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Improving Grid Stability with Hybrid Renewable Energy and Green Hydrogen Storage: A Study of Karimunjawa Island

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ABSTRACT

This study evaluates the technical and economic feasibility of a hybrid renewable energy system integrating photovoltaic (PV), wind turbine (WT), and green hydrogen storage for Karimunjawa Island, Indonesia. The intermittency of solar and wind energy presents challenges in maintaining grid stability, which are addressed by incorporating a hydrogen storage system. Green hydrogen is produced via electrolysis using excess renewable energy and stored for later conversion to electricity, enhancing system flexibility and reliability. Simulation and optimization used HOMER Pro to assess various system configurations based on key performance indicators, including Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Levelized Cost of Hydrogen (LCOH). The optimal configuration, comprising PV-WT-Grid-Converter-Electrolyzer, achieved an LCOE of \$0.281/kWh, an LCOH of \$7.546/kg, and an NPC of \$ 4.74 M. Furthermore, the proposed system reduced CO_2 emissions by up to 63%, demonstrating significant environmental benefits. Comparison with diesel grids shows the proposed hybrid system produces significantly lower CO_2 emissions, demonstrating improved efficiency and environmental sustainability. The findings provide a strategic roadmap for implementing similar hybrid renewable energy systems in remote areas, ensuring sustainable and reliable energy access.

1. INTRODUCTION

Islands far and distant in Indonesia struggle to obtain electric energy that is reliable, sustainable, and affordable [1, 2]. Indeed, fossil fuel-based power plants raise operational costs and engender carbon emissions with consequent environmental penalties [3, 4]. The magnified urgency for global energy transition provides an avenue for a solution to the problem through the use of renewable energy in a hybrid system [5, 6].

Karimunjawa Island has high potential for renewable energy in the form of solar (photovoltaic/PV) and wind turbine energy [7]. Therefore, implementing on-grid hybrid systems utilizing these two energy sources would increase supply reliability. However, the major challenge that renewable energy integration faces is its intermittency, which might affect grid stability [8]. As a solution to that challenge, energy storage technologies as a means to store renewable energy, such as green hydrogen, present an innovative pathway [9]. Green hydrogen obtained via the electrolysis of water using electricity from renewable energy sources can be stored for later conversion back into electricity at the time of need, thus enhancing the flexibility of the entire system [10].

Green hydrogen storage systems also provide an advantage of long-term energy storage capacity as opposed to conventional batteries [11, 12]. With hydrogen being the storage medium, excess energy from the PV and wind sources would be converted to hydrogen whenever production exceeds demand and then converted back to electricity during periods of high demand [13, 14]. This approach bolsters system efficiency for the integrated model, aiding grid stability in the on-grid set-up at Karimunjawa Island.

The study uses HOMER Pro to perform simulation-based optimization of the on-grid hybrid PV-Wind system with green hydrogen storage in Karimunjawa Island. The study will then determine the systems' technically and economically feasible configurations in search of the most efficient and sustainable option. The outcomes from this research shall contribute to the road mapping for energy transition in remote areas and prove to be a reference for implementing similar systems in different places facing related challenges.

Table 1 brings to light a literature review from previous studies that model hybrid photovoltaic (PV) and wind turbine (WT) dynamics with hydrogen storage in HOMER Pro software [15, 16]. Essentially, this review has taken a sample of a few essential features, such as feature extraction methods, observed parameters, and obtained results like the Levelized Cost of Energy (LCOE), Levelized Cost of Hydrogen (LCOH), the efficiency of the system, and the costs associated with production [17, 18]. The findings from these studies can be used to infer trends in the current research into hydrogen-based renewable energy systems [19, 20]. This will then serve as the base for designing more optimized approaches to the problems of improving efficiency and sustainability for energy systems, particularly in remote locales such as Karimunjawa Island.

Table 1. State of the art

Simulation Model	Feature Extraction Method	Observations	Research Results	Reference
HOMER Pro (Scenario modeling of hybrid PV/biogas/hydrogen systems)	LCOE, NPC, CO_2 emission calculations	Comparison between on-grid, off-grid, and fuel cell scenarios	LCOE: $0.2094/kWh (on-grid), fuel cell-based system showed high operability	[21]
HOMER Pro (PV-WT-hydrogen system optimization in India)	Sensitivity analysis, LCOE/LCOH estimation	Evaluated multiple solar tracking configs (NT, HAST, VAST, etc.)	LCOH ranged from $8.37 to $11.9/kg; best result: LCOH = $8.37/kg, LCOE = $0.3/kWh	[22]
HOMER Pro and MATLAB (Regression-based cost modeling in Türkiye)	Regression analysis using cost, efficiency, wind/solar data	Compared PV and wind-based hydrogen production across 46 sites	LCOH: $3.61–$7.01/kg (PV) and $1.31–$4.58/kg (wind); regression model validated with low error	[23]
HOMER Pro + PVsyst + MATLAB (FPV system on wastewater pond in Iran)	Assesses production costs and energy output	Evaluates LCOE and LCOH and cost reduction potential	LCOH of $1.55/kg and LCOE of $22.0/kWh	[24]
HOMER Pro (Hybrid PV-battery-hydrogen for ICT systems in Nigeria)	MCDM (CODAS, ARAS, EDAS, MOORA), Entropy weight method	Compared 7 solar tracking configs (NT, MAHA, WAHA, etc.)	Best config (VAST/CAHA) yields capacity factor: 18.2%, LCOH lower under DACA	[25]
HOMER Pro (3 isolated microgrid scenarios: PV/BAT/GH, WT/GH, PV/BAT/WT/GH)	LCOE, NPC, component cost breakdown	Campus case study in Cairo with load 236.06 kWh/day; compared 3 configurations	Best case (PV/BAT/WT/GH): LCOE = $0.413/kWh, NPC = $1.57M; others: PV/BAT/GH = $0.43/kWh, WT/GH = $0.476/kWh	[26]

