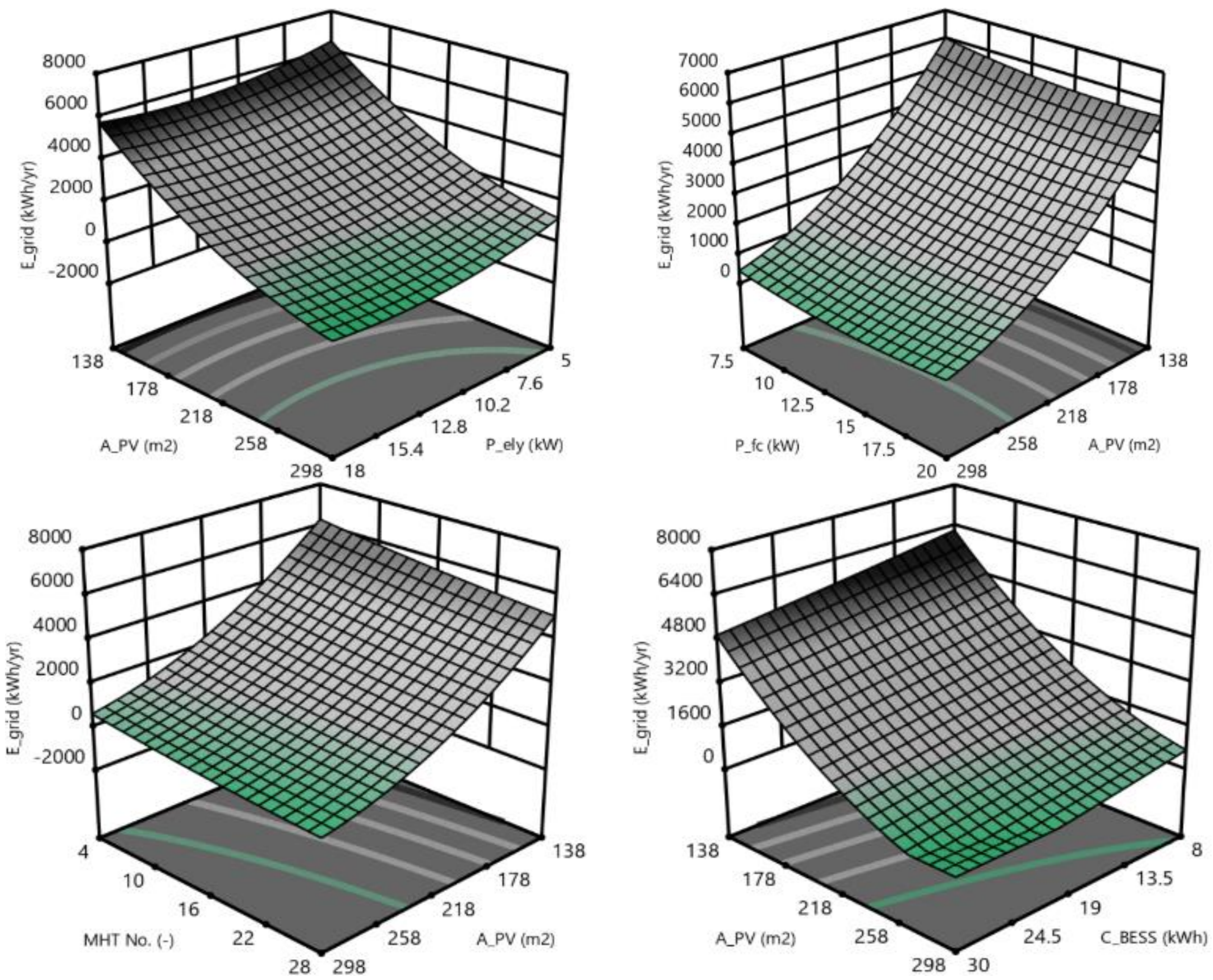


**Figure 4.** The interactions of design variables on the response factor

According to the specified DoEs, a series of dynamic simulations have been performed in order to obtain the optimal sizing of the hybrid systems components. Figure 4 illustrates the interactions of design variables on the response factor, namely required energy from the grid ($E_{grid}$). For the sake of brevity, only interactions of the PV surface with the second design factor are presented here. The figure demonstrates a distinctive behavior of the response function towards changes in each design factor, indicating the importance of the optimization of conflictive design variables, namely, the optimum sizing of components. To achieve the net-zero energy target, the optimization algorithm identifies the most efficient combination of design variables at the highest desirability, maximizing techno-economic feasibility of hybrid system.

