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Techno-Economic Analysis of Solar Hydrogen Hybrid Systems with In-Situ and Ex-Situ Hydrogen Production Approaches in Monggis Substation, Sabah, Malaysia

Vritney Clareena, Arlinnie Bibiana Jalisa*, Nur Lyana Jasmin Adil, Abel Alfeuz, Siti Nurfadilah Jaini, Mohd Azlan Ismail*
Faculty of Engineering, Universiti Malaysia Sabah, Malaysia

***Corresponding author:** arlinniebibiana7@gmail.com, lanz_mr@ums.edu.my

The intermittency of solar photovoltaic (PV) systems poses reliability challenges for off-grid energy systems. This study explores hydrogen energy integration into PV systems via two strategies: in-situ hydrogen production using electrolysis and ex-situ hydrogen supply through periodic external delivery. Three system configurations, base PV-battery, in-situ hydrogen, and ex-situ hydrogen systems, were modelled and simulated using HOMER Pro to evaluate their technical and economic performance. Component sizing was based on local solar potential and load data. Both hydrogen-based systems eliminated unmet electric load and improved battery performance by reducing deep discharges. The in-situ system offered greater energy independence but incurred high capital expenditure (CAPEX) (USD 57,369.75), net present cost (NPC) (USD 101,367.00), and levelized cost of energy (LCOE) (USD 2.39/kWh), with an annual operating expenditure (OPEX) of USD 3403.38. In comparison, the ex-situ system reduced CAPEX by 64% (USD 20,798.25), achieved a significantly lower NPC (USD 32,740.26), and reduced LCOE to USD 0.73/kWh, with an annual OPEX of USD 1170.11. This comparative analysis demonstrates hydrogen's potential as a long-duration storage solution for off-grid renewable systems. The findings support strategic planning for rural electrification and propose the feasibility of a green hydrogen hub in Ranau, Sabah.

Keywords: solar-hydrogen hybrid system, in-situ electrolysis, ex-situ hydrogen supply, techno-economic analysis, off-grid PV system, HOMER Pro.

Introduction

Climate change has intensified the global push for sustainable energy, with solar power emerging as a key clean alternative. However, challenges such as intermittency, scalability, and cost have driven research into integrating solar with energy storage and complementary renewables (Jin et al., 2009). Conventional battery storage helps mitigate these issues but suffers from finite capacity, degradation, and high replacement costs (Moosavi et al., 2024). To address this issue, a promising way to combine the advantages of various technologies is through hybrid renewable energy systems (HRESs) (Bayrak and Bayrak, 2017). For instance, combining solar energy with hydrogen production allows excess energy to be stored as hydrogen during peak sunlight, ensuring a more reliable energy supply (Sarsah et al., 2024).

A key design factor in solar-hydrogen hybrid systems is the hydrogen sourcing method, either onsite (in-situ) electrolysis or external (ex-situ) supply, which directly affects technical reliability and economic feasibility. In-situ manufacturing increases energy independence, but it also results in efficiency losses during conversion and storage and requires a large capital expenditure (CAPEX) for electrolysers and related infrastructure (Joshua et al., 2024). Conversely, ex-situ hydrogen procurement reduces upfront costs but introduces fuel logistics challenges, recurring expenses, and dependency on market availability. While hydrogen from natural gas remains the cheapest (USD 0.50–1.70/kg), electrolysis-based hydrogen is currently more expensive (USD 3.00–8.00/kg), though costs are expected to fall to around USD 1.30/kg by 2030 in resource-rich regions due to technological progress and wider adoption (IEA, 2021). Electrolysis system costs vary, but continued innovation is expected to drive prices down, supporting the broader feasibility of hydrogen as a clean energy source.

Existing research has largely examined the technical feasibility of solar-hydrogen systems, cost projections for green hydrogen, and hybrid system optimisation (Das et al., 2020; Balabel et al., 2023). However, few studies have directly compared the techno-economic trade-offs between in-situ and ex-situ hydrogen sourcing strategies for off-grid solar-hydrogen systems in remote contexts. To address this gap, this study hypothesises that purchasing hydrogen from external suppliers is more cost-effective than producing it on-site via solar-powered electrolysis due to lower capital and operational costs. To explore this, two research questions are posed:

a What is the key techno-economic trade-offs between in-situ and ex-situ hydrogen sourcing in solar-hydrogen systems?

b How can HOMER Pro be used to model and compare the performance of both strategies?