Certain aspects of the proposed project differ from what has been previously reported. The significant contributions of this research are the proposed hybrid PV-WT system-hydrogen storage system for the island of Karimunjawa, which is geographically constrained and faces energy supply challenges, and the applied simulation-based optimization method using HOMER Pro in assessing the technical and economic feasibility of the candidate system configurations concerning NPC, LCOE, and LCOH costs. While previous studies have successfully simulated hybrid renewable energy systems with hydrogen storage, most have focused predominantly on off-grid contexts, economic metrics, or single-variable optimization. There is limited attention given to the role of hydrogen in supporting grid stability and flexibility, especially in geographically isolated, yet grid-connected islands like Karimunjawa.

Another substantial merit of the research is the assessment of grid stability and system flexibility via hydrogen storage, which serves as an energy reservoir and a long-term solution for the reliability prospects of the on-grid power landscape. Our outcome is also relevant and provides insights for energy transition planning in remote areas, providing a reference point for implementing similar systems in other regions with similar challenges. This uniquely positions the research as a bridge between techno-economic feasibility studies and operational grid resilience, which remains an underexplored aspect in existing HOMER Pro-based hybrid energy simulations. Thus, this research is expected to contribute significantly to developing sustainable, reliable, and flexible energy systems for areas with limited access to conventional electricity networks.

2. METHODOLOGY

Other essential aspects of the methodology applied to the study are as follows:

- Simulation Study: We simulated an independent hybrid renewable energy system for Karimunjawa Island subject to solar photovoltaic (PV), wind turbine, and hydrogen storage technology. The simulation assessed the feasibility of integrating renewable energy sources to manage grid stability and provide long-term energy storage methods. These renewable sources are intermittent; thus, hydrogen storage was assessed as a potential option to reduce supply fluctuations and improve the overall system's performance.
- Software Tool: We considered the leading software tool for environmental, financial, and technological analysis of hybrid renewable energy systems to be HOMER Pro 3.14 (Figure 1). This software allows system configuration optimization through scenario analyses involving energy generation, storage capacity, and cost.
- Evaluation Criteria: Concerning several essential performance indicators, the feasibility assessment of the system has been carried out. The Net Present Cost (NPC) evaluates the system's total cost over its entire life span, while the LCOE gives the average electricity cost in terms of kWh. The LCOH shows the price per kilogram of hydrogen produced. Additionally, hydrogen and electrical production have been assessed to determine system efficiency. Oxygen production is another by-product of hydrogen production, which is considered for possible

application.

- A case study was conducted for Karimunjawa Island, Indonesia, as an example of the practical implementation of a framework. With its high solar and wind energy potential, Karimunjawa was thus considered ideal for implementing a hybrid renewable energy system. Energy demand, local climatic conditions, and grid limitations were considered when designing an optimized energy system for sustainability, reliability, and affordability.

After a simulation-based optimization, this methodology gives rise to detailed techno-economic analyses. Thus, it seeks to define a strategic energy transition roadmap for remote areas in the context of sustainable development and energy security.

