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Techno-economic and environmental evaluation of integrated microgrid systems for electrification and hydrogen production

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Abstract. The present work investigates the feasibility of electrolyzer-based hydrogen generation through a hybrid renewable energy system. Evaluations focusing on technical, economic and environmental evaluations are conducted to determine the optimized system architectures that maximize energy efficiency and environmental benefits. Three hybrid renewable energy systems were assessed, including grid-connected and grid isolated configurations of solar PV array, wind turbines (WT), hydrogen fuel cells, and backup battery bank. The lowest levelized energy cost, at 0.539 $/kWh, and the lowest cost of producing hydrogen, at 6.85 $/kg were achieved by integrating solar PV and wind turbine with the grid connectivity. Integrating Solar PV and wind turbine connected to the power supply grid resulted in the lowest levelized energy cost, at However, in the case of a grid-isolated system utilizing fuel cells or battery storage banks, the hydrogen cost rises above 8.0 $/kg due to the higher capital expenses associated with the system. With yearly carbon dioxide emissions of 240841.66 kg, the optimized system produces 111 877 kg of green hydrogen annually. Additionally, the optimized system (System 1) has the lowest Human Health Damage (HHD) and Ecosystem Damage (ESD), with its Human Development Index (HDI) slightly surpassing those of Systems 2 and 3. However, System 3 creates more jobs.

1. Introduction

Clean energy has gained popularity as a means of promoting sustainable development and lowering carbon emissions. Hydrogen is an intriguing replacement to fossil fuels, but the production process is energy-intensive and expensive. Research suggests hydrogen energy is expected to fulfil 11% of global energy requirements by 2025 and 34% by 2050 [1]. Renewable hydrogen production contains considerable ability to satisfy worldwide demands. As a result, it is critical to create economically viable and environmentally conscious techniques to produce green hydrogen, primarily using wind and solar energy sources. Several research have investigated the suitable design of hybrid PV/WT/H_2 systems [2, 3, 4, 5, 6]. Integration of

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solar and wind energy with electrolysers significantly improves hydrogen production efficiency, according to these studies. Akyuz et al. [7] investigated a hybrid system that combined photovoltaic cells and wind turbines for hydrogen production achieving 60% efficiency. Hasan and Genc [2] analyzed a hybrid renewable energy production system in Iraq that included solar PV array and wind turbines. The system's electrolyzers produced 49150 $/m^{3}H$_2$ of hydrogen annually at 0.752 $/m^{3}H$_2$, which can be reduced to 0.723 $/m^{3}H$_2$ by selling surplus energy. Okonkwo et al. [5, 6] evaluated hybrid systems for hydrogen production in Oman and Saudi Arabia, achieving economic viability by optimizing LCOH, COE, and NPC. Comprehensive studies of PV/WT based hybridized model of renewable energy systems for green hydrogen generation are presented by Alzahrani et al. [3] and Nasser et al. [8].

According to the literature, previous studies have mainly concentrated on the technical and economic analysis of hybrid renewable energy systems (HERS), focusing on their efficiency, cost-effectiveness, and hydrogen production potential while overlooking their environmental and social impacts. To fill this gap, the current study provides a comprehensive techno-economic and environmental assessment of three HERS configurations: grid connected PV/WT, grid isolated PV/WT with battery for excess energy storage, and grid isolated PV/WT integrated with hydrogen fuel cell.

2. Study Location and Weather Conditions

The Shagaya renewable energy power plant is located about 100 kilometers to the west of Kuwait City at 29.2055°N and 47.0524°E. The hybrid renewable energy system (HRES) modeling program used in this research was fed meteorological data for this area from Surface Meteorology and Solar Energy database of NASA. Average monthly temperatures, wind speeds, and levels of sunlight and irradiation of this site are shown in figure 1. . The solar radiation and wind speed distributions at the studied location clearly show a large potential for wind turbines and photovoltaic systems.

