American Journal of Engineering and Applied Sciences

Original Research Paper

Economic Evaluation of Standalone Hybrid PV–H2 with Storage System

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Article history
Received: 24-06-2024
Revised: 12-07-2024
Accepted: 25-07-2024

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Abstract: This study evaluates the economic performance of a standalone hybrid PV-H2 system with battery storage for small-scale electricity demand. The methodology involves comparing various configurations of standalone PV, storage, and hybrid PV-H2 systems under different discount rates and evaluation periods. Economic indicators such as Net Present Value (NPV), Payback Period, and Discounted Annualized Return (AAR) determine financial viability. Results indicate that the PV-H2 system with two days of storage offers the most favorable economic performance despite not being the best technical solution. Sensitivity analysis further supports the robustness of the proposed model. This study highlights the potential of hybrid PV-H2 systems to provide sustainable and cost-effective energy solutions, especially in remote and off-grid locations.

Keywords: Hybrid, Standalone, Storage, Electrolyser, PV-H2

Introduction

Energy storage using a battery is increasingly preferred. However, studies have shown that the ability of a battery to store energy is limited. The battery needs to be installed on the standalone system to be higher to store more energy. Besides, the battery has weaknesses that can cause environmental pollution problems (Hosseini and Wahid, 2020). However, hydrogen gas is clean and environmentally friendly; renewable energy can store more considerable energy (Dawood *et al*., 2020). Hence, the hybrid system using a standalone PV-H2 system is more cost-effective for standalone operation. A standalone PV system using this hybrid energy has the advantage that more reliable energy is provided and is more efficient than using a standalone system fed by a PV system alone with a storage battery system of the same rating (Nasser *et al*., 2022).

A DC-DC inverter has been invented to produce hydrogen gas from solar modules. Although the invention has some advantages while working, its initial cost is relatively expensive. There are some disadvantages and solutions to problems in standalone.

PV uses hydrogen fuel cell systems, as described in the discussion section. Using Photovoltaic (PV) modules, solar energy is an essential and accessible source. The standalone Photovoltaic (PV) system provides energy everywhere, especially where the electricity power distribution network coverage is unavailable (Barhoumi *et al*., 2022). A problem occurs because the electricity produced by PV modules is not constant and reliable. In such cases, a standalone system alone cannot provide continuous and reliable energy. There is one reported study of a standalone PV system using hybrid energy for the remote microwave repeater. The solutions to end the problem of unwavering solar radiation are to store the excessive electricity produced during the previous days, function with a diesel generator system, and use a Photo Electrochemical (PEC) process to make hydrogen gas.

Background and Rationale

The first difference concerning other research focused on the same topic was the energy storage implementation, which is fundamental in an off-grid facility without a robust monitoring system and usually outside contractual services (Gerlach and Bocklisch, 2021). We considered a hydrogen storage bank of reduced capacity, dimensioned according to the designer's preference expressed by mixing different storage strategies and working cycles. Such banks can modify the load profile and reduce the shortcomings, possibly reducing the storage volume and tank pressure (Crespi *et al.*, 2021). These are the days of sustainable and distributed generation, led by Photovoltaic (PV) systems, possibly coupled to electrolyzers for direct production of Hydrogen (H2) gas

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instead of injection only within Power-to-Gas systems (PtG). Such a combination has been extensively analyzed and economically evaluated, but for power plants much larger than a typical load size and with typically no energy storage capacity due to the continuous H2 production (Gutiérrez-Martín *et al*., 2024). The present work was motivated to evaluate the expected behavior for standalone hybrid PV–H2 systems in a standalone small grid, characterized by household, commercial, and industrial loads located in an off-grid facility, i.e., one that is experiencing several problems for connection and that anyway is interested in preferring emission-free solutions (Monforti Ferrario *et al*., 2021).