Therefore, by contrasting in-situ hydrogen production with ex-situ hydrogen supply options, this study aims to evaluate and optimise the integration of hydrogen into off-grid solar PV systems using HOMER Pro. Following that, using techno-economic key metrics, a comparative analysis of each configuration's technical performance, cost-effectiveness, and overall feasibility is conducted. The study aims to determine the most economical and reliable configuration for supplying remote sites by quantifying these trade-offs, which would aid in the wider implementation of renewable energy systems in off-grid settings.

Methods

This study uses HOMER Pro to design and assess solar-hydrogen hybrid systems with different hydrogen sourcing strategies. The HOMER Pro is particularly suited to this study because it is widely accessible, frequently used, and offers comprehensive capabilities ranging from detailed technoeconomic analysis to advanced optimization (Nwachukwu et al., 2026). The system sizing is conducted for three configurations: a baseline PV-battery system, an in-situ hydrogen production system, and an ex-situ hydrogen supply system, based on solar resource and load data from Monggis Substation. Next, the pre-sized systems are simulated and optimised in HOMER Pro to evaluate their technical performance, including energy reliability, hydrogen utilisation, and storage behaviour. Configurations are optimised until acceptable performance is achieved. Finally, a techno-economic analysis compares the systems based on metrics such as net present cost (NPC), levelized cost of energy (LCOE), CAPEX, and operating expenditure (OPEX).

Study site and load profile

The case study was based on Monggis Substation in Ranau, Sabah, a remote, off-grid area requiring a reliable energy supply. A fixed daily electrical load profile of 9 kWh was established based on historical data, serving as the reference for system sizing and simulation.

System sizing

To meet the 9 kWh/day load with one-day autonomy, key system components were sized as follows:

PV array

Required PV capacity was calculated by factoring in peak sun hours (PSH) and system losses:

$$equired\ PV\ Capacity\ (kW) = \frac{Daily\ Load\ (kWh)}{PSH\ (h)} \times System\ loss \tag{1}$$

This yielded 2.52 kW, rounded to 3 kW to allow for degradation and standard module sizing. A 550 W monocrystalline PV module was selected, thereby requiring six modules.

Battery

$LiFePO_4$ batteries were chosen for its high efficiency compared to other types of rechargeable batteries (Hua and Syue, 2010). The required capacity was calculated considering a nominal battery voltage of 51.2 V, 95% Depth of Discharge (DoD) and 98% round-trip efficiency:

$$Battery\ Capacity\ (Ah) = \frac{Total\ energy\ consumption}{DoD \times \eta \times nominal\ battery\ voltage} \tag{2}$$

Resulting in a required capacity of 190 Ah. Since each battery has a capacity of 100 Ah at 51.2 V, two batteries were required.

Inverter

To supply a total appliance load of 2355 W with a 20% safety margin, a 5-kW inverter was selected (Micheli et al., 2024).

$$Inverter\ Size = Load \times\ (1 + Safety\ Margin)\ =\ 2826\ W \tag{3}$$

Electrolyser

An alkaline electrolyser was selected for its proven reliability and technological maturity in off-grid applications (Rahman et al., 2013; Raji and Jimoh, 2022). Following established design guidelines, an optimal sizing ratio of 57.7% of the PV capacity was adopted (Phan-Van et al., 2023). For the 3 kW PV system in this study, this corresponds to approximately 1.73 kW, which was rounded up to 2 kW to accommodate implementation practicalities and handle excess solar energy.

Fuel cell

Fuel cells were sized to match the system's annual peak load using the relation:

$$P_{FC} = P_{Annual\ Peak\ Load\ Demand} \tag{4}$$

A 2 kW PEM fuel cell was selected to ensure supply stability, slightly oversized relative to the actual peak demand of 1.34 kW (Li et al., 2023).

Hydrogen tank

To ensure one day of autonomy, the hydrogen storage requirement is calculated using:

$$Hydrogen\ Amount\ (kg) = \frac{P_{FC}\ (kW) \times t(h) \times 3600\ s}{\eta\ (\%) \times LHV(\frac{kJ}{kg})} \tag{5}$$

For a 2 kW fuel cell operating 24 h/day at 50% efficiency, the system requires 3 kg/day. Using NIST data (NIST, 2025), hydrogen at 35 MPa has a density of 24 kg/m^3, resulting in a required tank volume of 125 L.