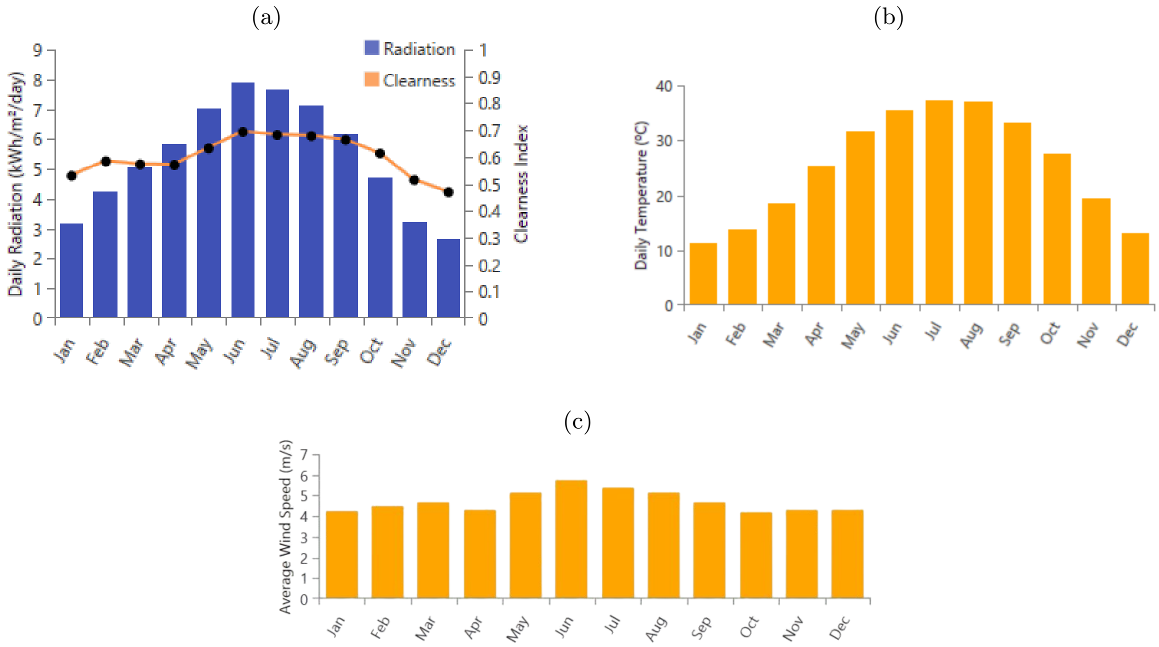

Figure 1. . Monthly average climatic variability for the study includes (a) solar irradiance and index of clearness, (b) atmospheric temperature, and (c) wind velocity.

3. Methodological Approach

The designed hybrid energy system produces 300 kg of green hydrogen per day through integrating wind power and solar energy to supply the load demand for both electricity and hydrogen. This energy is subsequently stored and used to generate electricity, which meets the demand for electrical consumption.

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Table 1. Techno-economic parameters of HRES components [10].

Photovoltaic		**Wind Turbine**	
Parameter	*Value*	*Parameter*	*Value*
Model	Generic	Model	XANT 330
Efficiency	20%	Cut-in speed	3 m/s
Capacity	1 kW	Cut-out speed	24 m/s
Capital cost	$1000/kW	Capacity	330 kW
Replacement cost	$1000/kW	Capital cost	$1200/kW
O&M cost	$10/year	Replacement cost	$1200/kW
Lifetime	25 years	O&M cost	$500/year
		Lifetime	20 years
Electrolyzer		**Hydrogen tank**	
Parameter	*Value*	*Parameter*	*Value*
Model	PEM	Capital cost	$100/kg
Efficiency	85%	Replacement cost	$100/kg
Capacity	1 kW	O&M cost	$1/year
Capital cost	$500/kW	Lifetime	25 years
Replacement cost	$400/kW		
O&M cost	$20/year		
Lifetime	15 years		
Fuel cell		**Battery, Inverter**	
Parameter	*Value*	*Parameter*	*Value*
Model	PEM	Model	Li-Ion, ABB MGS100
Efficiency	50%	Efficiency	90%, 95%
Capacity	1 kW	Capacity	1 kWh, 1 kW
Capital cost	$3000/kW	Capital cost	$550/kW, $500/kW
Replacement cost	$2500/kW	Replacement cost	$550/kW, $500/kW
O&M cost	$10/year	O&M cost	$0.01/h, $1/year
Lifetime	50000 h	Lifetime	15 years

3.1. Description of HERS Elements

The hybrid renewable energy system (HRES) examined in the current study includes solar PV arrays and wind turbines for electricity generation, an inverter, an electrolyzer, and storage solutions that use a battery and a hydrogen storage tank with a hydrogen fuel cell as a supplement. The structure of a hybrid renewable energy system significantly impacts its efficiency and electrical power generation [9]. Table 1. shows techno-economical parameters for the system components employed in this research.