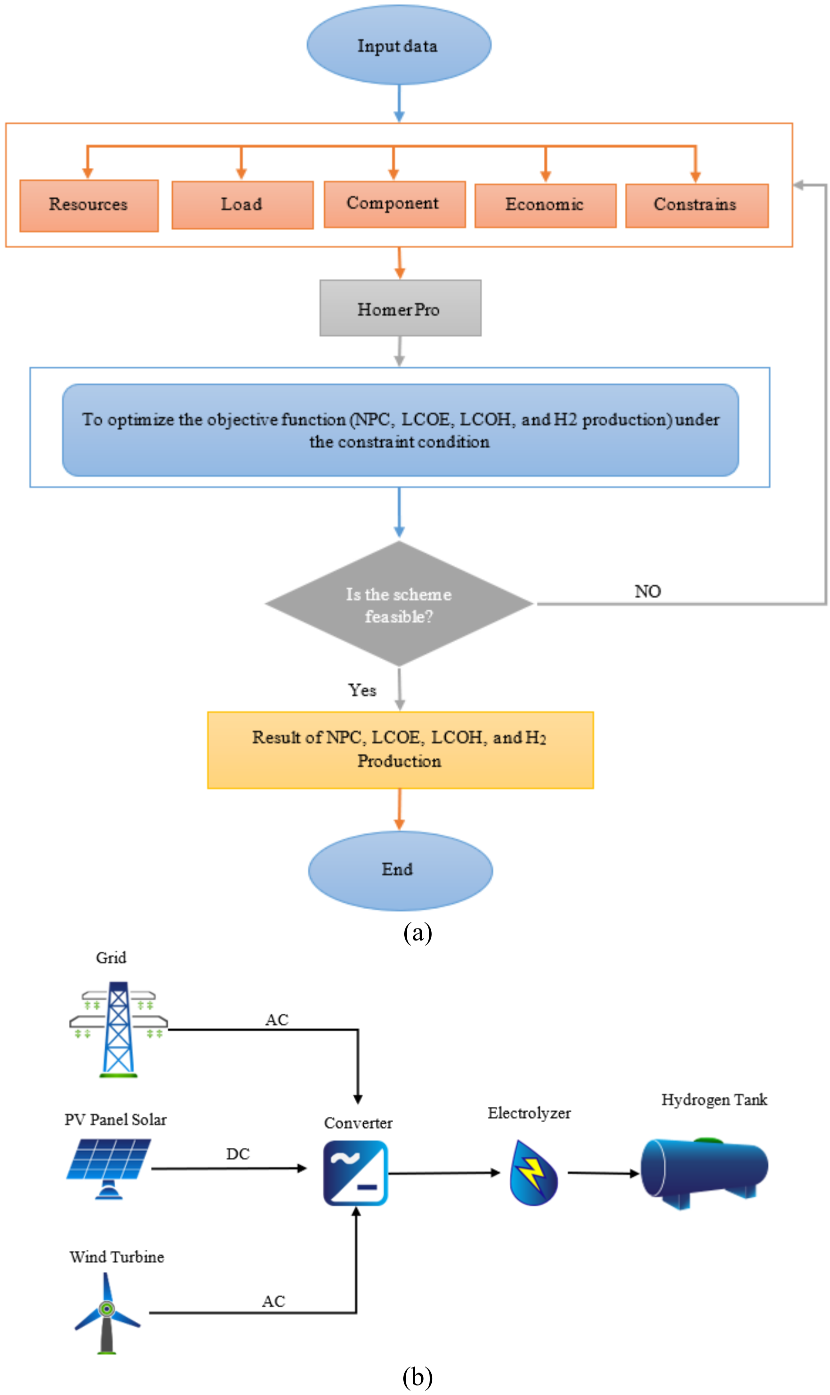


Figure 1. (a) Flowchart for HOMER Pro system, (b) System schematic [27, 28]

2.2 Equation

2.2.1 Energy generated by a photovoltaic (PV) system

The energy generated by a photovoltaic system can be calculated using the following equation:

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{GT}{G_{T,STC}}\right) \times [1 + \propto_p (T_c - T_{c,STC})] \quad (1)$$

where, P_{PV} is the solar panel's output power (watts), Y_{PV} is the PV system power drop factor (watts), f_{PV} is the derating factor for PV systems, GT is the solar radiation obtained at a specific time (W/m²), $G_{T,STC}$ is the standard solar irradiance (1000 W/m²), $\propto_p$ is the PV power temperature coefficient (%/°C), T_c is the PV cell temperature at normal conditions (25°C), and $T_{c,STC}$ is the cell temperature [29-31].

2.2.2 Energy generated by wind turbine system

The output power from a wind turbine is calculated using the following equation:

$$P_{WTG} = \begin{cases} 0,\ v < v_{cut-in} \\ P_{rated} \times \left(\frac{v^3 - v_{cut-in}^3}{v_{rated}^3 - v_{cut-in}^3}\right),\ v_{cut-in} \leq v < v_{rated} \\ P_{rated} \times \left(\frac{v^3 - v_{cut-in}^3}{v_{rated}^3 - v_{cut-in}^3}\right), v_{rated} \leq v \leq v_{cut-out} \\ 0, v > v_{cut-out} \end{cases} \quad (2)$$

where, $P_{WTG}(v)$ represents the output power of the wind turbine at wind speed v (in Watts), P_{rated} is the turbine's rated or maximum power output (in Watts), and vvv is the actual wind speed (in meters per second). The parameters v_{cut-in}, v_{rated} and $v_{cut-out}$ denote the cut-in, rated, and cut-out wind speeds, respectively, all measured in meters per second. This equation reflects the realistic power curve of a wind turbine, ensuring that no power is produced below the cut-in speed or above the cut-out speed, and that the turbine operates at its rated power between the rated and cut-out speeds [32].

2.2.3 Chemical reaction in the water electrolysis process

The following reactions can represent the water electrolysis process for producing hydrogen and oxygen [33]:

$$\begin{aligned} Anode &: 2H_2\,O + 2e^- \rightarrow H_2 + 2OH^- \\ Cathode &: 2OH^- \rightarrow OH_2\,O + 0.5O_2 + 2e^- \\ Overall\ reaction &: H_2\,O \rightarrow 0.5O_2 + H_2 \end{aligned} \quad (3)$$

2.2.4 Oxygen production calculation

In electrolysis, the mass ratio of hydrogen to oxygen is 1:8, so the amount of oxygen (O_2) produced can be calculated as follows:

$$m_{O_2} = \frac{M_{O_2}}{M_{H_2}} \times m_{H_2} \quad (4)$$

where, m_{O_2} is the mass of oxygen produced (grams), M_{O_2} is the molar mass of oxygen (32 g/mol), M_{H_2} is the molar mass of hydrogen (4 g/mol), and m_{H_2} is the mass of hydrogen produced (grams). Since the mass ratio of O_2: H_2 is 8:1, if the amount of hydrogen produced is known, the amount of oxygen can be calculated using the $m_{O_2} = 8 \times m_{h_2}$. Thus, in the context of hydrogen production from electrolysis, the total oxygen production can be calculated using this ratio, complementing the previous formulas in renewable energy system analysis [34, 35].

2.2.5 Net Present Cost (NPC)

NPC is computed as follows and offers a thorough understanding of the entire project cost expressed in terms of present value:

$$NPC\ (USD) = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t} \quad (5)$$

where, C_t is the total cost in year t, r is the interest rate (%), and N is the project lifespan (years) [31].