In the ex-situ configuration, hydrogen is delivered every three months using pre-filled, purchased storage tanks. To provide sufficient autonomy between deliveries and buffer against low solar availability, the tank was upsized to 5 kg, equivalent to 48 hours of full-load fuel cell operation. A 147 L Type IV tank at 35 MPa meets this capacity (James et al., 2016).

System configurations

Three system setups were developed for comparison:

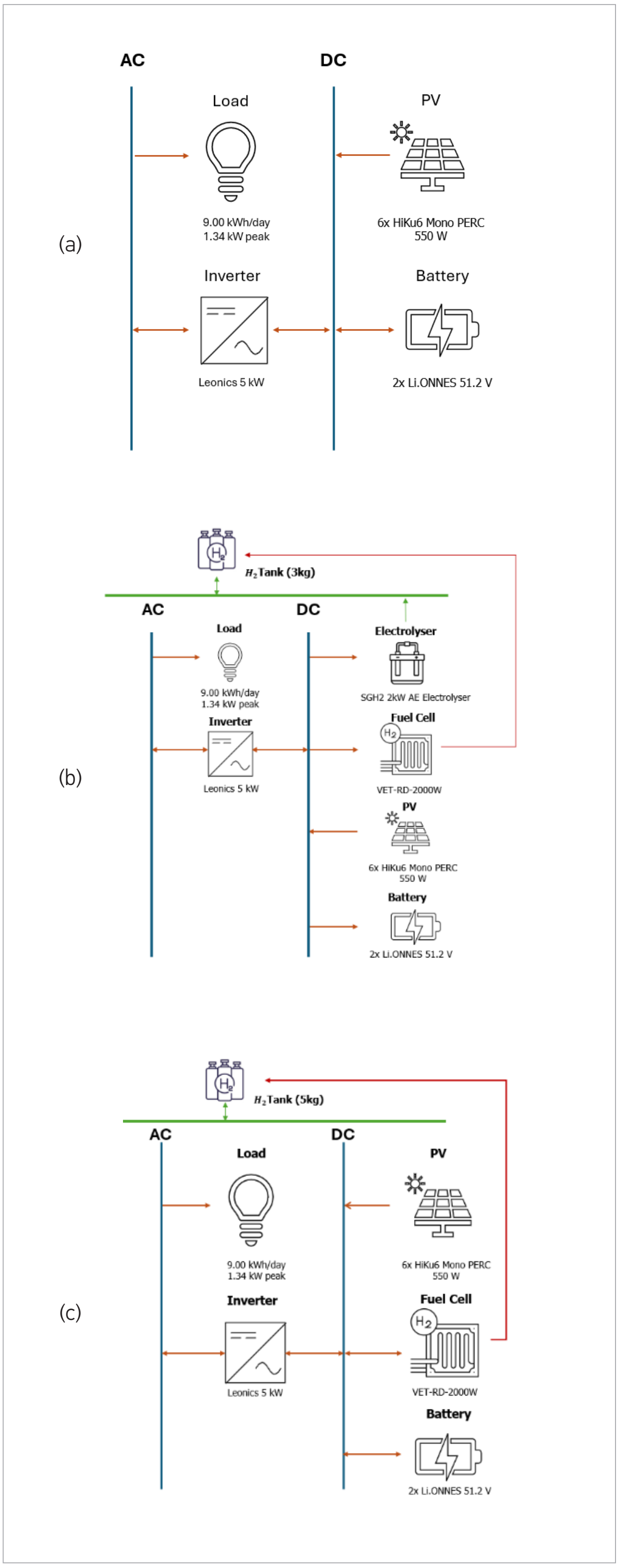
a Base PV-Battery System: PV + Battery + Inverter;
b In-Situ Hydrogen System: PV + Battery + Inverter + Electrolyser + Hydrogen Tank + Fuel Cell;
c Ex-Situ Hydrogen System: PV + Battery + Inverter + Hydrogen Tank + Fuel Cell (hydrogen delivered every 3 months).

Each configuration was designed to operate autonomously without grid support.

Results and Discussion

After establishing the system configurations and component sizing, simulation results from HOMER Pro are analysed to evaluate technical performance and

Fig. 1. *(a) System configuration of base PV-battery system (b) System configuration of in-situ hydrogen production system (c) System configuration of ex-situ hydrogen supply system*



economic feasibility. The following sections present and compare the performance of three system configurations: the baseline PV-battery system, the in-situ hydrogen system, and the ex-situ hydrogen system. Key metrics such as PV output, unmet load, excess electricity, and capacity shortage are analysed to assess system reliability and efficiency.

