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Optimization of Hybrid Renewable Energy System with Hydrogen Energy Storage for Enhanced Sustainability in Remote Areas: A Case Study of Enggano Island, Indonesia

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Hybrid Renewable Energy System, Hydrogen Energy Storage, Remote Areas, Photovoltaic, Net Present Cost.

ABSTRACT

The growing global energy demand and the impacts of climate change have accelerated the transition toward renewable energy, particularly in remote regions not connected to national electricity grids. This study investigates the design and optimization of a Hybrid Renewable Energy System (HRES) that integrates photovoltaic (PV) panels, diesel generators (DG), battery energy storage systems (BESS), and hydrogen energy storage systems (HESS) to meet the electricity demand of Enggano Island, Indonesia. The objective is to reduce dependence on fossil fuels, thereby lowering greenhouse gas emissions and improving cost efficiency.

Simulations were conducted using HOMER software to determine the optimal system configuration based on economic, technical, and environmental indicators, including Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Renewable Fraction (RF), and CO_2 emissions. The results show that the PV-DG-BESS configuration emerged as the most cost-effective and environmentally sustainable option, achieving an LCOE of \$0.293/kWh and reducing annual CO_2 emissions by 48.1% compared to the baseline diesel-only scenario. The Net Present Cost (NPC) for PV-DG-BESS was calculated to be \$5,387,226.63. While the PV-DG-BESS configuration is the most practical near-term solution, the integration of HESS demonstrates long-term potential for enhancing system resilience and supporting deeper renewable penetration. Overall, this study contributes to the development of sustainable and efficient renewable energy strategies for remote

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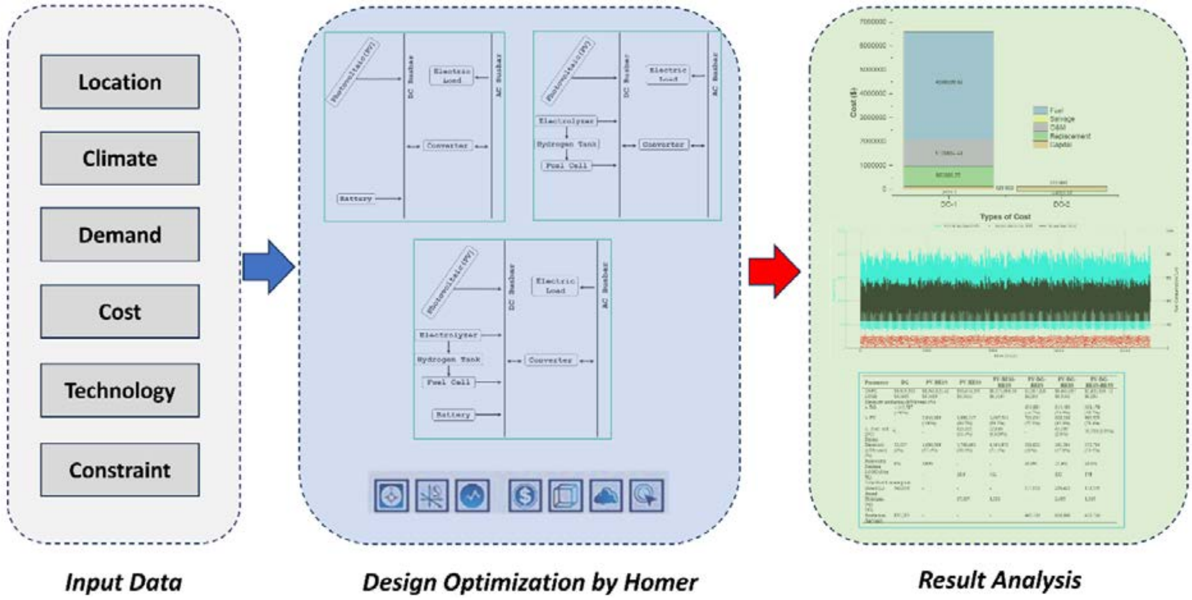
areas and provides valuable insights for policymakers and energy practitioners in Indonesia and other developing countries facing similar energy challenges.



Graphical Abstract.

تحسين نظام الطاقة المتجددة الهجينة مع تخزين الطاقة بالهيدروجين لتعزيز الاستدامة في المناطق النائية: دراسة حالة لجزيرة إنغانو، إندونيسيا

أربي س، فرانسيسكو دانانج ويجايا، جيمي تريو بوترا، وأريف بوديمان.

ملخص: زيادة الطلب العالمي على الطاقة وتأثيرات تغير المناخ قد سرعت الانتقال نحو الطاقة المتجددة، لا سيما في المناطق النائية غير المتصلة بشبكات الكهرباء الوطنية. هذه الدراسة تبحث في تصميم وتحسين نظام الطاقة المتجددة الهجين (HRES) الذي يدمج الألواح الكهروضوئية (PV)، والمولدات التي تعمل بالديزل (DG)، وأنظمة تخزين الطاقة بالبطاريات (BESS)، وأنظمة تخزين الطاقة بالهيدروجين (HESS) لتلبية احتياجات الكهرباء في جزيرة إنغانو، إندونيسيا.

الهدف هو تقليل الاعتماد على الوقود الأحفوري، مما يؤدي إلى تقليل انبعاثات الغازات الدفيئة وتحسين كفاءة التكلفة. تم إجراء المحاكاة باستخدام برنامج HOMER لتحديد التكوين الأمثل للنظام بناءً على المؤشرات الاقتصادية والفنية والبيئية، بما في ذلك صافي التكلفة الحالية (NPC)، وتكلفة الطاقة المعيارية (LCOE)، ونسبة الطاقة المتجددة (RF)، وانبعاثات ثاني أكسيد الكربون. أظهرت النتائج أن تكوين PV-DG-BESS هو الخيار الأكثر فعالية من حيث التكلفة والأكثر استدامة بيئيًا، حيث تم تحقيق LCOE قدره 0.293 دولار/كيلوات.ساعة وتقليل انبعاثات ثاني أكسيد الكربون السنوية بنسبة 48.1 % مقارنة بالسيناريو الأساسي الذي يعتمد فقط على الديزل. تم حساب صافي التكلفة الحالية (NPC) لتكوين PV-DG-BESS بمبلغ 5,387,226.63 $. بينما يعد تكوين PV-DG-BESS هو الحل الأكثر عملية في المدى القصير، فإن دمج HESS يظهر إمكانيات طويلة الأجل لتعزيز مرونة النظام ودعم زيادة penetration الطاقة المتجددة. بشكل عام، تساهم هذه الدراسة في تطوير استراتيجيات الطاقة المتجددة المستدامة والفعالة للمناطق النائية وتقدم رؤى قيمة لصانعي السياسات والمتخصصين في الطاقة في إندونيسيا والدول النامية الأخرى التي تواجه تحديات مماثلة في مجال الطاقة.

الكلمات المفتاحية – نظام الطاقة المتجددة الهجينة، تخزين الطاقة بالهيدروجين، المناطق النائية، الخلايا الشمسية، التكلفة الحالية الصافية.