2.2.6 Levelized Cost of Energy (LCOE)

LCOE is a key indicator in assessing the economic feasibility of an energy project, calculated using the formula:

$$LCOE = \frac{NPC}{E_{total}} \quad (6)$$

where, $LCOE$ is the total system cost (USD) and E_{total} is the total energy produced over the project's lifetime (kWh) [36, 37].

2.2.7 Levelized Cost of Hydrogen (LCOH)

LCOH is used to evaluate the economic feasibility of hydrogen production and is given by:

$$LCOH = \frac{I + \sum_{t=1}^{N} \frac{MC_t}{(1+i)^t}}{\sum_{t=1}^{N} H_t} \quad (7)$$

where, I is the initial investment cost (\$), M_{C_t} is the marginal cost (operational & maintenance) per year, H_t is the amount of hydrogen produced per year, iii is the discount rate, and N is the project lifespan (years) [38].

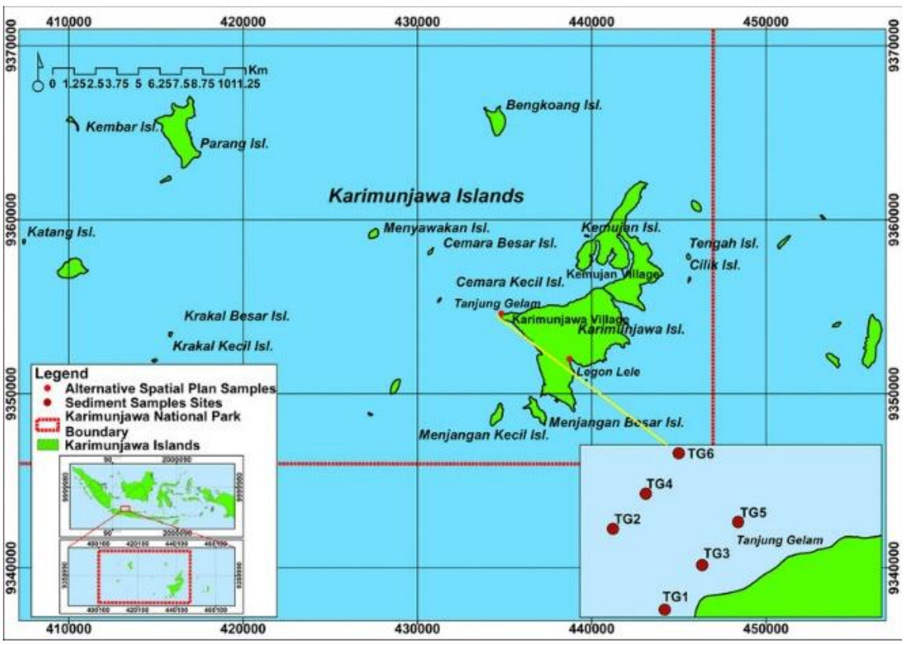


Figure 2. Map of the Karimunjawa islands [39]

Table 2. Coordinate of geography Karimunjawa

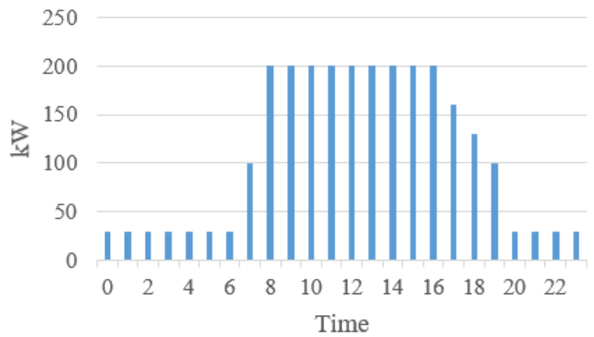
Islands	Province	Latitude (°N)	Longitude (°E)	Altitude (m)
Karimunjawa	Central Java	66.3755722	184.078125	506

2.3 Study area

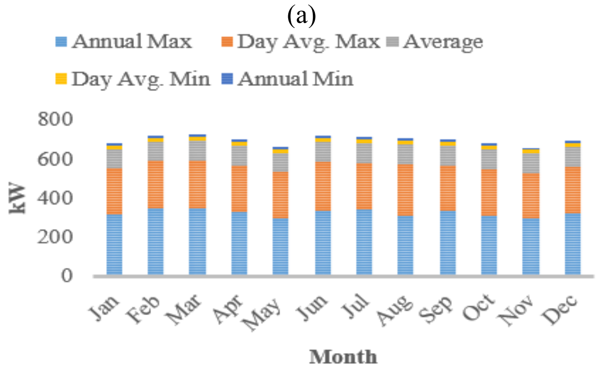
In the waters of the Java Sea, in an archipelago called Karimunjawa, which is administratively part of Central Java Province, the islands possess various kinds of ecosystems, such as mangrove forests, coral reefs, and seagrass beds, making it a conservation area abundant with marine biodiversity. The geographical position and characteristics of the Karimunjawa region can be viewed in Table 2, which presents geographic coordinates, as well as some other relevant environmental conditions. Figure 2 also shows a map of the Karimunjawa region, visually expressing the group's islands.

2.4 Load profile and meteorology of Karimunjawa

Karimunjawa's energy consumption pattern changes from time to time and throughout the year, along with various activities performed by the population and the weather changes. Therefore, understanding load profiles and meteorological conditions is essential in planning a hybrid energy system that delivers reliable and efficient energy. These consumption patterns change daily and must also be considered over the season, which helps ensure this energy's longer-term sustenance.