System performance of base PV-battery system

Table 1 summarises the annual energy flow for the Base PV-battery system.

Table 1. *Key performance metrics of the base PV-battery system*

Quantity	Value	
	kWh/yr	%
PV production	5346	100
AC primary load consumption	3223	100
Excess electricity	1963	33.5
Unmet electric load	61.6	1.88
Capacity shortage	101	3.08

Annual PV production reached 5346 kWh/yr, supplying 3223 kWh of AC load demand. Despite this, 1963 kWh/yr (33.5%) of generated energy was unused, and 61.6 kWh/yr (1.88%) of load went unmet. The battery is sized to provide one day of autonomy, but simulation results show it often reaches a high state-of-charge (SOC), suggesting underutilisation during surplus periods. Additionally, capacity shortage events totalling 101 kWh/yr (3.08%) highlight system vulnerability during low irradiance periods. Although the PV array and battery provide reliable supply during sunny periods, the occurrence of unmet load and capacity shortages indicates that additional energy storage or backup generation is necessary to maintain reliability under variable solar conditions.

System performance of In-situ hydrogen production system

The in-situ configuration integrates an electrolyser, hydrogen storage tank, and fuel cell into the baseline PV-battery system. The key performance metrics of the system can be found in *Table 2*.

Table 2. *Key performance metrics of in-situ system*

Quantity	Value	Units
Electrolyser input energy	1056	kWh/yr
Hydrogen produced	22	kg/yr
Fuel consumption	19.3	kg/yr
Excess electricity	758	kWh/yr
Unmet electric load	0	kWh/yr
Capacity shortage	0	kWh/yr

This configuration eliminated both unmet electric load and capacity shortages, improving reliability compared to the baseline. The electrolyser consumed 1056 kWh of excess PV energy to produce 22 kg/yr of hydrogen, of which 19.3 kg/yr was used by the fuel cell to generate electricity. By directing excess energy to hydrogen production, excess electricity was reduced from 1963 kWh/yr (base system) to 758 kWh/yr.

With a nearly full state at the end of the year (2.63 kg), the 3 kg hydrogen tank was adequate to meet demand, suggesting underutilisation. This configuration guarantees supply security, but it also raises the possibility of oversizing or the necessity of load variety. During low-solar periods, the fuel cell maintained system continuity by operating only when required, demonstrating the role of hydrogen storage in stabilising off-grid renewable systems.

Ex-situ hydrogen supply system

In the ex-situ setup, hydrogen delivered every three months in pre-filled 5 kg Type IV tanks and purchased from external vendors replaces the electrolyser. The system still uses the same PV-battery foundation and a 2 kW PEM fuel cell. *Table 3* presents the key performance outcomes.

Table 3. *Key performance metrics of ex-situ system*

Quantity	Value	Units
Hydrogen supplied (Annual)	20.0	kg/yr
Fuel consumption	19.5	kg/yr
Excess electricity	1814	kWh/yr
Unmet electric load	0	kWh/yr
Capacity shortage	0	kWh/yr

The system consumed 19.5 kg/yr of hydrogen to power the fuel cell during periods of solar intermittency. This approach effectively ensured zero unmet electric load and zero capacity shortage, demonstrating 100% system reliability throughout the year.

Despite this high reliability, the system recorded 1814 kWh of excess electricity since there was no mechanism to convert excess solar energy into hydrogen, as seen in the in-situ system. The absence of on-site hydrogen production simplifies system design and reduces operational complexity; however, the unused excess electricity indicates that available solar resources are not fully utilised in this configuration.

Summary

The reliability and energy performance of the three system configurations were evaluated through simulation. 0% unmet demand and 0% capacity shortage were achieved by both hydrogen-integrated systems, demonstrating how effectively they addressed reliability issues with the off-grid PV-battery system. The in-situ system demonstrated better utilisation of excess solar electricity by converting 1056 kWh of surplus energy into 22 kg/yr of green hydrogen, while the ex-situ system, despite its simplicity and operational ease, recorded a high amount of excess electricity (1814 kWh) due to lack of energy conversion capabilities.