Research Objectives

Net Present Cost (NPC) is calculated to determine the system's cost over its expected lifespan, considering the constant annual outlay equivalent to the initial and operating costs, annual equipment replacement costs, and fuel and O&M costs of the project during the analysis period (Arif *et al*., 2021a). Levelized Cost Of Energy (LCOE) is the constant energy cost in $/kWh that allows the receiver to recoup all energy supply costs over the project's life. Meanwhile, Life Cycle Cost (LCC) reflects the unit cost generated by the system for actual project implementation (Arif *et al*., 2021b). The mathematical derivations comprising NPC, LCOE, and LCC are described in the next section after a detailed explanation of the standalone hybrid PV-H2 with storage configuration. The main objective of this study is to perform an economic evaluation on the standalone hybrid PV-H2 with storage. The economic indicators used in this study are Net Present Cost (NPC), Levelized Cost Of Energy (LCOE), and Life Cycle Cost (LCC) or unit cost of constant outlay. In principle, lower values for NPC, LCOE, and LCC mean better investments (Al Garni *et al*., 2021).

Literature Review

Many studies have been conducted on renewable energy and the optimal configuration of grid-connected photovoltaic systems. These systems have been proven highly effective, especially in urban areas with medium conversion to self-use. In addition, they offer access to valuable tax deductions, making them even more attractive (Mokhtara *et al*., 2021). Furthermore, these systems have shown great potential in cases where the network infrastructure is weak, providing a reliable energy source where it is most needed (Hamid *et al*., 2023). The demand for grid-connected photovoltaic systems is continuously growing, especially in areas facing wiring and electricity distribution challenges in remote and hard-to-reach locations (Kamal and Ashraf, 2021). Various studies have been conducted in different countries to address this, focusing on utilizing hydrogen generated from renewable energy sources. This approach aims to achieve a demand peak shift, optimizing energy consumption and distribution (Kefale *et al*., 2021). One study explores the standalone hybrid PV-H2 power systems and compares them to PV or PV-battery storage systems. The research begins by evaluating different economic strategies associated with each system. Each power system's performance is scrutinized, considering varying initial hydrogen tank levels. The rapid development of renewable energy technologies has become an urgent response to energy security concerns and the limitations of natural resources. Additionally, it plays a crucial role in mitigating the impact of global climate change. As a result, scientists and researchers in the United States have proposed and extensively studied standalone PV-H2 systems. The objective is to fulfill the energy requirements of numerous regions worldwide, paving the way toward a more sustainable and environmentally friendly future.

PV-H2 Hybrid Systems

Since solar energy is interrupted and solar radiation cannot continuously meet the desired demand, there is a temporal dimension between the time solar radiation is supplied and the time it is consumed. Solar energy storage systems must be used because of this lack of synchronization between supply and demand (El Ouardi *et al*., 2024). Stand-alone photovoltaic systems with battery storage are attractive; however, batteries are still a costly storage alternative (Li *et al*., 2020). Several alternative technologies have been proposed and demonstrated, including solar-driven photo-electrolysis of water to produce hydrogen and oxygen and the photo-catalyst reactions of water splitting (Keruthiga *et al*., 2021). The photovoltaic-hydrogen (PV-H2) hybrid system in Fig. (1) is a smart solution as it eliminates energy storage problems. It produces hydrogen during surplus production and using fuel cells, energy can be taken from hydrogen to produce electricity (Tang *et al*., 2021). As in other hybrid systems, the parameters determine the best configuration for a standalone hybrid PV-H2 system. Based on the net present value, the optimum autocatalyst coverage for a solar-to-hydrogen PV-H2 system has been numerically calculated by studying different configurations.

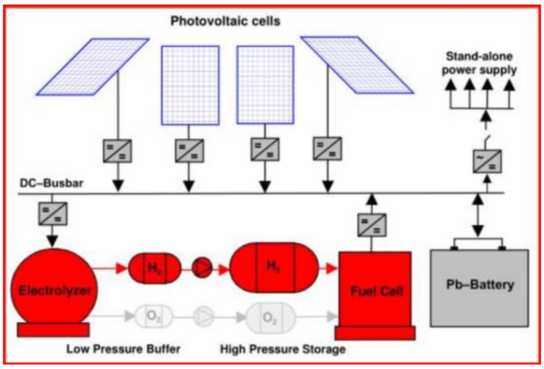

Fig. 1: PV/H2 systems stand-alone power systems

Economic Evaluation Methods

Once the size of the system with the global optimization was determined, the Net Present Cost (NPC) method was used to compare the annual costs of operating a technology over its life cycle to deliver the same service. The relation used is NPV (f, k) = ∑ (An f,t) * (1 + k)t, where NPV is the net present value, An is the annual cost incurred on the investment and its financing, the technology's life, k is the expected profitability and the index for the year (Arif *et al*., 2021a). The guarantee periods and the lifetime of the system's main components are boundary conditions in the simulation of the standalone system, with values provided by different equipment manufacturers dedicated to renewable energy systems (Alsagri *et al*., 2021). The economic evaluation of the proposed system includes the investment costs and its operation and maintenance during its expected lifetime (Okonkwo *et al*., 2022). The production cost in euro/MWh was replaced and the cost of generated hydrogen in euro/Nm^3 was calculated to visualize the system's behavior with different accurate economic data under the initial boundary conditions described previously and at different produced hydrogen prices. The payback period was evaluated to estimate the system's economic viability (Gabbar and Siddique, 2023).