1. INTRODUCTION

Global population growth and the rising demand for energy are the key drivers of increasing fossil fuel consumption, which substantially contributes to greenhouse gas (GHG) emissions and climate change. Currently, nearly 80% of the world's primary energy supply is derived from fossil fuels, and this share is projected to increase by 2.3% annually until 2040 [1]. Moreover, fossil fuel depletion is expected to become a critical challenge within the next fifty years, motivating countries to accelerate the transition toward sustainable and environmentally friendly energy sources [2]. In recent decades, renewable energy deployment for electricity generation has grown significantly, including in remote and isolated regions [3]. Nevertheless, providing reliable electricity in such areas remains challenging due to limited accessibility, dispersed settlements, and high infrastructure costs. Combined with the restricted financial capacity of local communities, these barriers often render conventional grid-based electricity systems both technically and economically unfeasible [4]. In off-grid contexts, electricity is predominantly supplied by diesel generators (DG), valued for their operational flexibility [5]. However, high fuel costs, logistical constraints, and unreliable supply chains present substantial barriers. In many cases, DG-based systems fail to fully satisfy local electricity demand. Furthermore, reliance on high-speed diesel (HSD) not only increases costs but also exacerbates GHG emissions, undermining global decarbonization efforts [6]. Consequently, integrating local renewable resources represents an important alternative for delivering cleaner and more reliable electricity. Yet, case studies show that systems relying exclusively on renewable energy are often infeasible due to intermittency, high production costs, and reliability issues. To overcome these limitations, DG is frequently combined with renewable energy—most notably solar photovoltaics (PV)—to form Hybrid Renewable Energy Systems (HRES) [7]. Solar energy is considered one of the most promising renewable resources, supported by continuous technological advancements and declining generation costs that enhance its economic competitiveness. However, the inherent intermittency of solar output can disrupt the balance between supply and demand if not properly managed [8]. To address this challenge, energy storage systems are essential for storing surplus electricity during periods of excess generation and releasing it when production is insufficient, thereby improving system stability and reliability. For this reason, storage technologies are integral to HRES, particularly in off-grid applications [9]. A variety of storage options are available, including super-capacitors, batteries, flywheels, pumped hydro, compressed air, and hydrogen. Most existing HRES applications rely on batteries [10][11]. In Indonesia, batteries dominate storage solutions in remote areas. While batteries are attractive due to their efficiency, cost-effectiveness, and operational flexibility, they also present challenges such as short lifespans, charging losses, environmental concerns from waste, and performance degradation [12]. By contrast, hydrogen energy storage has attracted growing attention for its high energy density, long-duration capability with minimal degradation, and zero-emission operation when paired with fuel cells (FC) [13][14]. These features make hydrogen storage a compelling alternative for future HRES integration[15]. The hydrogen storage approach aligns with the Power-to-Gas-to-X (P2G2X) concept, where "X" refers to various end-use applications [16]. In this study, a Power-to-Gas-to-Power (P2G2P) approach is adopted: surplus PV electricity is converted into hydrogen via electrolysis, stored in tanks, and later reconverted into electricity using FC. Determining the optimal system capacity is crucial to achieving efficient HRES performance, requiring a comprehensive assessment of local resources, demand profiles, and site-specific conditions to balance cost, reliability, and efficiency. Oversizing increases costs and wastes resources, whereas undersizing risks unmet community demand [17]. To address these complexities, systematic modeling and simulation tools are required to evaluate alternative system designs. Once local energy resources and demand characteristics are established, tools such as HOMER can simulate and optimize component configurations to identify solutions that minimize costs while ensuring reliability [18]. HOMER is widely applied in renewable energy studies due to its ability to assess Net Present Cost (NPC), Levelized Cost of Energy (LCOE), renewable penetration, and hydrogen production potential, making it one of the most widely used tools in hybrid energy system research worldwide [19]. Against this backdrop, the present study designs and optimizes an HRES integrating PV, DG, BESS, and HESS, with a specific focus on the technical, economic, and environmental performance of Enggano Island, Indonesia. To the authors' knowledge, this represents one of the first comprehensive techno-economic-environmental evaluations of PV-DG-BESS-HESS integration for a remote Indonesian island. The findings provide replicable insights for policymakers, researchers, and practitioners in developing countries seeking sustainable energy solutions for off-grid communities. Enggano Island was chosen due to its remote location, absence of grid access, and heavy reliance on DG, which lead to high electricity costs and limited 16-hour supply. With strong solar potential and national electrification targets, the island presents a suitable testbed for hybrid renewable energy systems. Findings from this study may also be relevant for similar off-grid islands facing comparable economic and infrastructural challenges. Finally, the remainder of this paper is structured as follows. Section 2 presents the literature review and site overview, including previous studies, geographical context, meteorological conditions, and load profiles of Enggano Island. Section 3 describes the system design and methodology, including the architecture of the HRES, component specifications, modeling framework, and optimization objectives. Section 4 discusses the simulation results and the techno-economic-environmental analysis of different configurations. Section 5 concludes with the key findings and recommendations.

2. LITERATURE REVIEW AND SITE OVERVIEW

2.1. Literature Review

Research on integrating HESS with HRES has been conducted globally across diverse applications. This combination shows strong potential for storing surplus energy from renewable sources, such as solar and wind[20][21]. Consequently, ongoing studies continue to investigate HESS applications under various geographic and climatic conditions to accelerate the shift toward cleaner energy. Table 1 provides a comparative overview of selected studies on HRES incorporating HESS worldwide, highlighting key performance parameters such as COE and TNPC.

This study develops and analyzes HRES configurations incorporating HESS to meet electricity demand in remote coastal areas, using Enggano Island as a case study. In line with global net-zero targets, it evaluates PV-HESS and PV-BESS as alternatives to conventional diesel power plants still prevalent in Indonesia. Beyond technical performance, the study offers a detailed economic analysis of multiple scenarios relevant to remote coastal contexts. While many previous works have examined HRES, very few have directly compared HESS and BESS configurations in terms of both system cost and reliability—particularly in Indonesia. This work contributes novel insights for policymakers and stakeholders by combining technical, economic, and environmental evaluations to guide renewable energy deployment in isolated areas.

While hydrogen-integrated hybrid systems have been widely studied, most focus on grid-connected or urban settings. Few explore off-grid island applications, especially in Southeast Asia. Comparative analyses between HESS and BESS under real-world conditions are also limited, as is sensitivity testing of key hydrogen parameters. This study fills these gaps by evaluating six system configurations using HOMER, incorporating site-specific constraints from Enggano Island, and offering practical insights for renewable energy planning in remote areas.

Table 1. Overview of Selected Studies on the Utilization of HRES with Hydrogen Technologies.