To showcase the level of hydrogen produced in the off-grid scenario, Figure 4 depicts the hourly hydrogen production rate in kg/hr over one year. Figure 5 shows that the hydrogen production rate reaches its peak between April and August, whereas the lowest production rate is observed during the winter period; the maximum annual production rate reaches 0.38 kg/hr. The elaboration of the results indicates that the mean hourly production rate over one year is equal to 0.037 kg/hr. In addition, the total annual hydrogen production within this design exceeds 326 kg/yr.

To demonstrate the performance of another ESS in the hybrid system, namely, the BESS, Figure 6 compares the monthly-averaged values of state-of-charge (SOC). The reported monthly values of the SOC represent the mean hourly value for each month. The figure demonstrates a pseudo-parabolic variation, with notable differences in the monthly SOC values. The lowest mean SOC occurs in December, while July shows the highest value of 0.79, which can be attributed to the greater availability of excess PV energy during the summer period.

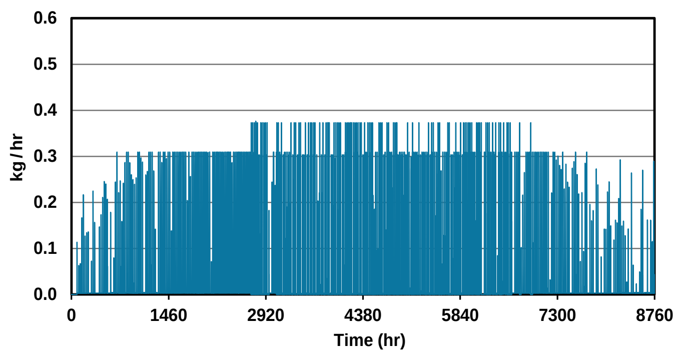


**Figure 5.** The hydrogen production rate for the optimal scenario (net-zero) over one year

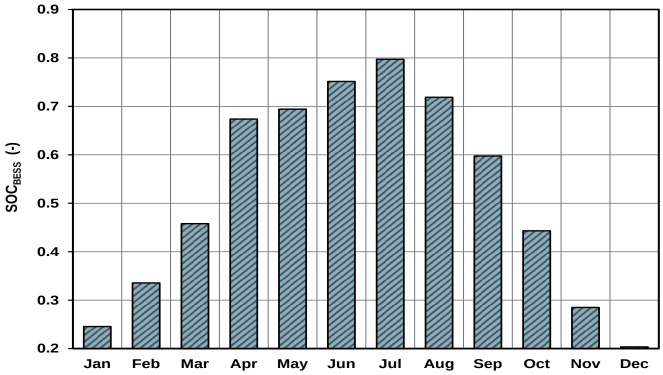


**Figure 6.** Comparison of the monthly mean SOC of BESS

To address the composition of electrification by source, Figure 7 compares the share of end-use electricity supply by each system. The end-use electricity supply consists of either direct PV use or through backup energy systems, namely hydrogen storage via fuel cell and electrical storage (battery). The figure shows that the share of direct PV electricity supply is about 59% corresponding to 18.7 MWh. Regarding ESSs, the results indicate that while the share of fuel cell is slightly higher than 23%, the BESS supplies 17.7% of the total required electricity, corresponding to 5.6 MWh. However, it should be noted that this composition is significantly dependent upon the sizing of the hybrid storage system.

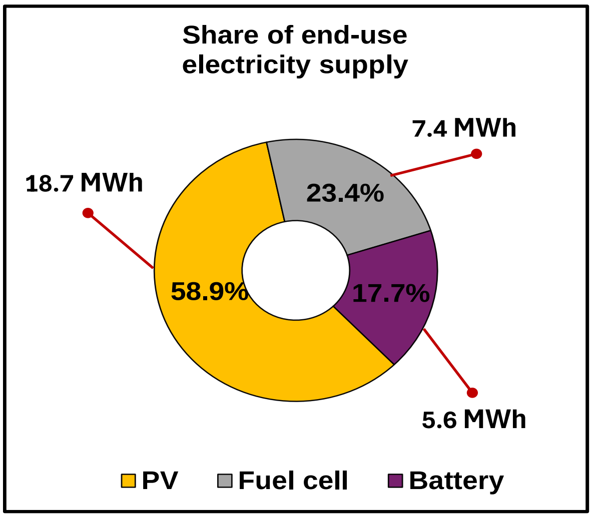


**Figure 7.** Comparison of the share of end-use electricity supply by each system

To provide an insight into the economical aspect of the off-grid solution, Table 1 reports data on the initial cost ($C_{in}$), operating cost ($C_{op}$), life cycle cost (LCC), levelized cost of electricity (LCOE), and levelized cost of hydrogen (LCOH). The table implies that the initial cost of the hybrid system comprises more than 60% of the LCC in a 20-year lifetime, implying a rather high initial cost of the system which is mainly due to the MHS equipment. Moreover, it can be observed that the operating cost is about 5% of the initial investment.