(a)



(b)

Figure 3. Overview of the hybrid energy system (a) Daily load (b) Seasonal load

Figure 3 shows the variation of load as a function of time. Figure 3(a) illustrates daily load profiles where certain hours peak, indicating increased energy consumption in community activity during the day. In contrast, Figure 3(b) shows the load distribution per season, ranging from annual maximum to maximum daily average, minimum daily average, and yearly minimum. This provides beneficial data on trends in energy consumption that can be exploited to optimize hybrid energy system planning in Karimunjawa.

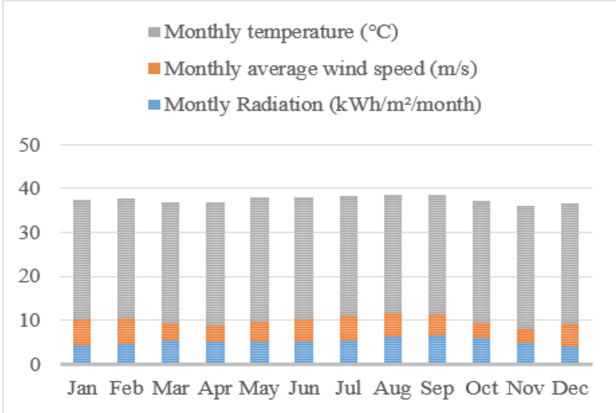


Figure 4. Meteorology data of Karimunjawa

Table 3. Specification of the component

Component	Indicator	Specification	Reference
Photovoltaic (PV)	Photovoltaic slope	31.25°	[38]
	Azimuth		
	Temperature effects on power	-0.38%/°C	
	NOCT	45°C	
	Cost of capital	$1300/kW	
	Cost of replacement	$1300/kW	
	O&M expenses	$20/year/kW	
	Lifespan	25 years	
Wind turbine	Hub height	38 meters	[18]
	Power rating	95 kW	
	Costs of capital	$50,000/kW	
	Costs of replacement	$50,000/kW	
	O&M expenses	$2000/year/kW	
	Lifespan	20 years	
	Quantity	1	
Converter	Costs of capital	$800/kW	[39]
	Costs of replacement	$800/kW	
	O&M expenses	$8/years/kW	
	Lifespan	10 years	
	Efficiency	95%	
Electrolyzer	Model	PEM	[30]
	Costs of capital	$500/kW	
	Costs of replacement	$500/kW	
	O&M expenses	$20/year/kW	
	Lifespan	15 years	
	Efficiency	85%	
	Capacity	0-300kW	
Hydrogen tank	Costs of capital	$1000/kW	[33]
	Costs of replacement	$1000/kW	
	O&M expenses	$0/years/kW	
	Lifespan	25 years	
	Efficiency	50%	
	Capacity	0-80 kW	

Table 4. Limitations of the software system [7, 21]

Items	Value
Project lifetime	25 years
Load following	Yes
Utilize the set point constraints.	Yes
A small portion of renewable energy	40%
Maximum percentage of capacity shortage per year	2%
Incorporate the current time step.	20%
Annual peak load	10%
The energy generated by solar panels	32.1%
Wind turbine-generated energy	38.2%

The meteorological data of Karimunjawa presented in Figure 4 reveal some significant climatic parameters such as monthly solar radiation, average yearly wind speed, and temperature throughout the year. According to the graph, the temperature offers relatively stable readings for all months, fluctuating between 27°C and 28°C. In comparison, solar radiation and wind speed showed profound variations, with one or the other being higher for specific months, affecting the efficiency of renewable energy sources such as solar panels and wind turbines. Knowledge of these meteorological factors is critical for optimizing the hybrid energy system within Karimunjawa toward a balanced interspersion of solar and wind energy resources to serve the area's energy demand effectively.

2.5 Specification of the component

The specifications of PV-wind turbine hybrid energy generation system parts with hydrogen storage are mentioned in this subsection. The requirements and costs for all the components, such as PV panels, wind turbines, converters, electrolyzers, and hydrogen tanks, are compiled in Table 3. The standard specification is taken from various relevant sources to make our study, simulation, and techno-economic analysis accurate.

It indicates the limitations, such as 25 years of project life, a minimum renewable energy limit of 40%, and a maximum annual capacity shortfall of 2%, that software under usage imposes, as shown in Table 4 [7, 21, 39]. The distribution of loads in the software system also shows power generation from solar panels (32.1%) and wind turbines (38.2%).

3. RESULT AND DISCUSSION

3.1 Economic result

In this section, we present the economic and emission analysis results of the different configurations of hybrid energy generation systems that have been simulated. Table 5 displays the main economic parameters, including the capacity of each component, such as PV, wind turbine, power grid, electrolyzer, hydrogen tank, and converter. Table 5 shows that configurations integrating PV and wind with hydrogen storage achieve the lowest LCOE and NPC, highlighting cost advantages through resource complementarity and efficient storage use. Moreover, the WT-grid configuration showed the lowest individual LCOE due to minimal capital investment, though it lacked long-term storage resilience. These trends underscore the balance between upfront cost and system robustness in long-term planning. In addition, we also include cost indicators, such as NPC, LCOE, LCOH, and operation and maintenance (O&C) costs, to assess the financial viability of each configuration. Meanwhile, Table 6 shows the emissions produced by each system architecture, including CO_2, SO_2, NO_x, and other particulate emissions.