Location and Application	Year	Grid	Primary (kWh/day) Peak Load (kW)	Configuration	COE ($/Wh)	TNPC ($)	Ref.
Countries of the African and Malagasy Council for Higher Education (CAMES)	2024	▪	172 and 22	Grid-PV-EL-HT-FC-CNV	0.238	183,536	[22]
India - Urban apartment buildings	2024	□	319.8 and 52.42	PV-BT-EL-HT-FC-CNV	0.880	1,614,712	[23]
Iran - Urban Area	2024	□	112.51 and 12.39	WT-EL-HT-FC-CNV	0.609	15,685	[24]
Malaysia - Rural Area	2024	□	165.59 and n. a	PV-MH-BT-EL-HT-FC-CNV	0.190	148,687	[25]
Pakistan - Educational Institute	2024	▪ □	900.79 and 136.2	• Grid-PV-WT-BT-EL-HT-FC-CNV. • PV-EL-HT-FC-CNV	• 0.155 • 0.3012	• 6,820,000 • 1,960,000	[26]
Saudi Arabia - Household and Public Utility	2024	□	n.a and 350	PV-WT-EL-HT-FC-CNV	0.4412	10,652,823	[27]
Saudi Arabia - Building of the University	2023	▪ □	940.78 and 74.1	• Grid-PV-WT-EL-HT-FC-CNV • PV-WT-BT-EL-HT-FC-CNV	• 0.0709 • 0.221	• 266,841 • 978,745	[28]
Spain - Commercial Area	2023	□	2,426.45 and 405.71	PV-BT-EL-HT-FC-CNV	0.654	7,496,203	[29]
Sweden - Data Center	2023	▪	2,400 and 100	Grid-PV-EL-HT-FC-CNV	0.671	6,800,000	[30]
Malaysia - Residential Area	2022	□	n.a and 50	PV-EL-HT-FC- CNV	0.4046	2,247,000	[31]
Thailand - Tourism Island	2022	▪ □	n.a and 104,000	• Grid-PV-WT-BT-EL-HT-FC-CNV • DG-PV-WT-BT-EL-HT-FC-CNV	• 0.132 • 0.204	• 242,000,000 • 358,000,000	[32]
Vietnam - Industrial Zones	2022	▪	24,000 and 1,833	Grid- PV-EL-HT-FC-CNV	0.0755	8,457,989	[33]
Coastal Isolated Area (Enggano Island-Indonesia) - Residential Area	2024	□	2,990 and 220.18	• PV -BT-EL-HT-FC-CNV • PV-Diesel-BT-EL-HT-FC-CNV	-	-	-
▪ = on grid □ = off grid							

2.2. Site Overview

This study was conducted under the specific climatic conditions of Indonesia, focusing on Enggano Island in Bengkulu Province, located at coordinates 5.3747°S and 102.2319°E (Figure 1). Situated in the Indian Ocean, Enggano Island is one of Indonesia's outermost islands and has strong potential for renewable energy generation, particularly from solar power. The research site lies approximately 110 nautical miles from the nearest port [34], creating logistical challenges for accessibility and transportation. This remoteness, however, makes it an ideal case for evaluating sustainable off-grid renewable energy systems that can be replicated in similar locations across Indonesia.

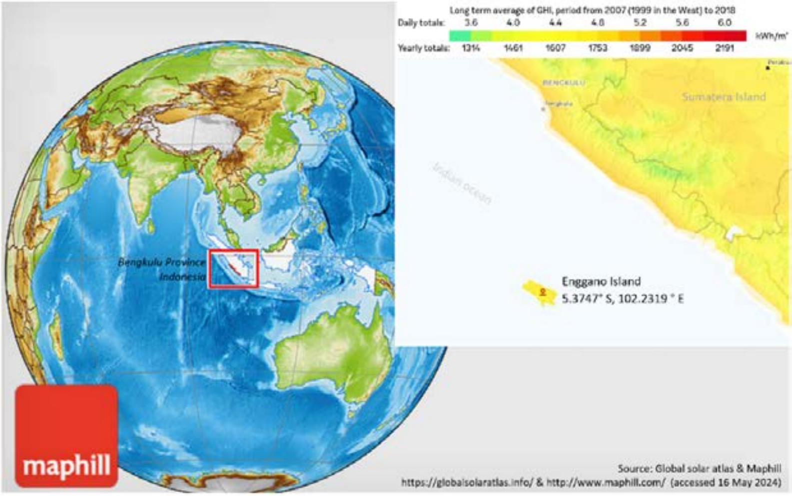


Figure 1. The Geographical Location and Global Horizontal Irradiation of Enggano Island, Indonesia.

Accurate meteorological data are essential for assessing renewable energy potential and efficiency. In this study, solar radiation, clearness index, and temperature data were obtained from HOMER software. As shown in Figure 2, the average monthly daily solar radiation is 4.91 kWh/m²/day, with a minimum of 4.59 kWh/m²/day in December and a maximum of 5.37 kWh/m²/day in September. The total annual global solar radiation is 1,669.1 kWh/m², indicating excellent potential for large-scale PV deployment. The clearness index reflects the favorable atmospheric conditions, suggesting that solar energy can be harnessed efficiently on the island.

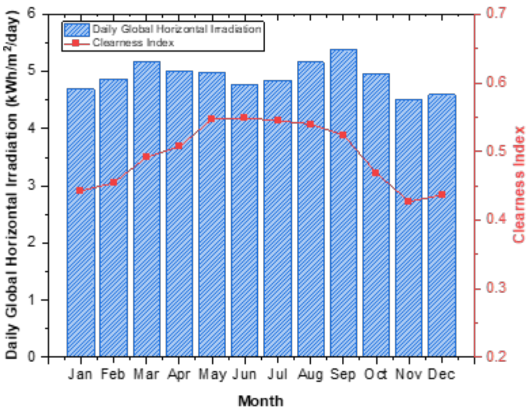


Figure 2. Solar Radiation and Clearness Index for Enggano Island.

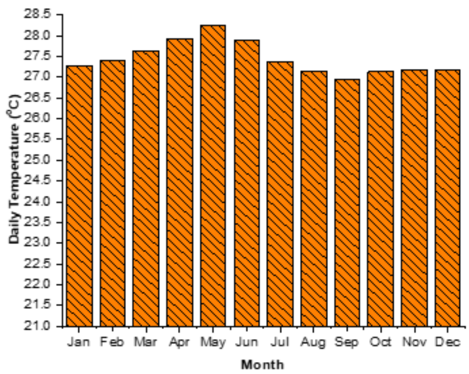


Figure 3. Average Monthly Ambient Temperature in Enggano Island.

As illustrated in Figure 3, the average daily temperature variation for each month on Enggano Island, with an annual average temperature of 27.45°C. This value indicates favorable conditions for PV development in the area. The temperature data serves as an essential input for HOMER software, which uses it as one of the meteorological parameters in the simulation of PV system performance. Additionally, the daily load profile is presented in Figure 4.

As shown in Figure 4, the load profile assumes a 24-hour electricity supply scenario—an upgrade from the current 16-hour supply provided by a single diesel power plant. This projected profile was developed using estimated demand patterns based on local surveys and system capacity, given the absence of historical real-time load data.

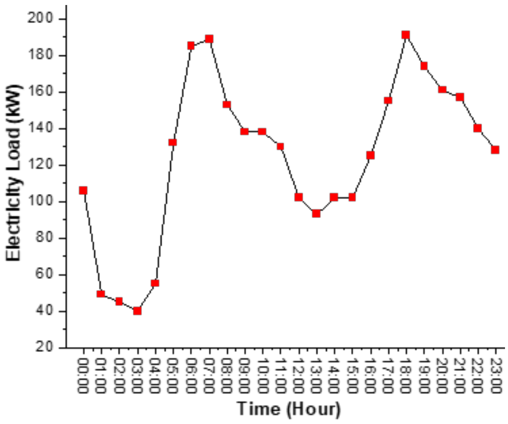


Figure 4. Baseline Daily Average Load Profile in Enggano Island, Bengkulu [35].

To capture daily demand fluctuations, a random variability of ±5% was applied with a 2%-time step, without changing the total daily energy consumption. While detailed seasonal load data were unavailable, the simulation focuses on average daily performance, which is appropriate for system sizing and comparative analysis. The resulting profile (Figure 5) shows an average daily consumption of 2,990 kWh, with an average demand of 124.58 kW, a peak load of 220.18 kW, and a load factor of 0.57. These values served as key inputs for sizing and evaluating the HRES components in terms of efficiency, cost, and emissions.