4. Optimization Constraint of the System

This research utilizes the HOMER Pro system optimization software [11] to model, simulate the system architecture, optimize, and perform sensitivity studies on the examined HRES. It assesses both the installation and operating expenses of the proposed system during its operational lifespan. Input data needed for HOMER Pro optimization includes demand profiles, the availability of solar energy at the designated location, and technical and financial information about system components. The system's configuration is optimized to satisfy load demands while minimizing NPC, COE, and ensuring reliability. The software sizes electrolyzers, hydrogen storage tanks, photovoltaic cells, wind turbines (WT), battery banks, and electrical converters based on specified data in Table 1. .

4.1. System Architectures of HRES

Figure 2. shows three different HRES configurations analyzed during simulations: grid-connected PV/WT, grid-isolated PV/WT keeping battery as backup energy supplier and storage, and grid isolated PV/WT integrated with a hydrogen fuel cell. Initial setup of the HRES involves connecting solar PV panels and wind turbines to hydrogen production subsystems (electrolyzers), AC/DC power conversion subsystems (converters), hydrogen storage tanks withthe electrical grid connectivity. Figure 2. (a) illustrates how the

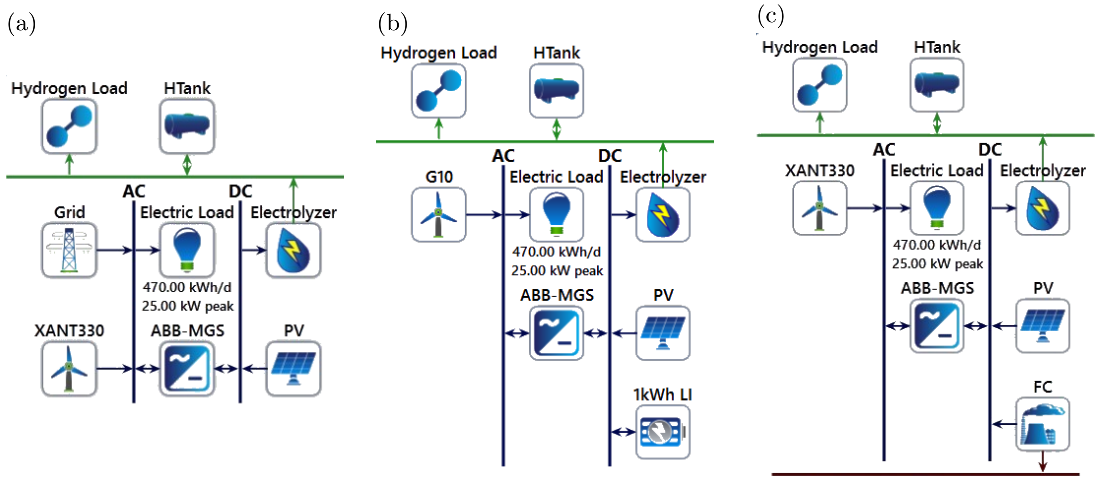

Figure 2. The layouts of hybrid energy systems for hydrogen production: (a) grid integrated PV/WT HRES variant, (b) Grid-isolated PV/WT HRES variant with battery storage, and (c) PV/WT HRES variant with hydrogen fuel cell.

PV/WT integrated HRES variant may link to the electrical supply grid and meet electrical load demands during low solar radiation or low wind velocity gradient. A key benefit of the PV/WT system with grid connectivity is the capacity to export surplus electrical power to the grid. Figure 2. (b) demonstrates the grid-isolated PV/WT HRES variant unified with battery for energy storage and backup power supply. This system runs on a decentralized basis from the traditional grid, necessitating battery storage to provide electrical power when solar and wind re- sources are insufficient. The energy generated by the solar PV array and wind turbine meet the electrical power demand, while excess power is utilized by the electrolyzer to convert into hydrogen and hydrogen tanks are used to store the hydrogen as a reliable energy storage method. The third system architecture is developed with integrated fuel cells for generating electrical power from stored hydrogen, as shown in Figure 2. (c). In scenarios where solar and wind energy are inadequate, the deficit electrical load demand is supplied by hydrogen fuel cells.