Techno-economic analysis

While the previous section examined system reliability and energy performance, this section presents a techno-economic assessment of each configuration. To provide a realistic estimate of system costs, all base prices obtained via Ex-Works quotations are adjusted using cost uplifts that account for expenses commonly incurred during actual deployment. These include shipping, taxes, installation, and contingencies. The applied cost uplift percentages are detailed in *Table 4*.

Cost analysis

This section outlines the capital cost of major components used across all three system configurations. The prices are based on supplier quotations, manufacturer datasheets, and literature estimates, including the cost uplifts mentioned in the previous section. *Table 5* summarises the cost details of the components included in the system simulations.

Table 4. *Cost uplift assumptions for system components*

Cost Category	Description	Cost Uplift	Source
Shipping and insurance	Covers logistics and protection during transport	15%	Ramsebner et al. (2024)
Import duties and taxes	Includes customs duties, sales and services taxes (SST) and regulatory charges	10–15% (component dependent)	International Trade Administration (2024)
Installation and cabling	Labour, wiring, and on-site system integration	10–15% (component-dependent)	IRENA (2021)

Table 5. *Cost breakdown of each component in the system*

Component	Quantity	Capital cost (USD)	Replacement cost (USD)	O&M cost (USD/yr)	Lifetime (yr)	Source
PV Array	6	972.00	720.00	60.00	25	CSI Solar Co., Ltd. (n.d.)
Battery	2	2600.00	2000.00	0.00	10	Sunlight (n.d.)
Inverter	1	780.00	600.00	20.00	10	Leo Electronics Co. Ltd. (n.d.)
Electrolyser	1	39150.00	34800.00	1957.50	15	Fuel Cell Store (n.d.)
Fuel cell	1	8000.00	5000.00	200.00	10	Ningbo Miami Advanced Material Technology Co. Ltd. (n.d.)
Hydrogen tank (3 kg)	1	5867.75	3000.00	50.00	15	Shin and Ha (2023)
Hydrogen Tank (5 kg)	1	8446.25	6000.00	50.00	15	Shin and Ha (2023)
Hydrogen Supply	(22 kg/yr @ USD 10.52/kg)	-	-	205.14	-	IESR (2022; Purwanto and Rusli (2024)
Hydrogen Delivery	(Quarterly @ USD 30/trip)	-	-	120.00	-	Reddi et al. (2017)

Table 6. *Summary of NPC of in-situ hydrogen production system*

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Fuel (USD)	Salvage (USD)	Total (USD)
PV	972.00	0.00	775.65	0.00	0.00	1747.65
Hydrogen Tank (3 kg)	5867.75	1272.82	646.38	0.00	−239.56	7547.39
Inverter	780.00	530.06	258.55	0.00	−71.87	1496.74
Battery	2600.00	1766.88	0.00	0.00	−239.56	4127.32
Electrolyser	39150.00	14764.73	25305.61	0.00	−2778.87	76441.47
Fuel cell	8000.00	0.00	2581.37	0.00	−574.94	10006.43
Overall total	57369.75	18334.49	29567.56	0.00	−3904.79	101367.00

NPC analysis

This section presents a detailed NPC breakdown for both the in-situ hydrogen production system and the ex-situ hydrogen supply system, enabling a comparative evaluation of their long-term economic feasibility over a 25-year project horizon.

NPC analysis for in-situ hydrogen production system

Table 6 summarises the NPC breakdown of each component in the in-situ hydrogen production system as derived from HOMER Pro.

As shown in *Table 6*, the electrolyser is the largest cost driver in the in-situ system, contributing USD 76,441.47 to the NPC due to its high capital, replacement, and O&M expenses over a 15-year lifespan. The fuel cell and hydrogen tank also add significantly to costs, while the battery's shorter lifespan results in multiple replacements across the 25-year period. In contrast, the PV array and inverter contribute minimally due to their longevity and low maintenance.

Fig. 2 illustrates the annual distribution of discounted costs. The bulk of CAPEX occurs in year 0, dominated by the electrolyser, battery, and fuel cell. Ongoing costs are mainly due to electrolyser maintenance, with smaller contributions from other components. Replacement spikes appear in years 10, 15, and 20, with a major peak in year 15 from the electrolyser. Subsequently, year 25 reflects salvage value offsets. The chart proves the electrolyser's dominant cost impact and the economic trade-offs of in-situ hydrogen production.

NPC analysis for ex-situ hydrogen supply system

Table 7 summarises the NPC breakdown of each component in the ex-situ hydrogen supply system as derived from HOMER Pro.