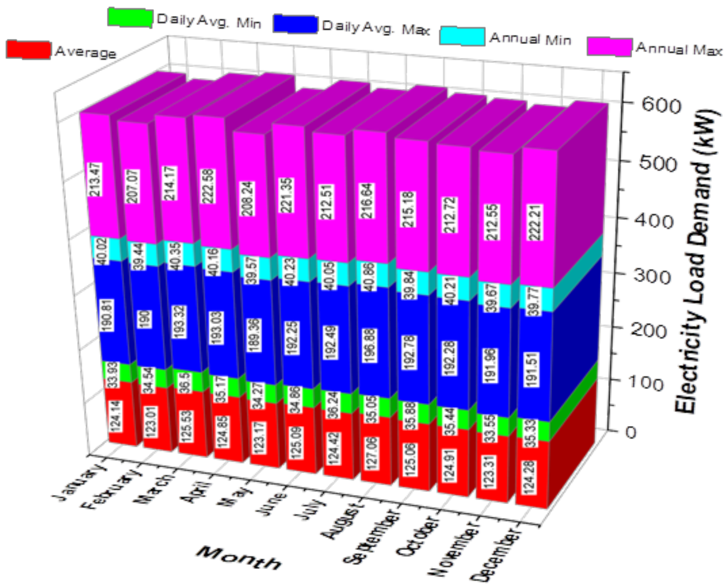


Figure 5. Monthly Electricity Load Demand Profile.

3. SYSTEM DESIGN AND METHODOLOGY

3.1. System Architecture

This section presents the design framework and analysis methodology for the Hybrid Renewable Energy System (HRES), which integrates photovoltaic (PV), diesel generators (DG), hydrogen energy storage systems (HESS), and battery energy storage systems (BESS), modeled using the HOMER software. The overall design process is summarized in a flowchart (Figure 6), which outlines the main stages—from system preparation and optimization to final result analysis.

In this study, six distinct system configurations were simulated using HOMER. The first three scenarios employ PV as the sole power generation source, each paired with a different storage system—BESS, HESS, or their combination—as illustrated in Figure 7. The next three scenarios combine PV and DG as joint power sources while maintaining the same storage variations, as shown in Figure 8. For comparison, a baseline scenario that relies entirely on DG is also included. This comprehensive scenario analysis enables the identification of the most efficient and cost-effective configuration to meet the electricity demand of Enggano Island.

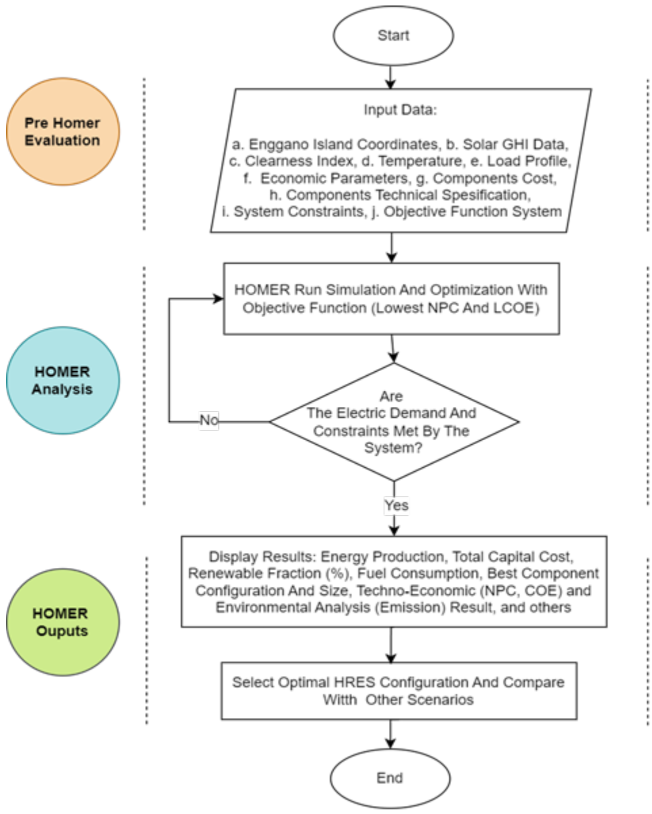
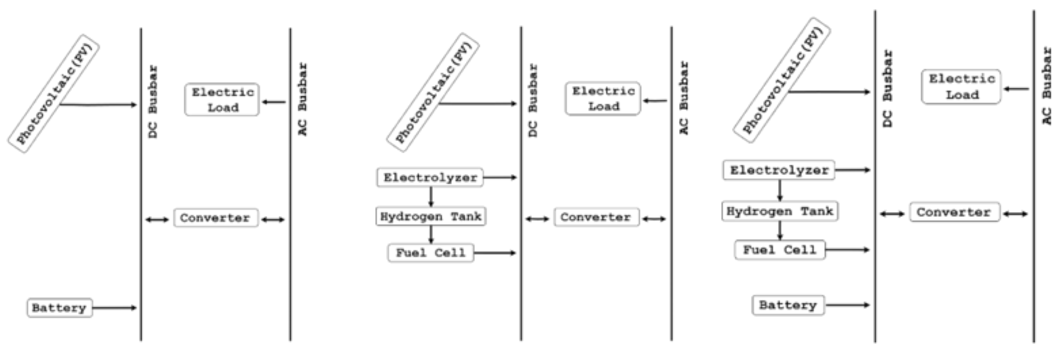


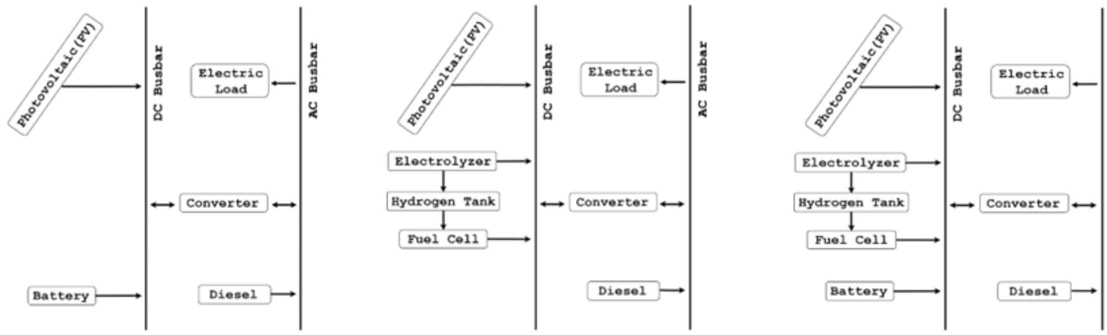
Figure 6. Flowchart Diagram of the System Simulation Using HOMER Software.



(a) (b) (c)

Figure 7. System – PV-Based Energy Systems: (a) with Battery, (b) with FC, (c) with Battery and FC.

Figure 7 (a–c) illustrates three PV-only off-grid system configurations, where BESS and HESS serve as backup storage solutions, ensuring electricity supply during periods when PV generation is unavailable (e.g., nighttime or cloudy conditions). HESS, in particular, comprises three core components: an electrolyzer that converts surplus PV electricity into hydrogen; a storage tank that retains the hydrogen; and a FC that reconverts the stored hydrogen into electricity when required. In remote and isolated regions, meeting electricity demand solely with renewable energy remains challenging. Consequently, fossil fuels—particularly diesel—are still required to ensure system reliability, although their gradual reduction remains a long-term policy objective.