5. Performance Indicator of HRES

The Net Present Cost (NPC) over the duration of the project is determined as [12, 13]

$$\mathrm{NPC} = \frac{C_{\text{ann, tot}}}{\mathrm{CRF}(i,n)}, \tag{1}$$

$$C_{\text{ann, tot}} = C_{\text{cap}} + C_{\text{rep}} + C_{\text{O\&M}} - R_{\text{salv}}, \tag{2}$$

$$i = \frac{\acute{i} - f}{1 - f}, \tag{3}$$

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{4}$$

where $C_{\text{ann, tot}}$ (\$/year) is the total annual cost, CRF represents the capital recovery factor, i denotes the annual interest rate (%), and n refers to the lifespan of the hybrid energy system. The terms $C_{\text{ann, tot}}$, C_{rep}, $C_{\text{O\&M}}$ and R_{salv} signify the total annual cost, replacement cost, total operating and maintenance cost and salvage value, respectively. The nominal interest rate is shown as $\acute{i}$ and f represents the annual inflation rate.

The LCOE is defined as the ratio of the total annual cost (\$) to the total energy generated by the system (kWh) [14] as

$$\mathrm{LCOE} = \frac{C_{\text{ann,tot}}}{E_{\text{tot}}}. \tag{5}$$

The levelized cost of Hydrogen (LCOH) is an important paprmeter for evaluating the feasibility of an energy system. It is defined as the ratio of the total annual cost (\$) to the annual hydrogen produced (kg H_2) as [15]

$$\mathrm{LCOH} = \frac{C_{\mathrm{ann,tot}}}{M_{H_2}}, \tag{6}$$

where LCOH is the levelized cost of hydrogen M_{H_2} and M_{H_2} represents the annual hydrogen produced (kg/year).

The annual lifecycle emissions of the hybrid renewable energy system (HRES) can be determined using the following formula [16]

$$\mathrm{LCE} = \sum_{m}\sum_{i=1}^{T} \psi_m E_{m,i}, m \in \{PV, WT, BAT, FC, \mathrm{Electrolyzer}, \mathrm{Grid}\} \tag{7}$$

where ψ is the lifetime CO_2 emissions equivalent, E is the amount of energy stored or transformed while the HRES continues to meet power requirements throughout the specified period, T (8760 hours).

The human development index (HDI) can be calculated as [17]

$$\mathrm{HDI} = 0.0978 \ln\left[\frac{(E_{\mathrm{load}} + \min(f_{\mathrm{ex,\ max}} \times E_{\mathrm{ex}}, f_{\mathrm{load\ ,\ max}} \times E_{\mathrm{load}}))}{\text{Number of People}}\right] - 0.0319. \tag{8}$$

The terms E_{load} and E_{ex} represent the system's annual AC power demand and the yearly excess energy, respectively. The parameters $f_{\mathrm{ex,\ max}}$ and $f_{\mathrm{load\ ,\ max}}$ are assumed to have values of 0.2 and 0.5, respectively.

The job creation factor illustrates the potential for generating new employment opportunities within the community, correlated with the consumption of electrical power, thereby aiding in reducing unemployment in a specific region, which can be determined as [18, 19]

$$\begin{aligned} \mathrm{JC} = {} & \mathrm{JC_{PV}} \times \mathrm{P_{PV}} + \mathrm{JC_{WT}} \times \mathrm{P_{WT}} + \mathrm{JC_{Elect}} \times \mathrm{P_{Elect}} + \mathrm{JC_{FC}} \times \mathrm{P_{FC}} + \\ & \mathrm{JC_{HT}} \times \mathrm{P_{HT}} + \mathrm{JC_{BATT}} \times \mathrm{E_{BATT}}, \end{aligned} \tag{9}$$

where JC is the job quantities per MW for each components power generation P in MW.

System components substantially affect human health and the environment, due to their carbon dioxide emissions. These emissions contribute to the rise in global average temperatures and climate change, negatively impacting ecosystems and human health. Premature deaths and the reduction in healthy life years due to disabilities in a given year are quantified using disability-adjusted life years (DALYs). Ecosystem damage (ESD) is assessed in species years, representing the total species lost within a specific area over a defined period. This analysis quantifies the impact on human health and the environment at 1.40×10^{-6} DALYs per kg of CO_2 equivalent and 7.93×10^{-9} species years per kg of CO_2- eq, respectively [20].