Figure 5 presents a comprehensive analysis of the cost distribution in the studied system, covering significant components such as converters, electrolyzers, grids, hydrogen tanks, photovoltaics, and wind turbines. The analysis results show that capital costs are a major contributor to the total system cost, with a predominance of photovoltaic technology, as demonstrated by the significant proportion in the diagram. In addition, operating costs also make a substantial contribution, mainly coming from converters and electrolyzers. Meanwhile, replacement and salvage costs account for a relatively small proportion compared to other cost components. No cost allocation in the resource category indicates that the system does not rely on purchasing external raw materials in the analyzed scenario. Overall, Figure 5 illustrates that the initial investment in this renewable energy system is relatively high, with the most significant financial burden concentrated on photovoltaic technology and converters, which are the main components of the system infrastructure.

Figure 6 compares the cash flows between the base and proposed systems over 25 years. The cash flow curves show that both systems experience a downward trend in cash flow values over time, reflecting accumulated operating and investment costs. However, the proposed system has a better financial performance than the baseline system, indicated by the higher curve position throughout the analysis period. This shows that the proposed system has more efficient cost management and generates more significant savings than the baseline system. In addition, the point of intersection between the two curves around the 18th to 20th year indicates that in that period, the proposed system starts to be more profitable than the baseline system in the long run. Overall, Figure 6 illustrates that the implementation of the proposed system can provide better economic benefits compared to the baseline system in a long-term perspective.

Several recent studies have explored hybrid renewable and hydrogen-based systems using various simulation tools and configurations. For instance, research [21] compared on-grid, off-grid, and fuel cell-based scenarios using HOMER Pro, finding that the on-grid system achieved an LCOE of $0.2094/kWh, while the fuel cell configuration showed superior operability. Similarly, a study in India [22] utilized HOMER Pro to optimize a PV-WT-hydrogen system, integrating sensitivity analyses and cost estimations across different solar tracking technologies. The most favorable outcome yielded an LCOH of $8.37/kg and LCOE of $0.3/kWh when using a vertically adjustable single-axis tracker (VAST). In Türkiye, the study [23] employed a hybrid modeling approach combining HOMER Pro and MATLAB for regression-based cost analysis across 46 sites. The results indicated that PV-based hydrogen production had an LCOH ranging from $3.61 to $7.01/kg, whereas wind-based systems achieved a lower range of $1.31 to $4.58/kg, with validation showing minimal prediction error. Another study [24] assessed a floating PV system on a wastewater pond using HOMER Pro, PVsyst, and MATLAB. This configuration demonstrated the potential for substantial cost reductions, reporting an LCOH of $1.55/kg and an LCOE of $22.0/kWh. A techno-economic assessment in reference [25] applied multiple decision-making methods (CODAS, ARAS, EDAS, MOORA) in conjunction with entropy-based weighting within HOMER Pro. Seven solar tracking scenarios were evaluated, and the combined VAST/CAHA configuration showed the best results with a capacity factor of 18.2% and a relatively lower LCOH under the DACA scenario. Lastly, a case study in reference [26] investigated three isolated microgrid setups PV/Battery/GH, Wind/GH, and a hybrid PV/Battery/Wind/GH systemwith a daily load of 236.06 kWh. The most favorable configuration (PV/BAT/WT/GH) reported an LCOE of $0.413/kWh and an NPC of $1.57 million, outperforming the PV/BAT/GH ($0.43/kWh) and WT/GH ($0.476/kWh) systems in overall cost efficiency.

Table 5. Economic result

Architecture	PV (kW)	Wind (kW)	Grid(kW)	Electrolyzer (kW)	H_2 tank (kg)	Converter (kW)	NPC ($)	LCOE ($)	LCOH ($)	O&C ($)
Grid	0	0	999,999	0	0	0	1.39M	0.100	0	88,485
PV-grid-converter	250	0	999,999	0	0	158	5.08M	0.362	0	81,776
PV-grid-converter-electrolyzer	250	0	999,999	100	80	158	5.23M	0.374	8,335	86,909
WT-grid	0	1	999,999	0	0	0	880,928	0.0565	0	49,775
WT-grid-converter-electrolyzer	0	1	999,999	100	80	0.817	1.03M	0.0663	1,986	54,951
PV-WT-grid-converter-electrolyzer	250	1	999,999	100	80	158	4,74M	0.281	7,546	48,985

Table 6. Emission production by the system

Architecture	CO_2 (kg/yr)	CO (kg/yr)	SO_2 (kg/yr)	NO_X (kg/yr)	Unburned Hydrocarbons (UHCs) (kg/yr)	Particulate Matter (PM) (kg/yr)
Grid	559,226	0	2,424	1,186	0	0
PV-grid-converter	355,485	0	1,541	754	0	0
PV-grid-converter-electrolyzer	340,411	0	1,412	640	0	0
WT-grid	363,508	0	1,576	771	0	0
WT-grid-converter-electrolyzer	350,500	0	1,400	702	0	0
PV-WT-grid-converter-electrolyzer	206,191	0	894	437	0	0