(a) (b) (c)

Figure 8. System – PV-Diesel Hybrid Energy Systems: (a) with Battery, (b) with FC, and (c) with Battery and FC.

For instance, Enggano Island's current electricity generation remains heavily dependent on diesel-based power plants [36]. To address this issue, this study also considers hybrid configurations where PV and DG are combined as power sources. As illustrated in Figure 8 (a–c), these hybrid scenarios incorporate the same storage variations (BESS, HESS, and their combination) as in the PV-only systems. The aim is to evaluate each system's reliability, cost-effectiveness, and renewable energy contribution under diverse generation scenarios.

3.2. Modeling, Component Specification, and Objective Functions of the System

3.2.1. Component Specification

This subsection outlines the technical and economic specifications of the components used in the simulation of the proposed hybrid energy system. The main components include PV panels, DG, electrolyzers, hydrogen storage tanks, FC, batteries, and power converters. Table 2 summarizes the specifications of each component integrated into the simulation model.

Table 2. Technical and Economic Component Specifications.

Description	Capital Cost	Replacement Cost	Operating & Maintenance Cost	Lifetime	Min. Load Ratio	Electrical Bus	Efficiency	Ref.
PV	$1,073/kW	$1,073/kW	$10/year	25 years	-	DC	-	[37]
DG	$500/kW	$500/kW	$0.03/kW	20,000 hours	25%	AC	-	[38]
Electrolyzer	$2,000/kW	$1,500/kW	$50/year	15 years	25%	DC	85%	[39]
Hydrogen Tank	$1,500/kg	$1,350/kg	$15/year	25 years	-	-	-	[40]
FC	$4,000/kW	$3,500 /kW	$0.1/op.hour	40,000 hours	25%	DC	80%	[31]
Battery	$300 /kWh	$300 /kWh	$25 /year	10 years	-	DC	95%	[41]
Converter	$500 /kW	$450 /kW	$50 /year	15 years	-	DC/AC	-	[42]

*Derating factor of PV: 80%, HSD Fuel price: $0.78, Hydrogen Initial tank level relative to tank size: 25%, battery nominal voltage: 12 V, battery nominal capacity: 1 kWh, and battery maximum capacity: 83.4 Ah.

These parameters were incorporated into HOMER to optimize the system configuration by comparing multiple energy scenarios. The software evaluates each configuration against predefined performance criteria, including system cost, carbon dioxide (CO_2) emissions, and overall operational efficiency. The resulting analysis facilitates the selection of the most efficient and economically viable energy system tailored to the specific electricity demand of Enggano Island. The economic parameters used in this study—including capital costs, replacement costs, and O&M costs for PV, DG, BESS, and HESS components—were obtained from recent literature sources [34–39] and cross-referenced with vendor data and comparable project benchmarks within Southeast Asia. The diesel fuel price of \$0.78/liter reflects Indonesia's 2024 national average, as reported by the Ministry of Energy and Mineral Resources. Inflation and discount rate assumptions were derived from national macroeconomic indicators to ensure realism and consistency across all economic evaluations.

3.2.2. Economic and Environmental Modeling

3.2.2.1. Economic Modeling

In HOMER, the optimal configuration of the Hybrid Renewable Energy System (HRES) is determined by minimizing the Net Present Cost (NPC). NPC represents the present value of all lifetime system costs—including capital, replacement, operation and maintenance (O&M), and fuel—offset by revenues. As a key economic metric, NPC provides the basis for evaluating the long-term financial viability of different configurations and is calculated using Eq. (1) [43]:

$$C_{NPC,Tot} = \sum_{n=0}^{N}\left[D_F \times \left(\sum_{g=1}^{j} C_C + C_R + C_{OM} + C_F - C_{sv}\right)\right] \quad (1)$$

where $C_{NPC,\,Tot}$ is Total Net Present Cost (\$), n is the year index, N is the project lifetime (in years), D_f is the discount factor, j is the component index (e.g., PV, DG, battery, electrolyzer, hydrogen tank, FC, converter), C_C is the capital cost of the component (\$), C_R is the replacement cost of the component (\$), C_{OM} is the operation and maintenance cost of the component (\$), C_{sv} is the salvage cost for the component (\$), and C_F is the fuel cost for power generators (\$). In HOMER, the hourly fuel consumption of the DG is estimated using Eq. (2), while the total annual fuel consumption in liters (TAFCIL) is derived from Eq. (3) [44]:

$$F_{DG}(t) = \tau P_{DG} + \varphi P_{DG-Out}(t) \quad (2)$$

$$TAFCIL = \sum_{t=1}^{8760} F_{DG}(t) \quad (3)$$

Where F_{DG} *(t)* is the DG fuel consumption rate (l/h), τ is the intercept coefficient of the DG fuel curve (l/h/kW$_{Rated}$), φ is the DG fuel curve slope (l/h/kW$_{Output}$), P_{DG} is the DG rated capacity (kW), and $P_{DG\text{-}Out}(t)$ is the output power of the DG at the current time step (kW).
After calculating the hourly fuel consumption $F_{DG}(t)$, the fuel consumption cost $FCC_{DG}(t)$ can be determined by multiplying the fuel consumption rate $F_{DG}(t)$ by the fuel price FP_{DG} as shown in Eq. (4) [45]:

$$FCC_{DG}(t) = FP_{DG} \times F_{DG}(t) \quad (4)$$

The discount factor is a ratio used to calculate the present value of cash flows over the project's lifetime. In HOMER, the discount factor is calculated using Eq. (5)[1]:

$$D_F = \frac{1}{(1+i)^n} \quad (5)$$

Where D_F is the discount factor, i is the real discount rate [%], n is the number of years (from 0 to *N*). Furthermore, the real discount rate (real interest rate) can be calculated using Eq. (6) [46]:

$$i = \frac{i_o - f}{1+f} \quad (6)$$

Where *i* is the real discount rate (%), io is the nominal discount rate (%), and f is the expected inflation rate (%). The annualized cost of the system can be calculated from the NPC and the capital recovery factor values, as defined in Eq. (7) [47]:

$$C_{A,T} = CRF(i,N) \times C_{NPC,Tot} \quad (7)$$

where $C_{A,T}$ is the total annualized cost of the system (\$/year), *CRF (i, N)* is the function returning the capital recovery factor, i is the annual real discount rate (%), N is the project Lifetime (years), and $C_{NPC,\,Tot}$ is the Total Net Present Cost ($). The CRF the ratio used to calculate the present value of an annuity. The *CRF* value can be calculated using Eq. (8) [48]:

$$CRF\left(i,N\right)=\frac{i\left(1+i\right)^{N}}{\left(1+i\right)^{N}-1} \quad (8)$$

Furthermore, the levelized cost of energy (LCOE) in HOMER software is defined as the average cost per kWh of electrical energy generated by the system. To calculate the LCOE value, Eq. (9) can be used [49]

$$COE=\frac{C_{A,T}}{E_{Served}} \quad (9)$$

Where COE is the cost of energy ($/kWh), $C_{A,T}$ is the total annualized cost of the system ($/year), E_{served} is the total electricity load served (kWh/year). In the feasibility study of hydrogen production, the Levelized Cost of Hydrogen (LCOH) can be calculated using Eq. (10) [50]:

$$COH=\frac{C_{A,T}}{M_{H_2}} \quad (10)$$

Where COH is the levelized cost of hydrogen ($/kgH2), CA, T is the total annualized cost of the system ($/year), and M_{H_2} is the annualized hydrogen mass produced (kg/year). The during operation. The hourly CO_2 emissions from the DG can be estimated based on its hourly fuel consumption, which can be calculated using Eq. (11) [45]:

$$CO_2\left(t\right)=SE_{CO_2}\left(\frac{kg}{l}\right)\times F_{DG}\left(t\right)\left(\frac{l}{h}\right) \quad (11)$$