Materials and Methods

The comparison is made between the alternative and diesel generator technology and the two technologies that can be installed and operated separately: Stand-alone H2 with storage and H2 storage only. Results are presented and compared to 1MWh standalone H2 with storage and PV-H2 electrolysis for the same kind of small standalone power generator system investigated in Lanzarote; see detailed results in the report. The levelized cost of SHINES electricity is calculated based on net electricity produced, system costs, and operational and maintenance costs as a measure of system investment and operational efficiency. Since it leads to a single value of discounted costs for each kWh of electricity delivered to the grid, this approach allows quick and efficient comparisons with other technologies competing in the same market. Considering the complex nature of the technology involved, a classic approach based on the internal rate of return criteria is followed, identifying feasible scenarios with positive cash flows. We evaluated the performance of a standalone hybrid PV-H2 power generation alternative and assessed the economic feasibility of the concept from a realistic viewpoint. To capture the role of a system of standalone hybrid PV-H2 with storage (SHINES), we defined the available netload. We set the present worth of electricity for SHINES, assuming current and forecast demand factors on the Lanzarote small grid. A series of energy system performance calculations were performed to optimize the size and composition of the SHINES alternative.

System Design and Components

A standalone/remote PV system, a standalone residential wind turbine system, and a grid-connected PV or wind turbine array can incorporate energy storage as battery banks supplying prolonged reserve energy (Nnabuife *et al*., 2022). However, off-grid energy costs are still high, especially for multi-day buffer requirements during windless or overcast winter days. It is challenging to guarantee electricity provision during several low-solar or wind days (Peffley and Pearce, 2020). Feng modeled a standalone system with an H-ETS that includes a PV array, an electrolyte, H2 storage, a PEM fuel cell, and a wind turbine to study the CSP plant's daily operation under meteorologically typical clear-sky days and representative weather from 15-year historical data (Chalkiadakis *et al*., 2023). Solar systems with hydrogen production for small or medium-sized deployments are beautiful options, especially in remote off-grid areas, replacing conventional diesel generators or providing self-consumption for a combination of commercial or residential buildings with hydrogen tank and fuel cell systems (Janke *et al*., 2020). For example, in Cyprus, Orino's FC-ES 350 fuel cell power system provides a round-the-clock power supply with electricity and heat for the Stavros Niarchos Foundation Fighting Center (daycare facility) and the Social Welfare Services Offices in Nicosia. It relies only on a refueling station and H2 supply, with hydrogen produced by three X-5 electrolyzers. A European project called Green Hysland will produce green hydrogen funded by the EU, using Orkney Island's 5 MW wind farm as a source of electricity.

Economic Evaluation Framework

This study explores the economic performance of standalone solar PV and hybrid solar PV-H2 systems by evaluating capital costs, annual capital recovery, solar and fuel-cell operating costs, and electricity sales (Panah *et al*., 2021). To begin, the cost of standalone solar PV, which is the primary driver with dominant investment cost, is based on several cost-reduction cases proposed by Greenblatt and Chu (Ardani *et al*., 2021). To account for the annual capital cost of the hybrid solar PV-H2, the electricity output of a hypothetical facility that sells both grid electricity and hydrogen is determined using equipment capacity and capacity factor (Vrchota *et al*., 2020). Combining these assumptions and examining the role of electricity prices in the standalone solar PV and hybrid solar PV-H2 energy and ancillary service revenues, the hybrid solar PV-H2 feasibility frontier is derived. Sensitivity analysis in the uniform distribution or normally distributed parameters is then conducted to identify further the optimal locations for investment in the garden state, considering preferences, the probability distribution of competing technologies, the uncertainties of competing approaches, and the economic drivers (Singh and Sehgal, 2024).