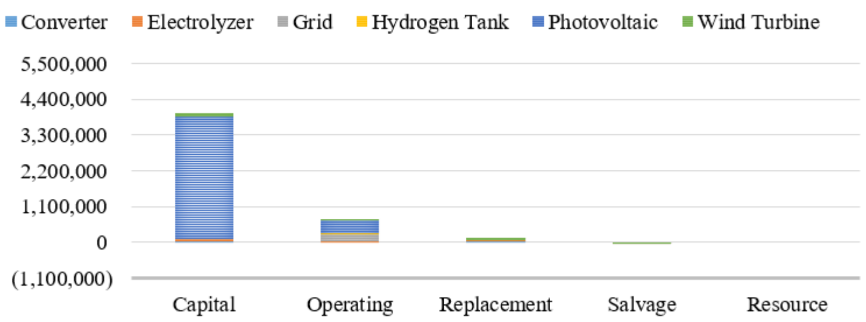


Figure 5. Cost summation of the system

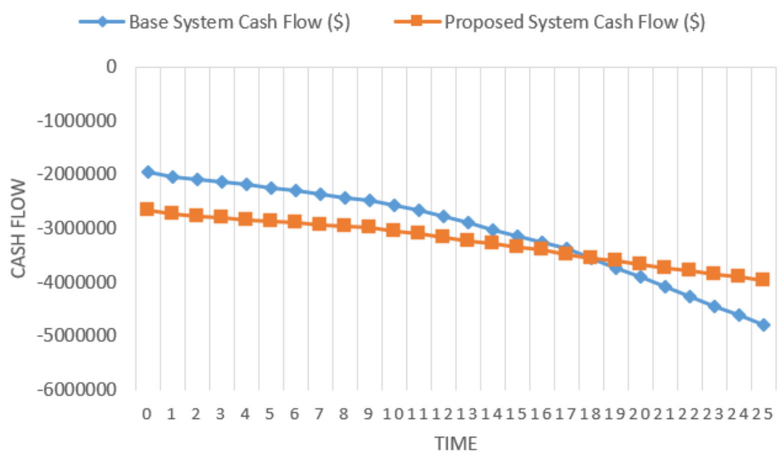


Figure 6. Comparison of the basic system and the proposed system

3.2 Life Cycle Assessment (LCA)

This study also carried out a LCA to evaluate a hybrid renewable energy system with green hydrogen storage in Karimunjawa, regarding understanding the environmental impact. It also assesses the whole life cycle of the system from production to recycling, which allows for identifying possible emission source reductions and resource efficiency.

- The production phase: We assessed the environmental impact of producing solar panels, wind turbines, electrolyzers, and hydrogen tanks. Our data shows that CO_2 generation for 250 kW of solar panels is approximately 10 to 12.5 tons, while wind turbines will generate around 3.75 to 5 tons.
- Transportation and Installation Phase: During the delivery of components to Karimunjawa, we also estimated the emissions derived from transportation and those for installation. Maritime transports estimate about 2.5 kgs of CO_2 emissions per km per ton for transported materials.
- Operational Phase: According to simulations using this system, it is possible to reduce CO_2 emissions by as much as 206,191 kg every year (shown in Table 6) in comparison to a traditional grid-based system, which produces 559,226 kilograms of CO_2 per annum. Such a decrease considerably impacts Karimunjawa's carbon footprint reduction.
- Recycling and Disposal Phase: We have looked into the recycling potential of the system components at the end of life. About 80% can be recovered when recycling solar panel material, whereas wind turbine recycling is about 85%.
- Beyond CO_2 emissions, the hybrid system also significantly reduces other pollutants such as NO_x and SO_2 as detailed in Table 6. The elimination of particulate matter and unburned hydrocarbons further enhances air quality. Lifecycle analysis also indicates a reduced environmental footprint in manufacturing and disposal compared to fossil-fuel systems, supporting a more holistic sustainability assessment.

Our analysis shows that this system can reduce CO_2 emissions by up to 63% compared to conventional grid-based systems.

3.3 Socio-economic impact analysis

In addition to environmental impacts, we evaluated how this system can benefit the Karimunjawa community socially and economically.

- Despite the promising techno-economic results, implementation faces barriers including high upfront capital costs (NPC $4.74M) and limited local technical capacity. These challenges may be mitigated through blended financing schemes, government subsidies, carbon credits, or green energy investment incentives. Capacity building and community-based technical training are also essential to ensure system operation and maintenance sustainability
- Improved Energy Access: One of the main challenges in Karimunjawa is the limited access to stable electricity. With this system, we estimate that available electricity capacity can increase by up to 40%.
- Economic Efficiency: Based on our calculations, this system's LCOE is $0.281/kWh, which is more competitive than fossil fuel-based power plants.
- Opportunities for Green Industry Development: In addition to household electricity needs, green hydrogen production from this system can also be utilized in the transportation and coastal industry sectors. With a production capacity of approximately 338 kg of hydrogen per month, there is potential to support hydrogen-powered fishing vessels.

Our research findings show that this hydrogen-based renewable energy system benefits the environment and has tangible social and economic impacts on the Karimunjawa community.

3.4 Electrical and hydrogen result

The information on electric generation and consumption is in Table 7 above for the system under study. In terms of generation, a total amount of energy equal to 1,097,540.00 kWh per annum has been generated through different sources in the system, with significant contributions coming from wind turbines at 38.2%, through PV at 32.1%, followed by the grid at 29.7%. On the one hand, the primary load AC consumes about 82.2% of the total annual consumption of 1,076,545 kWh, leaving behind the other domestic load consumption. In addition, energy sold to the grid stands at 17.8% surplus consumption, which indicates the scope of maximum use of renewable energy in this system.

In Figure 7, the distribution of monthly electricity production shows that the most significant contribution comes from wind turbines, followed by PV, and the rest comes from the grid. Electricity production fluctuates during the year, with the highest production occurring in August, reaching more than 110 MWh. Higher electricity production in certain months reflects more optimal environmental conditions, such as higher solar radiation intensity and stronger wind speeds.