6. Results and Discussion

6.1. System Performance and Economic Factors Analysis

The specifications, system sizing, and economic metrics for the optimal system architectures identified through modelling are summarized in Table 2. . The findings in Table 2. . reveal that the system with grid connectivity emerges as the most favorable option when considering system costs, energy costs, and hydrogen production costs. This system achieves the lowest Net Present Cost (NPC), Cost of Energy (COE), and Cost of Hydrogen (COH), establishing it as the most efficient configuration. The sizing includes 6395 kW of photovoltaic power, two wind turbines, an electrolyzer rated at 2500 kW, a hydrogen storage tank with a 3000 kg capacity, and a 337 kW inverter.

The net present cost (NPC) of this system amounts to 9.91 M, with a capital expenditure of 8.91 M. In comparison, the NPC for the standalone off-grid PV-WT systems paired with batteries and fuel cells are $11.61 million and $13.68 million, respectively. While the standalone PV-WT system integrated with batteries has a lower NPC than the one combined with fuel cells, its NPC remains higher than that of the grid-integrated PV-WT variant of HRES.

Figure 3. presents the evaluated hybrid systems' overall LCOE and LCOH. System 1 achieved an LCOE of 0.539 $/kWh and an LCOH of 6.85 $/kg. In contrast, system 3 showed the highest costs, with an LCOE of 6.18 $/kWh and an LCOH of 9.06 $/kg, just behind system 2, which had an LCOE of 5.23 $/kWh and an LCOH of 8.02/kg. Compared to local feed-in tariffs, the significantly higher LCOE of standalone hybrid systems suggests that grid-connected PV-WT systems would be more economically feasible for electricity and hydrogen generation.

Table 2. A comparative analysis of the technical and economic aspects of various system configurations.

HRES Variant	I: *grid-connected*	II: *grid-isolated*	III: *grid-isolated*
Components	PV, WT, Inverters, Electrolyzers, HTanks	PV, WT, Inverters, HTanks, Electrolyzers, Batteries	PV, WT Inverters, Electrolyzers, HTanks, FC
PV capacity	6395 kW	6432 kW	8287 kW
WT capacity	660 kW	990 kW	990 kW
Renewable energy fraction	98.4%	100%	100%
Annual hydrogen production	111 877 kg	111 905 kg	116 903 kg
Total NPC	9.91M $	11.61M $	13.68M$
Operating cost	77 659.30 $	174 342.30 $	189 798.70 $
Initial capital	8.91M $	9.36M $	11.20M $
LCOE	0.539 $/kWh	5.23 $/kWh	6.18 $/kWh
LCOH	6.85 $/kg	8.02 $/kg	9.06 $/kg

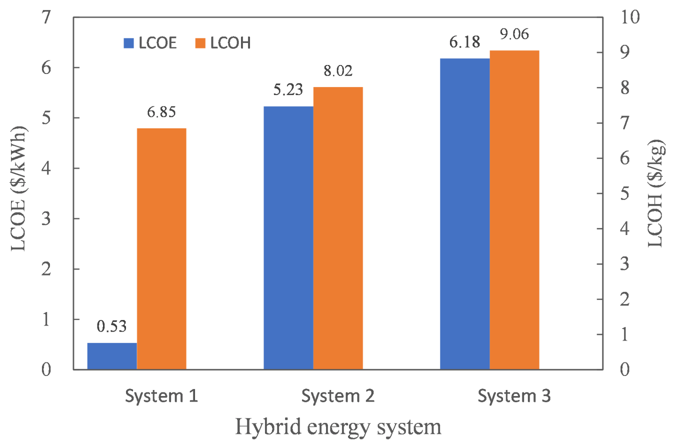

Figure 3. LCOE and LCOH for systems 1-3.

6.2. Environmental-Economic Analysis

Figure 4. compares the three configurations regarding major environmental and social factors that are responsible for extensive analysis of their wider scale performance. The HRES contains a Lifecycle Carbon Emission equivalent (LCE) expressed in kg CO_2-eq/kWh. Though the renewable energy-utilizing components do not release any CO_2 during operation, this parameter covers emissions from manufacturing, transportation, and recycling, giving a complete carbon footprint for all of its ingredients. System 1 is responsible for the LCE equivalent of 240,841.66 kg CO_2/year (PV, wind, electrolyzer and grid system components). The main reason is the offset by 285,858.85 kg CO_2/year grid emissions. Since the HRES export a higher amount of energy to the grid while importing a lesser amount, it helps to remove the carbon emission relevant to that amount of energy generated from non-renewable sources connected to the grid. That's why the LCE equivalent of net grid emission is negative for the HRES. Conversely, System 3, which combines PV, wind, electrolyzer and fuel cell, has the highest LCE of 672,735.99 kg CO_2/year, whereas System 2 stands between these two with an LCE equivalent of 536766.11 kg CO_2/year.