In terms of the LCOE, the obtained result falls within the range reported in the literature for integrated BESS and hydrogen (high-pressure tank) storage systems in PV-driven hybrid systems, specifically between 0.080 and 0.700 $/kWh, depending on the application and design. However, there is limited data available in the literature on PV-driven MHS-based hybrid systems for similar applications.

**Table 1.** Summary of the techno-economic analysis for the proposed hybrid system

| $C_{in}$ ($) | $C_{op}$ ($) | LCC ($) | LCOE ($/kWh) | LCOH ($/kg) |
|---|---|---|---|---|
| 158,837 | 7,942 | 263,533 | 0.379 | 6.14 |

## 4. CONCLUSIONS

This study focused on the techno-economic feasibility analysis of a hybrid hydrogen-based energy system for off-grid electrification. The proposed hybrid PV-driven system incorporated an energy storage solution combining solid-state hydrogen storage (MHS) and BESS. A coupled EnergyPlus-TRNSYS model was developed to simulate the hybrid system and assess the interactions between its components. The optimization model facilitated trade-offs between conflicting design variables and enabled the efficient sizing of system components.

The obtained results showed that while the share of direct PV electricity supply is 58.9%, the MHS and BESS account for 23.4% and 17.7% of the end-use electricity, corresponding to 7.4 and 5.6 MWh, respectively. It was found that the total annual hydrogen production within this hybrid system exceeds 320 kg/yr. Additionally, the mean values of the SOC demonstrated a pseudo-parabolic variation, with notable differences between months.

Economic analysis of the proposed system revealed LCOE and LCOH values of 0.379 $/kWh and 6.14 $/kg, respectively. Elaboration of the results highlighted the high sensitivity of the techno-economic outcomes to the optimal combinations of hybrid system components. Future work will focus on further examining optimal off-grid solutions, considering varying significance levels of design factors (and desirability) and their impact on the techno-economic metrics.


## ACKNOWLEDGMENT

The authors acknowledge the support of the following projects: PRIN PNRR 2022 NETPLUS - Neighborhood Energy Transition: towards Positive energy balance and carbon neUtral diStricts; Partenariato NEST - Network 4 Energy Sustainable Transition, MUR – M4C2; and PNRR Sustainable Mobility Center (MOST - CN00000023).


## REFERENCES


[1] The Paris Agreement | UNFCCC. (2015). https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[2] Ozkan, O., Ewede, B.S., Usman, O. (2024). Assessing the impact of resource efficiency, renewable energy R&D spending, and green technologies on environmental sustainability in Germany: Evidence from a Wavelet Quantile-on-Quantile Regression. Journal of Cleaner Production, 450: 141992. https://doi.org/10.1016/j.jclepro.2024.141992