Fig. 2. *Stacked bar chart of discounted annual costs by component (25-year project horizon) for in-situ system*

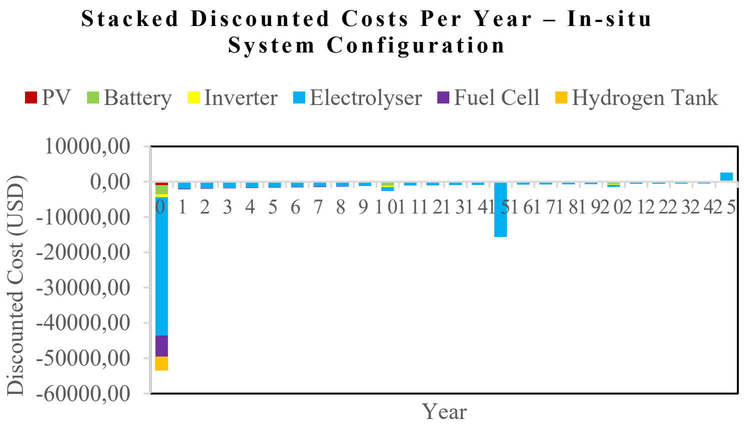


Table 7. *Summary of NPC of ex-situ hydrogen supply system*

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Fuel (USD)	Salvage (USD)	Total (USD)
PV	972.00	0.00	775.65	0.00	0.00	1747.65
Inverter	780.00	530.06	258.55	0.00	–71.87	1496.74
Battery	2600.00	1766.88	0.00	0.00	–239.56	4127.32
Fuel Cell	8000.00	0.00	2581.37	0.00	–574.94	10006.43
Hydrogen tank and delivery services	8446.25	2545.64	2,205.17	2,638.19	–473.13	15362.12
Overall total	20798.25	4842.58	5820.74	2638.19	–1,359.50	32740.26

As shown in *Table 7*, the total NPC of the ex-situ hydrogen supply system is USD 32,740.26, indicating a more cost-effective configuration compared to the in-situ system. This cost reduction is primarily attributed to the exclusion of the electrolyser, significantly lowering both capital investment and long-term O&M expenses. Instead, hydrogen is procured externally, introducing a recurring fuel cost of USD 2638.19 over the system's lifetime based on an annual consumption of 19.5 kg.

Fig. 3 illustrates the discounted NPC distribution for the ex-situ hydrogen system over 25 years. Major capital costs occur in year 0, driven by the hydrogen tank, fuel cell, and battery. Hydrogen delivery begins immediately with an upfront cost of USD 120. Annual costs are mainly due to hydrogen delivery and fuel cell maintenance, with discounted values declining over time due to the 6% discount rate. Cost spikes in years 10, 15, and 20 reflect scheduled replacements of the battery, inverter, and hydrogen tank. Year 25 includes salvage values for components with remaining life.

Comparative cost analysis

Fig. 4 presents a side-by-side comparison of the NPC distribution for the in-situ and ex-situ hydrogen systems. The electrolyser dominates the in-situ system, making up the biggest portion of its total NPC. This is the most visible distinction between the capital cost allocations. In contrast, the ex-situ system eliminates this cost, shifting the financial burden toward recurring fuel expenses and hydrogen delivery.

Fig. 3. *Stacked bar chart of discounted annual costs by component (25-year project horizon) for the ex-situ hydrogen system*

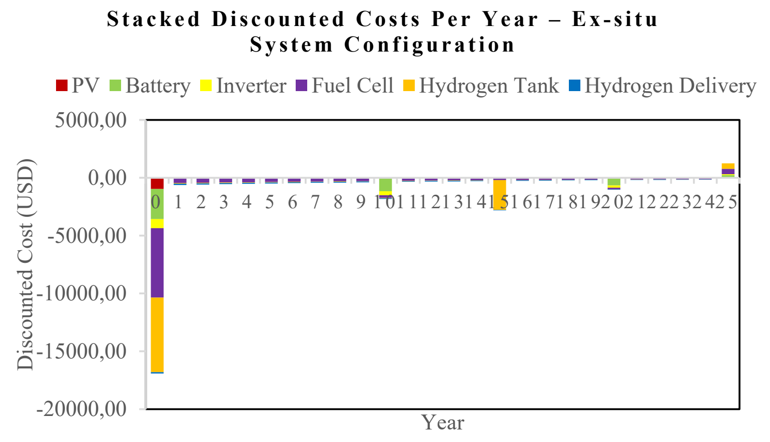


Fig. 4. *(a) Pie chart of total NPC of in-situ hydrogen system by components (b) Pie chart of total NPC of ex-situ hydrogen system by components*