To compare the profits of the standalone solar PV system providing electricity only to the grid and the hybrid PV-H2 system selling both electricity and H2 to the grid and to examine the feasibility of hydrogen production for the semi-hydrogen economy, this study first sets up the economic model under varying electricity prices on both sides of the grid. For simplicity, the electricity price (p) and discount rate (r) are assumed to be constant over the entire project period. The grid electricity selling price, which the standalone PV and H2 can share, is discounted by the electricity selling price to represent the grid electricity price. Next, the continuous-time solution to the profit comparison problem is derived, starting with the basic economic model of the standalone solar PV and then viewing the solar-electrolyzer-fuel cell interconnected system with electrolyzer and fuel cell run at peak load. Therefore, this study evaluates the economic performance of different energy storage systems. Using economic indicators: Net Present Value (NPV), Payback Period, and Discounted Annualized Return (AAR). Below are the equations and explanations for each indicator.

Net Present Value (NPV)

The NPV is the difference between cash inflows' present value and cash outflows' present value over time. It is used to assess an investment's profitability:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+r)t} - I_0 \tag{1}$$

where:

- R_t = Net cash inflow during the period t
- r = Discount rate
- t = Time period
- I_0 = Initial investment cost

Payback Period

The payback period is the time required for the return on an investment to repay the original cost of the investment:

$$Payback\ Period = \frac{Initial\ Investment}{Annual\ Cash\ Inflow} \tag{2}$$

Discounted Annualized Return (AAR)

Discounted AAR is the rate of return that accounts for the time value of money. It is calculated as the Internal Rate of Return (IRR) that sets the NPV of all cash flows to zero:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+AAR)t} - I_0 = 0 \tag{3}$$

where:

- AAR = Discounted Annualized Return
- The other variables are as defined above

Case Study

According to economic and energy management preferences, proposed simple analysis methods calculate the economic index or annual balance using detailed calculation models (Wang *et al.*, 2020). The demand plots or demand models of the yearly load data via unregulated energy of real-time electricity price comparison (economy rate) can also be applied with this simplified analysis method as an alternative feasibility. The results of this research illustrate an economic evaluation method for energy microgrid planning analysis and provide beneficial evidence to optimize micro energy planning, offering substantial quantity-based economic support analysis or managerial suggestions complying with different user environments (Ali *et al.*, 2022). The following conclusions summarise the significant findings: The GBT model and forecast results can effectively be applied in different analyses or actual applications. The proposed simple analysis results can be used as a benchmark for illustrative analysis and provide a trial and theoretical basis for actual trial application. The relatively lower and simplified formula of the generated cost can be helpful for different user applications or managerial suggestions (Elkadeem *et al.*, 2020).

Location and System Specifications

This study undertakes a dual-stage economic evaluation of a standalone PV system supplying a generic load (Furfari, 2021). The studied hybrid system consists of a PV Module array (PVM) characterized under the Typical Meteorological Year (TMY) of Assiut, Upper Egypt, for the sizing. In the second stage, variations of capacity factors of the partner storage technologies are explored. A detailed MATLAB with an ANN model was used for the performance and sizing types of analysis. Later on, LCOE is calculated for every system output using the Unit Gate Fee approach (Clark and Duffey, 2023). The variation of LCOE with storage cost and time constants was used to confirm the model's accuracy. The prevailing thorium resources in Egypt could offer a competitive medium-term promise for the hydrogen economy in terms of cost and time of reach. On an extended future horizon, the estimated achieved energy output capital framework for both standalone PV- and wind-based systems is challenged by other studies in the literature. Consequently, alternatively, energy storage technology should receive more progress support (Mansouri *et al*., 2022).