Where rm SE_{CO_2} the specific CO_2 emission per liter, with a value of 2.7 kg/l, and $F_{DG}(t)$ is the DG fuel intake during operation (l/h). The total annual CO_2 emissions from the DG can be calculated using Eq. (12) [51]:

$$TA_{CO_2}emission=\sum_{t=1}^{8760}CO_2\left(t\right) \quad (12)$$

Furthermore, to evaluate the composition of renewable energy usage in the system, HOMER software provides the parameter Renewable Fraction (RF). RF is defined as a measure of the portion of renewable energy used by the system to meet the load. RF represents the fraction of energy consumed by the load that is generated calculation of the economic parameter values (I and CRF) used in this study was performed using Eq. (3) and (5), with the results presented in Table 3.

Table 3 Economic Parameter.

Description	Specification
Nominal Discount Rate (i_o)	6.5%
Real Discount Rate (i)	3.3%
Expected Inflation Rate (f)	3.1 %
Capital Recovery Factor (*CRF*)	0.0594
Lifetime Project (*N*)	25 years
Currency	1 USD = Rp 15,367.00

3.2.2.2. Environmental modeling

In this study, the DG was still used as part of the designed system configuration, meaning that emissions were still produced from renewable energy sources and is expressed in Eq. (13) [52]:

$$\%RF = \left(1 - \frac{E_{non-ren,a}}{E_{served}}\right) \times 100 \quad (13)$$

Where $E_{non-ren,a}$ is the amount of energy derived from non-renewable resources (kWh/year), and E_{served} the total electrical energy load served (kWh/year).

3.3. Formulation of Objective Function

A primary goal of this study was to determine the optimal HRES capacity configuration while minimizing system costs. Consequently, the objective function focused on reducing the Net Present Cost (NPC), as defined in Eq. (1). In this context, R_{rem} represents the remaining lifespan of a component at the end of the project period (in years), and R_{comp} denotes the total lifespan of the component (in years). The mathematical representation of the study's objective function is provided in Eq. (14):

$$Min\ (C_{NPC,Tot}) = Min \sum_{n=0}^{N} \left[\frac{1}{\left(\frac{1+i_o}{1+f}\right)^n} \left(\sum_{g=1}^{j} C_C + C_R + C_{OM} + \left(\sum_{t=1}^{8760} FCC_{DG}(t) \right) - C_{SV} \left(\frac{R_{Rem}}{R_{Comp}} \right) \right) \right] \quad (14)$$

The optimization in this study was conducted using HOMER Pro software with the primary objective of minimizing the Net Present Cost (NPC) over a 25-year project lifetime. While NPC served as the main criterion for system feasibility, CO_2 emissions and renewable fraction were also analyzed as secondary indicators for environmental comparison. HOMER automatically adjusted system component sizes—including PV capacity, DG rating, battery quantity, and hydrogen system components—through iterative simulations to identify the least-cost configuration that reliably meets the specified load demand. This sizing process was constrained by the economic, technical, and operational parameters defined in Eq. (14) – (20). The overall optimization workflow is illustrated in Figure 6, summarizing the steps from input definition to final scenario selection.

$$0 \le N_{j,s} \le N_{j,s,max} \quad (15)$$

$$\sum PS_{gen} \ge \sum LS_{dem} \quad (16)$$

$$P^{min}_{PV,DG,EL,BAT,FC,INV} \le P_{PV,DG,EL,BAT,FC,INV} \le P^{max}_{PV,DG,EL,BAT,FC,INV} \quad (17)$$

$$r_{load} = 10\%\ ,\ and\ r_{solar} = 25\ \% \quad (18)$$

$$E_{cs} \le f_{cs} \times E_{demand,elect} \quad (19)$$

$$f_{cs} \le 5\% \quad (20)$$

Where, s is the scenario of the system configuration, j refers to the system components, including PV, DG, battery, electrolyzer, hydrogen tank, FC, and converter., N_j, s is the number of component j in scenario s , $N_{j,s,max}$ denotes the maximum allowable value of component j for scenario s, and $N_{j,s}$ must be an integer. PS_{gen} is the total power generated by the system (kW), LS_{dem} is the system's load demand (kW), r_{load} defines the operating reserve as a percentage of the variable load during the current time step, r_{solar} specifies the operating reserve as a percentage of the variable solar power output, E_{cs} is the total capacity shortage (kWh/Year), f_{cs} is the capacity shortage fraction (%), and $E_{demand,elec}$ is the total annual electrical demand (kWh/Year).

4. RESULTS AND DISCUSSION

4.1. Component Optimization Results

4.1.1. Baseline scenario (DG-1 and DG-2)

The baseline scenario serves as the fundamental reference configuration in this study. In this setup, no renewable energy sources or energy storage technologies are incorporated, resulting in system performance, operating costs, and greenhouse gas (GHG) emissions being entirely dependent on diesel fuel consumption. The HOMER software simulation of this scenario, including calculations for Total Net Present Cost (TNPC) and Levelized Cost of Energy (LCOE), is based on Eq. (1) to Eq. (9). The optimization is further constrained by the objective and constraint functions defined in Eq. (14) to Eq. (20). The simulation outcomes for this configuration are illustrated in Figures 9 and 10.

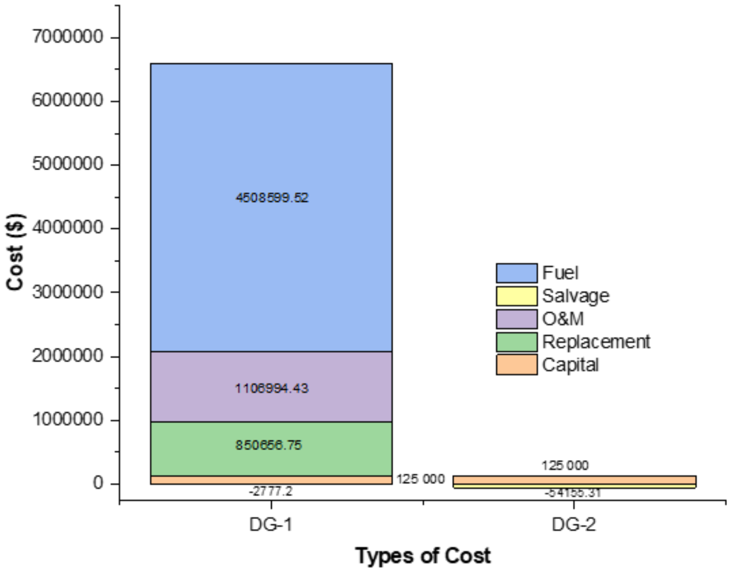


Figure 9. Cost Summary for the Baseline Scenario (DG1-DG2).