[3] Jahanbin, A., Valdiserri, P., Semprini, G. (2023). Multi-

objective study on an innovative system for domestic hot water production: A pilot building in Southern Europe. Energy and Buildings, 293: 113181. https://doi.org/10.1016/j.enbuild.2023.113181
[4] Huang, X., Li, F., Lu, L., Li, Z., Yang, X., Yan, J. (2023). Depth optimization of solidification properties of a latent heat energy storage unit under constant rotation mechanism. Energy and Buildings, 290: 113099. https://doi.org/10.1016/j.enbuild.2023.113099
[5] Hassan, Q., Algburi, S., Sameen, A.Z., Salman, H.M., Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. Results in Engineering, 20: 101621. https://doi.org/10.1016/J.RINENG.2023.101621
[6] Paul, D., Mishra, D.K., Dordi, A. (2021). Commercializing battery storage for integration of renewable energy in India: An insight to business models. International Journal of Sustainable Development and Planning, 16(4): 783-789. https://doi.org/10.18280/ijsdp.160419
[7] Song, Y., Xu, L., Li, J., Taherian, H., Zhang, Y., Liu, D., Li, Z., Hou, G. (2024). Multi-objective optimization and long-term performance evaluation of a hybrid solar-hydrogen energy system with retired electric vehicle batteries for off-grid power and heat supply. International Journal of Hydrogen Energy, 62: 867-882. https://doi.org/10.1016/j.ijhydene.2024.03.105
[8] Ghirardi, E., Brumana, G., Franchini, G., Aristolao, N., Vedovati, N. (2024). The role of hydrogen storage and electric vehicles in grid-isolated hybrid energy system with high penetration of renewable. Energy Conversion and Management, 32: 118154. https://doi.org/10.1016/j.enconman.2024.118154
[9] Khakimov, R., Moskvin, A., Zhdaneev, O. (2024). Hydrogen as a key technology for long-term & seasonal energy storage applications. International Journal of Hydrogen Energy, 68: 374-381. https://doi.org/10.1016/J.IJHYDENE.2024.04.066
[10] Nnabuife, S.G., Oko, E., Kuang, B., Bello, A., Onwualu, A.P., Oyagha, S., Whidborne, J. (2023). The prospects of hydrogen in achieving net zero emissions by 2050: A critical review. Sustainable Chemistry for Climate Action, 2: 100024. https://doi.org/10.1016/J.SCCA.2023.100024
[11] Amirthan, T., Perera, M.S.A. (2022). The role of storage systems in hydrogen economy: A review. Journal of Natural Gas Science and Engineering, 108: 104843. https://doi.org/10.1016/J.JNGSE.2022.104843
[12] Drawer, C., Lange, J., Kaltschmitt, M. (2024). Metal hydrides for hydrogen storage – Identification and evaluation of stationary and transportation applications. Journal of Energy Storage, 77: 109988. https://doi.org/10.1016/j.est.2023.109988
[13] Dong, Z., Wang, Y., Wu, H., Zhang, X., Sun, Y., Li, Y., Chang, J., He, Z., Hong, J. (2022). A design methodology of large-scale metal hydride reactor based on schematization for hydrogen storage. Journal of Energy Storage, 49: 104047. https://doi.org/10.1016/j.est.2022.104047
[14] Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15(3): 259-263. https://doi.org/10.1127/0941-2948/2006/0130
[15] Climatic data for building design standards - ASHRAE Standard. (2013). https://xp20.ashrae.org/standard169/169_2013_a_20201012.pdf.
[16] ANSI/ASHRAE/IES 90.1-2022: Energy Standard for Buildings. (2022). https://blog.ansi.org/ansi-ashrae-ies-90-1-2022-energy-standard/.
[17] Governo della Repubblica Italiana. Decreto interministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici. Gazz. Uffciale della Repubb. (2015). https://www.mise.gov.it/images/stories/normativa/DM_requisiti_minimi.pdf.
[18] Sadhasivam, T., Kim, H.T., Jung, S., Roh, S.H., Park, J.H., Jung, H.Y. (2017). Dimensional effects of nanostructured Mg/MgH2 for hydrogen storage applications: A review. Renewebale and Sustainable Energy Reviews, 72: 523-534. https://doi.org/10.1016/j.rser.2017.01.107
[19] Jahanbin, A., Abdolmaleki, L., Berardi, U. (2024). Techno-economic feasibility of integrating hybrid battery-hydrogen energy storage system into an academic building. Energy Conversion and Management, 309: 118445. https://doi.org/10.1016/j.enconman.2024.118445
[20] Sinaei Nobandegani, M., Sardashti Birjandi, M.R., Darbandi, T., Khalilipour, T.T., Shahraki, F., Mohebbi-Kalhori, D. (2016). An industrial steam methane reformer optimization using response surface methodology. Natural Gas Science and Engineering, 36: 540-549. https://doi.org/10.1016/J.JNGSE.2016.10.031
[21] Abdolmaleki, L., Jahanbin, A., Berardi, U. (2024). Net-zero energy management through multi-criteria optimizations of a hybrid solar-hydrogen energy system for a laboratory in Toronto, Canada. Energy and Buildings, 312: 114186. https://doi.org/10.1016/j.enbuild.2024.114186

## NOMENCLATURE

| | |
|---|---|
| $A_{PV}$ | PV surface area, m$^2$ |
| $C_{BESS}$ | BESS energy capacity, kWh |
| $C_{in}$ | Initial investment cost, $ |
| $C_{op}$ | Operating cost, $ |
| $E_{grid}$ | Electricity from grid, kWh |
| LCC | Life cycle cost, $ |
| LCOE | Levelized cost of electricity, $/kWh |
| LCOH | Levelized cost of hydrogen, $/kg |
| *MHT No.* | Number of metal hydride tanks, - |
| $P_{ely}$ | Electrolyzer rated power, kW |
| $P_{fc}$ | Fuel cell rated power, kW |
| SOC$_{BESS}$ | State of charge of BESS, - |