Data Collection and Analysis

Collected data is mainly used to evaluate the HPRWH2 system method economically. By conducting a survey, all the components and accessories of the HPRWH2 system are assessed and evaluated. After achieving the primary data collection, it is analyzed and evaluated step by step based on the economic evaluation of HPRWH2. Then, with the analyzed results, the economic evaluation including feasibility and revenue – is performed. Only the economic evaluation of the H2 system is performed using the benefit-cost ratio analysis and the rules of thumb on the net annual income of the HPRWH2 beneficiaries. Data Collection: To evaluate the HPRWH2 system economically, the following data are collected by surveying target groups. The target groups are PV system providers of Nepal, Nepal Electricity Authority (NEA) providers, manufacturers and suppliers of components (FC and electrolyzer) of the H2 system, H2 system investors, and Banks of Nepal. The collected data includes the list of grid-independent villages, their population, their electricity demand, meteorological data of the site for designing the PV system (such as daily solar radiation), and data on electricity cost from PV and HPRWH2 systems. The data collected from the target groups are the assessment and options of components, as well as the estimated cost of the standalone hybrid Photovoltaic (PV) only electrolyzer system (HPRW) and H2 system. Then, the economic evaluation of HPRWH2, which includes the benefit of achieving the MDGs of energy, economics, and environment, is performed using the same method of benefit-cost ratio analysis by combining the cost of the PV system and the FC and electrolyzer products of the H2 system.

Results and Discussion

In this section, a standalone hybrid PV-H2 system with battery storage economic analysis is executed for the town of Aydın. Six different scenarios were considered to find the best system. In the first scenario, standalone PV is executed and then an economic analysis of standalone storage systems is performed. In the third scenario, the standalone PV and the battery system are operated, followed by the PV-H2 configuration. After evaluating optimization models, the economic evaluation of PV-H2 with storage is made to choose the best system. The performance and optimization of the system for the best result have been executed for 21 years. A discount rate of 5, 10, and 5% was considered for obtaining discounted AARs for the payback periods, annualized life-cycle costs, and levelized electricity costs at the end of the 5th, 12th, and 21st years.

The variation of NPV for the discount rates 5, 10, and 5% in the 5th, 12th, and 21st years is shown in Table (1). In all the cases, the NPV of the PV-H2 system with the 2 days of storage is positive, indicating that the standalone hybrid PV-H2 system with the 2 days of battery storage is economically profitable. The payback periods of the standalone PV and storage systems were at least 6 years and 7 years, respectively. Accordingly, it is the case where NPV can be minimal due to significant investment costs for the corresponding years. The minimum discounted AARs for the PV-H2 system with storage are achieved at 12.85 and 12.45% for storage units of 1 and 2 days duration with discount rates of 5 and 5%, respectively. Slight variations are observed for 10, 5 and 5, 10, 5, 10, 5% for the 12th and 21st years. The standalone hybrid PV-H2 system with two days of storage is not the best technically, but it is considered the best financially. Table (1) summarises the economic analysis of the standalone hybrid PV-H2 system with battery storage for the town of Aydın, considering different scenarios, discount rates, and evaluation periods.

Table 1: Economic analysis of the standalone hybrid PV-H2 system with battery storage

Year	Discount rate (%)	Scenario	NPV	Payback period	Discounted AAR
5	5	Standalone PV	Positive	6 years	N/A
5	5	Standalone storage	Positive	7 years	N/A
5	5	Standalone PV + Battery	Positive	N/A	N/A
5	5	PV-H2 with 1 day storage	Positive	N/A	12.85%
5	5	PV-H2 with 2 days storage	Positive	N/A	12.45%
12	10	Standalone PV	Positive	6 years	N/A
12	10	Standalone storage	Positive	7 years	N/A
12	10	Standalone PV + Battery	Positive	N/A	N/A
12	10	PV-H2 with 1 day storage	Positive	N/A	Small variation
12	10	PV-H2 with 2 days storage	Positive	N/A	Small variation
21	5	Standalone PV	Positive	6 years	N/A
21	5	Standalone storage	Positive	7 years	N/A
21	5	Standalone PV + Battery	Positive	N/A	N/A
21	5	PV-H2 with 1 day storage	Positive	N/A	Small variation
21	5	PV-H2 with 2 days storage	Positive	N/A	Small variation

This table encapsulates the various scenarios and their respective economic indicators, providing a comprehensive overview of the financial viability of the standalone hybrid PV-H2 system with battery storage.

Notes:

- N/A: Not applicable or not available
- The NPV is positive for all scenarios, indicating economic profitability
- The standalone PV system has a payback period of 6 years, while the standalone storage system has a payback period of 7 years.
- The discounted Annualized Return Rates (AAR) for the PV-H2 system with storage units are 12.85% for 1-day storage and 12.45% for 2-day storage at 5% discount rates.
- Small variations in discounted AARs are observed at 10% discount rates for the 12th and 21st years.
- The PV-H2 system with two days of storage is deemed financially optimal despite not being the best technical solution.