Figure 8 displays the monthly hydrogen and oxygen production due to electricity utilization for water electrolysis. Hydrogen production tends to follow the trend of electricity production, with the highest figures occurring in August and September, at 338 kg. Similarly, oxygen production peaked at 2,704 kg during the same period. The value of oxygen is more significant because the ratio of oxygen to hydrogen is 8:1. It is important to note that the system experiences efficiency losses during storage and reconversion of hydrogen, with electrolyzer and hydrogen tank efficiencies at 85% and 50%, respectively. To improve overall system efficiency, the produced hydrogen can also be utilized directly in industrial applications such as ammonia production or transportation. Furthermore, oxygen by-products from electrolysis may serve medical or aquacultural uses, enhancing system value and resource circularity.

Table 7. Electrical production and consumption in the system

Production	kWh/year	Percentage (%)
PV	352,014	32.1
Wind Turbine	419,274	38.2
Grid	326,252	29.7
Total	1,097,540	100
Consumption	**kWh/year**	**Percentage (%)**
AC Primary Load	884,852	82.2
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	191,693	17.8
Total	1,076,545	100

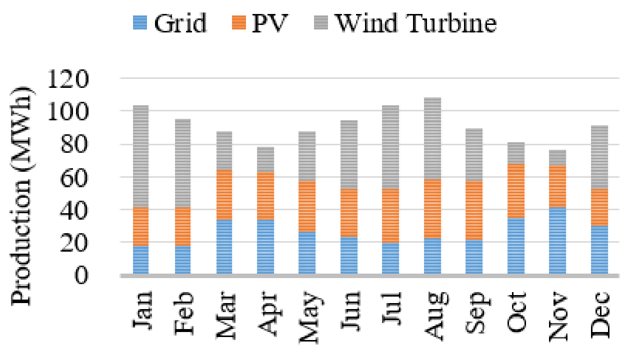


Figure 7. Monthly electrical production

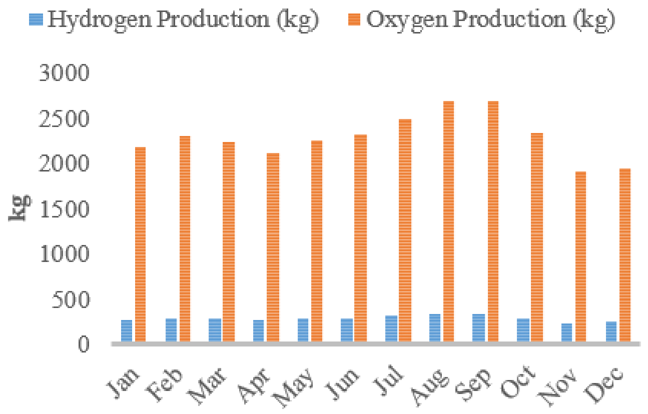


Figure 8. Monthly hydrogen and oxygen production

4. CONCLUSIONS

This study examines and establishes the technical and economic viability of a combined renewable energy system of hybrid photovoltaic (PV) and wind turbine (WT) with green storage hydrogen in Karimunjawa Island. Based on optimization through simulation with HOMER Pro, the hybrid system has shown that the most favorable condition is represented by the configuration of PV-WT-Grid-Converter-Electrolyzer leading to a LCOE equal to $0.281/kWh, a LCOH of $7.546/kg, and an NPC of $4.74M. In addition, it reduces CO_2 emissions by up to 63% compared to a system with a grid only, highlighting the fact that it can give environmental advantages. The co-storage of hydrogen will efficiently eliminate the intermittent nature of such renewable energy resources and harmonize the system further with prolonged safety in the provision of long-term energy reliability. The findings of this research work provide a guiding road map for the energy transition in remote areas, establishing green hydrogen as a core component in shaping sustainable and resilient energy systems.

Further to the argument of the excellent performance of the hybrid systems is the production and storage capacity. The system generated 1,097,540 kWh/year, of which wind turbines generated 38.2%, PV panels contributed 32.1%, and the grid contributed 29.7%. Total energy consumption was 1,076,545 kWh/year, of which 82.2% was for primary AC load, and 17.8% was sold to the grid, meaning that the system generated surplus energy. The monthly production trend closely follows the seasonal variation, showing the peak season as August, attributed to wind speed and solar irradiance. This excess energy was further transformed into electrolytic production of around 338 kg of hydrogen and 2,704 kg of oxygen monthly, enhancing the system's capability to store renewable energy and convert it into a steady power supply. The cooperative balance attained between all three, namely, energy generation, storage, and consumption, further skews heavily toward the reliability and success of this system as an exemplary role model in sustainable energy development in remote regions worldwide.

Beyond the local context of Karimunjawa, the findings of this study hold broader significance for island and remote communities globally that face similar challenges of energy access, grid instability, and dependence on fossil fuels. Integrating green hydrogen storage with hybrid renewable sources presents a replicable model that enhances energy resilience while reducing environmental impact. Unlike most previous works that emphasize either cost optimization or off-grid systems, this research uniquely bridges the gap between techno-economic feasibility and operational grid stability in geographically isolated yet grid-connected regions. The proposed system architecture and methodology also serve as a reference for policymakers and energy planners aiming to design sustainable transition strategies in coastal or archipelagic areas. This study's novelty lies in its dual focus on optimizing renewable integration while ensuring long-term flexibility and environmental sustainability through green hydrogen storage.

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