In terms of the environmental performance of these three systems, the lifecycle emissions evaluations indicate that there are substantial differences between them. With a per kg CO_2 cost of 0.015 [17], the annual carbon penalty from System 1 is 3,612.62, whereas system 2 emits 536,766.11 kg CO_2 per year, resulting in a charge of 8,051.49. Being the HRES that emitted the most, system 3 is charged 10,091.04 based on 672,735.99 kg CO_2 per year. The manufacturing of system components, as well as their transport and disposal, account for a significant fraction of the total environmental footprint. From the environmental viewpoint, this is critical for policy-makers and system designers who are looking for strategies to lessen environmental impact. It was also found that the total Human Health Damage (HHD) of system 1 is 0.337178 DALYs/year (Disability Adjusted Life Years per year), which is much

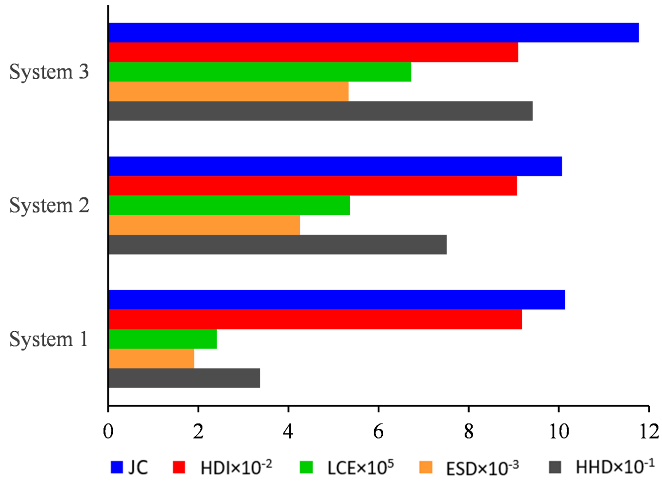

Figure 4. Socio-economic and environmental indicators for systems 1-3.

lower than reported elsewhere as in system 3 (0.941830 DALYs/year). System 1 is also extremely good for the ecosystem of the plant area, which stands out with the lowest Ecosystem Damage factor (ESD) of 0.0019099 species.yr/year, where system 2 and system C result in ESD of 0.0042566 species.yr/year 0.0053348 species.yr/year.

On the factors of the social front, all the systems score almost equally, but system 1 exhibits a slightly higher value on the Human Development Index (HDI): $1 < 2 < 3 : 0.9186 < 0.9097 < 0.9076$. System 3, however, provides the highest job creation with 11.78 jobs/year, system 1 offers the least number of 10.14 jobs/year, whereas system 2 offers 10.07 jobs/year. The results concluded that although system 1 has better environmental adaptability and social benefits, system 3 is likely also a good option for generating social benefits. Still, there is a trade-off between environmental sustainability and economic-social gain.

7. Conclusion

This research focuses on three distinct HRES configurations: grid-connected PV/WT variant, grid-isolated PV/WT variant with batteries, and grid-isolated PV/WT with hydrogen fuel cells. In that effort, several techno-economic, environmental, and social factors are considered to evaluate the three optimized systems' performance. The grid-connected configuration displays the most favorable performance, with an NPC of \$9.91 M, COE of 0.539 \$/kWh, and COH of 6.85 \$/kg. System 1 also outperforms the two off-grid systems from an environmental perspective, with the least carbon emissions at 240,841.66 kg CO_2/year and a subsequent penalty cost of \$3,612.62. A lower LCE leads to an HHD of 0.337178 DALYs/year and an ESD of 0.001909874 species. yr, which are the lowest among the three configurations. While System 3 offers higher job creation potential, System 1 remains superior in terms of economic viability, environmental sustainability, and human development, making it the most optimal choice. This work serves as a foundation for policymakers and system designers to devise an economical and sustainable approach for large-scale production of hydrogen via a grid-connected HRES.

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