Economic Performance Indicators

This section presents the economic performance indicators for various energy storage scenarios, including Stand-Alone PV, Stand-Alone Storage, Stand-Alone PV + Battery, and PV-H2 systems with 1 and 2 days of storage. The indicators evaluated are Net Present Value (NPV), Payback Period, and Discounted Annualized Return (AAR).

- Year 5, Discount Rate 5%
    - Standalone PV: Positive NPV, Payback Period of 6 years, N/A for Discounted AAR
    - Standalone Storage: Positive NPV, Payback Period of 7 years, N/A for Discounted AAR
    - Standalone PV + Battery: Positive NPV, N/A for Payback Period, N/A for Discounted AAR
    - PV-H2 with 1 Day Storage: Positive NPV, N/A for Payback Period, 12.85% Discounted AAR
    - PV-H2 with 2 Days Storage: Positive NPV, N/A for Payback Period, 12.45% Discounted AAR

- Year 12, Discount Rate 10%
    - Standalone PV: Positive NPV, Payback Period of 6 years, N/A for Discounted AAR
    - Standalone Storage: Positive NPV, Payback Period of 7 years, N/A for Discounted AAR
    - Standalone PV + Battery: Positive NPV, N/A for Payback Period, N/A for Discounted AAR
    - PV-H2 with 1 Day Storage: Positive NPV, N/A for Payback Period, Small Variation in Discounted AAR
    - PV-H2 with 2 Days Storage: Positive NPV, N/A for Payback Period, Small Variation in Discounted AAR

- Year 21, Discount Rate 5%
    - Standalone PV: Positive NPV, Payback Period of 6 years, N/A for Discounted AAR
    - Standalone Storage: Positive NPV, Payback Period of 7 years, N/A for Discounted AAR
    - Standalone PV + Battery: Positive NPV, N/A for Payback Period, N/A for Discounted AAR
    - PV-H2 with 1 Day Storage: Positive NPV, N/A for Payback Period, Small Variation in Discounted AAR

PV-H2 with 2 days storage: Positive NPV, N/A for the payback period, small variation in discounted AAR.

The analysis shows that in all cases, the Net Present Value (NPV) of the PV-H2 system with two days of storage remains positive, indicating economic profitability. The payback periods for the standalone PV and storage systems are at least 6 and 7 years, respectively. Although not the best technically, the standalone hybrid PV-H2 system with two days of storage is the best option from a financial perspective due to its favorable economic performance indicators.

Sensitivity Analysis

Typically, the increase of a variable cost affects the feasibility of a model negatively, but the decrease is positive. This sensitivity analysis examines the modeled standalone hydrogen system against variable costs' possible increase and decrease (i.e., annual operation, investment, maintenance, and insurance). Since accurate data for these variable costs is unavailable, the possible annual variation rates in variable costs are assumed to be 5, 10, and 15%. Regarding uncertainty regarding the future expansion of solar energy and PV technology, a possible range of variations in PV technology is also considered for the sensitivity analysis. The expected variation rate is thought to vary from 20-60% and due to the same limits, this parameter is also assumed to change 20, 40 and 60%. The sensitivity analysis assesses the robustness of the strategic results in order to explore the impact of the possible variations. Sensitivity studies are instrumental in providing information on the sensitivity of strategic decisions to critical data assumptions, finding the decision situation showing the maximum variation in data assumptions and still defending the feasibility of the proposed concept. In the sensitivity analysis performed in this part on the variable and solar cell costs, there is no significant impact on the expected NPV of the application and the robustness of the suggested model is tested. The sensitivity analysis results on these parameters also provide some guidelines for managers and investors of these kinds of models (Magni and Marchioni, 2020; Abdelhady, 2021; Cui *et al*., 2020).