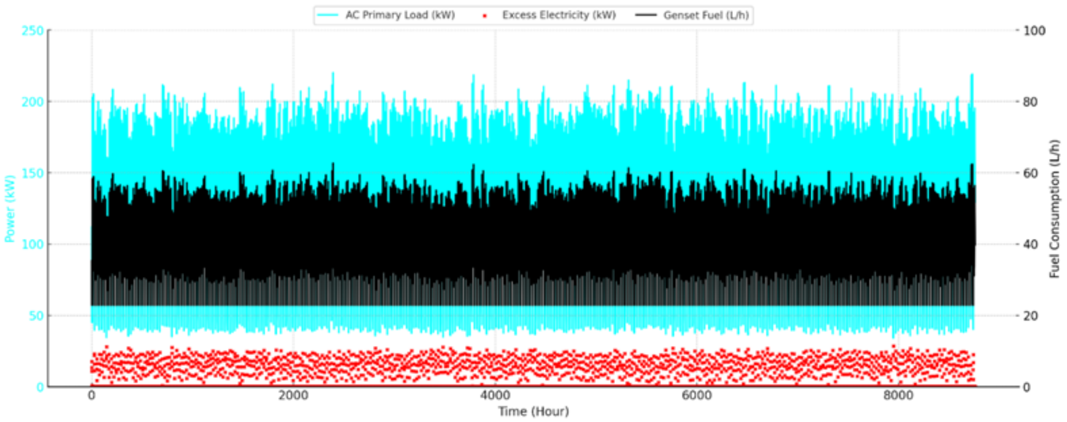


Figure 10. AC Load Profile, DG Fuel Consumption, and Excess Electricity from Baseline Scenario.

As shown in Figure 9, the TNPC over the project's lifetime comprises five major cost components: capital costs amounting to $250,000; fuel costs totaling $4,508,599.52; operation and maintenance (O&M) costs at $1,106,994.43; replacement costs of $850,656.75; and a salvage value of $56,932.51. Disaggregated by unit, the total cost associated with DG-1 is $6,588,473.50, while DG-2 incurs $70,844.69. Notably, fuel costs represent the largest share of TNPC at 67.70%, followed by O&M costs at 16.62%. In this configuration, DG-1 operates as the primary electricity source, whereas DG-2 functions as a backup unit; both generators have an installed capacity of 250 kW. The dominant share of fuel costs underscores the system's heavy reliance on fossil fuels, which not only inflates operational expenditures but also contributes significantly to environmental degradation. While this configuration is technically capable of meeting the electricity demand, its dependence on high-speed diesel (HSD) poses sustainability concerns. Furthermore, the geographical isolation of Enggano Island makes fuel logistics highly weather-dependent, introducing potential vulnerabilities in fuel supply. These limitations highlight the importance of transitioning toward hybrid systems that integrate renewable energy sources. Such integration would reduce fuel dependency, enhance system resilience, and improve long-term sustainability of the island's energy supply.

4.1.2. Renewable Energy Scenario (PV-BESS, PV-HESS, and PV-BESS-HESS)

This scenario explores a fully renewable energy system in which PV power serves as the sole electricity generation source for the community. To ensure energy reliability and load balancing, three configurations of energy storage are evaluated: BESS, HESS, and a combination of both (PV-BESS-HESS). These configurations are designed to operate independently from fossil fuel inputs, providing a sustainable solution tailored for isolated regions such as Enggano Island.

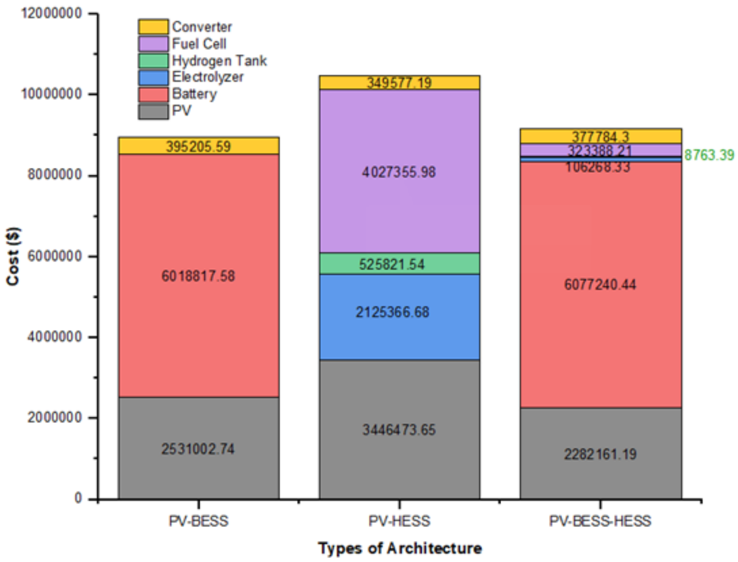


Figure 11. Component Cost Summary for PV-BESS, PV-HESS, and PV-BESS-HESS Configurations.

As illustrated in Figure 11, the breakdown of the Total Net Present Cost (TNPC) for the PV-BESS-HESS configuration shows that energy storage technologies—particularly BESS and HESS—are the dominant contributors to overall system costs. BESS plays a central role by storing excess electricity generated during peak solar hours and supplying it during low irradiance, ensuring short-term reliability. In contrast, HESS provides long-term storage flexibility through its electrolyzer, hydrogen tank, and FC, which enables extended-duration balancing but adds higher cost due to system complexity and low round-trip efficiency. Although the simulation confirms the technical feasibility of achieving a fully renewable system, the high cost of storage remains a critical barrier to practical implementation. These results underscore the importance of carefully assessing trade-offs among energy reliability, storage capacity, and economic sustainability. Detailed component sizes for all renewable scenarios are provided in Appendix Table A1.
As demonstrated in Figure 12, capital investment constitutes the largest cost component, primarily driven by the PV array and associated energy storage systems. Among the alternatives, the PV-HESS configuration incurs the highest capital expenditure, reflecting the substantial upfront investment required for hydrogen-based storage integration. Despite this, the PV-HESS system records the lowest replacement cost. However, it simultaneously exhibits the highest operation

and maintenance (O&M) costs compared to the other configurations. This outcome suggests that while the durability of HESS components reduces replacement requirements, the technological complexity of electrolyzers, hydrogen tanks, and FC increases routine maintenance expenses.

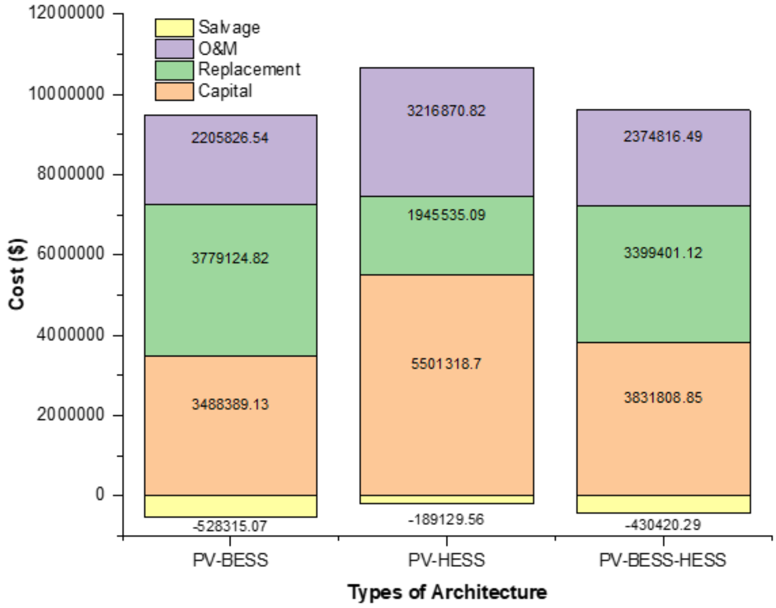


Figure 12. Cost Type Summary for the PV-BESS, PV-HESS, and PV-BESS-HESS Configurations.