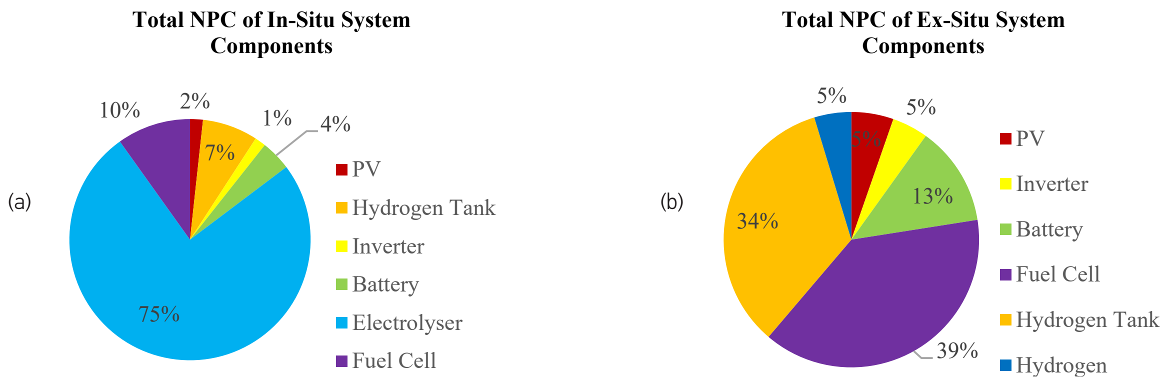


Table 8 summarises the findings for both the in-situ hydrogen production system and the ex-situ hydrogen supply system.

Table 8. *Summary of cost metrics for in-situ and ex-situ hydrogen systems*

Metric	In-situ system	Ex-situ system
CAPEX (USD)	57369.75	20798.25
NPC (USD)	101367.00	32740.26
LCOE (USD/kWh)	2.39	0.73
Operating cost (USD/yr)	3403.38	1170.11

Based on *Table 8*, the in-situ hydrogen system has a high CAPEX (USD 57,369.75), mainly due to the costly electrolyser (USD 39,150.00) and hydrogen tank. While it offers fuel autonomy by producing hydrogen on-site, its NPC reaches USD 101,367.00 with a high LCOE of USD 2.39/kWh, driven by substantial O&M costs. In contrast, the ex-situ system eliminates on-site hydrogen production, resulting in a much lower CAPEX (USD 20,798.25) and NPC (USD 32,740.26). It achieves a more favourable LCOE of USD 0.73/kWh and lower annual OPEX (USD 1170.11), mostly from hydrogen delivery and fuel cell maintenance. Overall, the ex-situ system is more cost-effective, offering lower lifecycle costs and better economic performance. While the in-situ setup provides energy independence, it remains less feasible under current cost conditions.

Conclusions

This work evaluated and compared the performance of two hydrogen-integrated systems. Both hydrogen-based systems successfully eliminated unmet load and capacity shortage, significantly improving system reliability. The in-situ system effectively utilised excess solar energy to produce hydrogen, providing energy independence but at the cost of a high NPC of USD 101,367.00 and a LCOE of USD 2.39/kWh. In contrast, the ex-situ system offered a lower NPC of USD 32,740.26 and an LCOE of USD 0.73/kWh, making it the more economically feasible option. Overall, while the in-situ system supports long-term autonomy, the ex-situ configuration emerged as the more practical and cost-effective solution for off-grid renewable energy applications.

Future studies should concentrate on enhancing system efficiency by integrating energy management systems to coordinate component functioning in real time and optimising hydrogen storage management. Subsequently, investigating fuel cell waste heat recovery may improve total energy use because a significant portion (approximately 45–60%) of the energy content of hydrogen is released as heat during fuel cell operation (Islam et al., 2015). Next, improving system sizing and dispatch techniques may lessen excess generation. Furthermore, conducting sensitivity analysis and integrating dynamic hydrogen prices would yield more reliable financial assessments. Finally, expanding this research to centralised hydrogen production hubs, such as those in solar-rich places like Ranau, could facilitate the use of green hydrogen in remote and isolated regions and encourage larger integration of renewable energy.

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