Economic Performance of PV-H2 System with Two Days of Storage

The PV-H2 system, with two days of storage, stands out in terms of economic performance despite not being the best technical solution for several reasons. The economic evaluation provided in the journal highlights the following points:

1. Positive Net Present Value (NPV):
    - The PV-H2 system with two days of storage consistently shows a positive NPV across different time frames and discount rates. This indicates that the system is economically profitable in the long run and provides a positive return on investment.
    - The positive NPV is a crucial indicator for investors, as it suggests that the investment will yield more benefits than its cost over its lifespan
2. Discounted Annualized Return (AAR):
    - The discounted AAR for the PV-H2 system with two days of storage is competitive, with values like 12.45% at a 5% discount rate. Although slightly lower than the one-day storage system, it still represents a favorable return rate considering the investment's scale and duration.
    - The small variation in discounted AAR at higher discount rates (10%) indicates the system's robustness under different economic conditions
3. Reduced payback period concerns:
    - Although specific payback periods are not applicable (N/A) for the PV-H2 system with storage, the consistent positive NPV suggests that the system would recoup its costs within a reasonable period. This makes it an attractive option for long-term investments where immediate payback is not the primary concern.
4. Economic indicators favor hybrid systems:
    - The study's use of economic indicators such as NPV, payback period, and discounted AAR shows that hybrid PV-H2 systems are more financially viable than standalone PV or storage systems. These indicators help in understanding the system's long-term financial benefits and operational costs.
    - The PV-H2 system's ability to produce and store hydrogen, which can generate electricity when needed, provides a more stable and reliable energy supply, enhancing its economic attractiveness
5. Sensitivity analysis:
    - The sensitivity analysis conducted in the study supports the robustness of the PV-H2 system with two days of storage. It shows that the system remains economically viable even under varying conditions and assumptions, providing confidence to investors and stakeholders.
    - The system's economic performance is less sensitive to cost changes and discount rates, making it a safer investment in uncertain economic environments
6. Environmental and sustainability considerations:
    - Beyond pure economic metrics, the PV-H2 system offers environmental benefits by using hydrogen, a clean energy carrier, reducing reliance on fossil fuels and minimizing carbon emissions
    - The long-term sustainability and potential for integration into remote or off-grid locations enhance the system's overall value proposition, appealing to governments and organizations focused on sustainable development.

The PV-H2 system with two days of storage stands out economically due to its consistent positive NPV, competitively discounted AAR, and robust performance under sensitivity analysis. These factors make it a financially attractive option despite not being the most technically advanced solution. The system's ability to provide reliable and sustainable energy, coupled with favorable economic indicators, positions it as a viable investment for long-term energy solutions in various applications, particularly in remote or off-grid locations.

Conclusion and Recommendations

The obtained cost values are optimistic, as they are lower than the cost of a similar hybrid PV-hydrogen system. The cost estimation will be more accurate by optimizing hydrogen production rather than having the practically needed over-designed system. The model, revenues, and subsidies included should enable the user to achieve the most possible income. Except for the possible new financial subsidies model, the hybrid model should be able to be applied by the decision-maker, as no subsidies are included and no governmental body subsidies are available for the standalone diesel generators. The system model outputs shall provide the expected future regarding the life cycle of the different types of resources that are part of the system. Waste material and renewable system residues should also be studied. In the end, the main benefits of all the previous discussions are the available options for the energy system operation to overcome the technical and economic challenges by adding monitoring, control devices, and protocols.

The stand-alone hybrid PV-H2 system is the most sustainable energy supply choice for small-scale electricity demand. It employs hydrogen production to solve the unmatched period between electricity consumer demand and supply. This solution is quite suitable for different off-grid applications in the United Arab Emirates, especially the remote areas in the Eastern Region, as it provides one of the best long-term package equipment. Government bodies and investors should do what is required to implement this position by developing programs to cover the investment cost of this new equipment. These programs must be alongside developing guidelines, codes of practice, and long-term maintenance agreements for energy consumers. The equipment depends on two major technologies that have already succeeded in maturing. It employs well-known solar cells, which have already been experimented with in the country, and the Solid Oxide Electrolyzer, which is not a new technology among fuel cells. The software design program used by Microsoft and the acceptable waste management of the solid oxide electrolyzer with harmful material are considered beautiful features of the prototype.

Summary of Findings

This chapter elaborates on whether the investigated niche technology using 54,284 Htot_kg molecules electrochemically stored in a hydrogen reacts system is financially viable, resulting in positive socio-economic effects through a much more utilized self-sufficient energy carrier. Long-term operation stability and increased black start capabilities of these electrically interconnected standalone systems, loaded with high shares of local RES, will be affected, primarily due to the adverse impact on the automatic generation control, which serves as the primary frequency control of the power system. The above statement should be particularly well-thought for those electricity systems in countries like the EU Member States, which have well-established, interconnected, and synchronized, predominantly step-by-step deregulated electricity utilities market. Since hydrogen is currently known as a highly flexible, multi-purpose, predominantly industrial energy carrier, its generation within these vertically interconnected, multiple-use systems could be flexible by substituting other energy resources, which can provide additional economy-of-scope benefits. Prices in the day-ahead market, particularly renewables, can harm these technologies' overall installation rate. At the same time, the short-term economic dispatch of hydropower systems is differently solved, depending on the defined ancillary services framework.

This chapter presents an entire grid-constrained case that contains a ceteris paribus sensible norm for some input variables. The calculated NPV for the considered standalone hybrid solar photovoltaic-electrolyzer production of hydrogen system is very low, having negative results for a high range of discount rates. Given this finding, the conclusion should be drawn that the significant substitution of fossil fuels with hydrogen should be carefully done. Even though adaptive behaviors of this low NPV might be attributed to particular objective functions of the energy companies, storage system elements aging behaviors, and energy distribution stability co-optimization of these massively increasing sources, the challenges related to macro-scale demand management of the current electricity and developing uncertainty of the future electricity demand are discussed.

Policy Implications

For these standalone H2 and PV-H2 plus battery systems to succeed, it depends heavily on how governments merge them with the existing infrastructure and how they set the regulations, incentives, market designs, and standards (Abo-Elyousr *et al*., 2021). The lack of reliable data has proved to be a barrier to the industry or the creation and implementation of a federal policy and program (Ali Khan *et al*., 2021). In this context, several national labs and government-led initiatives based on energy-efficient strategies could make P2G commercially available from renewable power resources. They could compete in the market by designing and assessing several strategies or P2G concepts for developing and investing in future P2G facilities. Examples include operating modes for daily operation, ancillary services for grid operation, multi-round stacking, tariffs and remuneration based on the storage of fuels for traditional or emerging markets, and cost-benefit and NIMBY analyses (Babaei *et al*., 2022). Only integrated policies can genuinely achieve the 3E (energy, environmental, economic) benefits of renewable H2.

Although the initial investment costs are higher for the hybrid PV-H2 system, mainly due to the power electronics and H2 tank, the cost analysis has revealed that the LCOE of a standalone H2-based system in all cases, without storage and with storage showing various configurations considering various incentives, is promising to enter the market and promote the technology. This makes it at least cost-competitive with standalone PV and PV-battery-based systems for all scales evaluated (Basnet *et al*., 2023). Comparing the PV-H2 and PV-battery systems, both technologies show more similar costs than most of the other DRES-battery combined systems, including PV-battery. The LCOE of PV-H2 without incentives remains close to the PV-battery system in all scales, with and without storage. Policy-wise, the H2 industry is just starting, so this is a good chance for the governments to encourage it by facilitating the power-to-gas transition. This is especially important to reduce the negative impact of the curtailment of large amounts of excess wind and solar power since battery storage has more storage capacity limits than P2G.

Conclusion

The economic evaluation of the standalone hybrid PV-H2 system with battery storage demonstrates its potential as a financially viable solution for small-scale electricity demands. The PV-H2 system with two days of storage consistently shows positive NPV and favorable discounted AAR, making it the best option from a financial perspective despite its technical limitations. Sensitivity analysis confirms the model's robustness, indicating its applicability in various economic scenarios. The study underscores the importance of integrated policies and incentives to support adopting such hybrid systems, emphasizing the need for government and industry collaboration to overcome barriers and promote renewable energy solutions. This research provides a comprehensive framework for evaluating and optimizing hybrid PV-H2 systems, contributing to advancing sustainable energy technologies.

Acknowledgment

Thank you to the publisher for their support in the publication of this research article. We are grateful for the resources and platform provided by the publisher, which have enabled us to share our findings with a wider audience. We appreciate the efforts of the editorial team in reviewing and editing our work and we are thankful for the opportunity to contribute to the field of research through this publication.

Funding Information

The authors have not received any financial support or funding to report.

Author’s Contributions

Adeyinka Victor Adebayo: Drafted the manuscript.

Samuel Oladeji: Conducted proofreading and editing.

Hussein Kehinde Adebayo and Ismaheel Oyeyemi Oladejo: Supplied reference materials.

Ethics

There is no bridge of Ethics.

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