Overall, although this fully renewable scenario demonstrates strong potential for environmental sustainability, the elevated cost of energy production presents a major economic challenge. These findings highlight the need to explore alternative solutions, particularly hybrid approaches such as the PV-DG-BESS-HESS configuration, which may offer a more balanced trade-off between cost efficiency, technical feasibility, and environmental performance.

4.1.3. Fossil and Renewable Energy Scenario (PV-DG-BESS, PV-DG-HESS, and PV-DG-BESS-HESS)

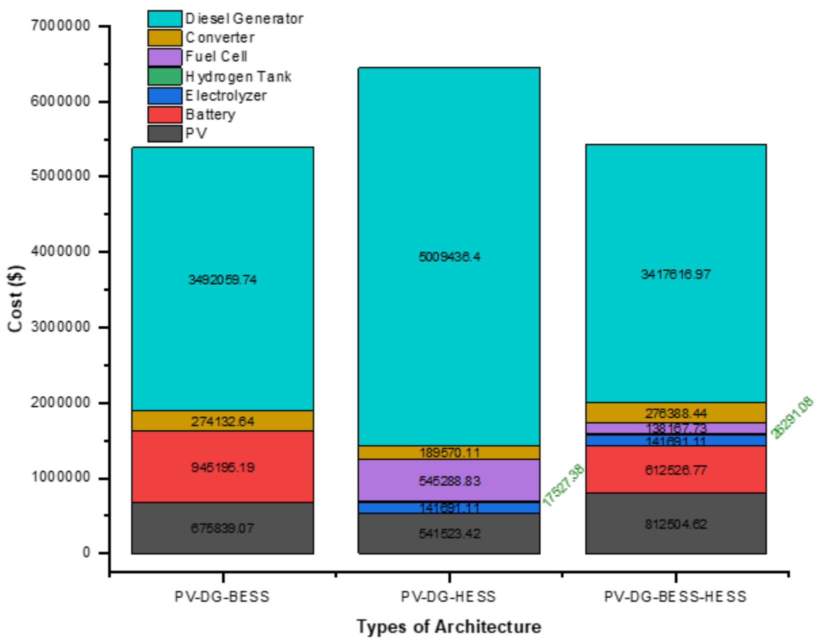


Figure 13. Component Cost Summary for the Fossil and Renewable Energy Configurations.

This scenario integrates PV systems with DG as the primary power sources, supported by different energy storage configurations: BESS, HESS, and a hybrid of both. The detailed cost distribution of each component is presented in Figure 13.
As shown in Figure 13, the DG component remains the dominant cost contributor across all configurations, accounting for 62.9–77.7% of TNPC, which confirms the system's continued reliance on fossil fuel despite renewable and storage integration. Appendix Table A2 shows only minor differences in DG capacity among the three systems (250–280 kW), indicating that DG sizing has limited influence on overall optimization, with storage playing only a secondary role. Figure 14 further highlights the significant share of fuel costs, particularly from high-speed diesel (HSD), in shaping the overall cost structure. Although the inclusion of PV reduces diesel consumption and contributes positively to both economic and environmental sustainability, DG still plays a central role, constraining the transition toward a fully renewable energy system.

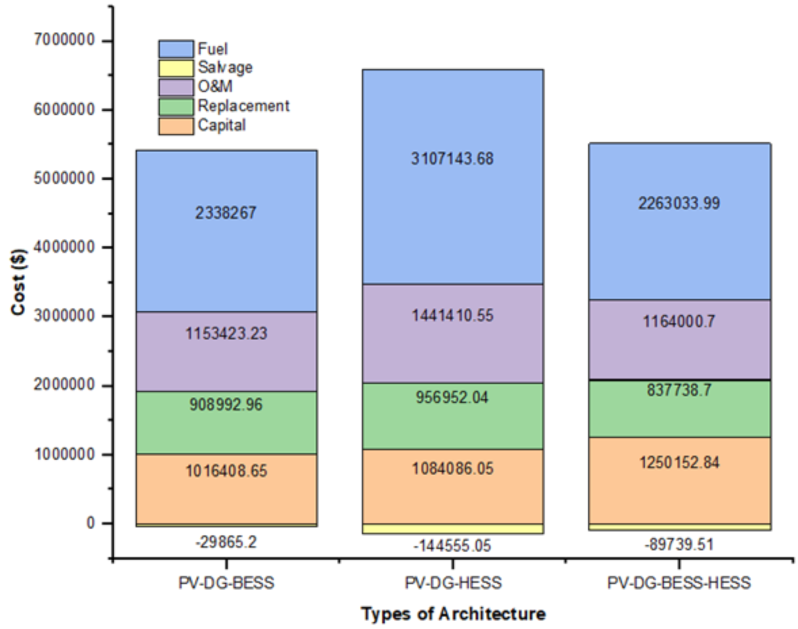


Figure 14. Cost Type Summary for the PV-DG-BESS, PV-DG-HESS, and PV-DG-BESS-HESS.

4.2. Comparison of the Proposed Energy Systems

This section compares the performance of each proposed scenario based on key parameters, as summarized in Table 4. The evaluation considers electricity generation, renewable penetration, excess energy, hydrogen production, fuel consumption, CO_2 emissions, and economic performance.
In terms of electricity generation, the contribution of FC in the PV-HESS and PV-BESS-HESS configurations is minimal. Because of the relatively high cost of electricity from FC, HOMER prioritizes PV to meet demand, activating FC only when PV output is insufficient. A similar trend is observed in the hybrid PV-DG configurations, where FC contributes less than 3% of total generation. By contrast, the share of PV exceeds 42% in all configurations, underscoring its role as a reliable and competitive renewable resource.
In the hybrid PV-DG systems, the Renewable Fraction (RF) ranges between 25% and 43%, demonstrating that renewable sources continue to play a significant role even when supported by DG. Excess electricity, however, varies considerably across scenarios. In the 100% renewable systems, particularly those involving BESS and HESS, excess electricity exceeds 50% due to PV fluctuations and limited storage capacity. In contrast, in the PV-DG configurations, excess electricity is much lower (17.6–23.5%), as DG helps offset variability in PV output. These results

indicate that optimizing storage capacity is essential to reduce curtailment and avoid unnecessary storage-related costs.

Table 4. Comparison of Performance of Each Configuration.

Parameter	DG	PV-BESS	PV-HESS	PV-BESS-HESS	PV-DG-BESS	PV-DG-HESS	PV-DG-BESS-HESS
TNPC	$6,659,318	$8,945,025.42	$10,474,595	$9,175,606.16	$5,387,226	$6,445,037	$5,425,186.72
LCOE	$0.3621	$0.5029	$0.5855	$0.5167	$0.293	$0.3505	$0.295
Electricity production (kWh/year) (%)							
a. DG	1,113,587 (100%)	-	-	-	634,994 (44.7%)	814,493 (54.9%)	613,159 (38.7%)
b. PV	-	2,936,189 (100%)	3,998,217 (86.5%)	2,647,511 (99.2%)	784,034 (55.3%)	628,216 (42.3%)	942,578 (59.4%)
c. FC	-	-	623,121 (13.5%)	22,046 (0.826%)	-	41,580 (2.8%)	30,250 (1,91%)
Excess Electricity (kWh/year) (%)	22,237 (2%)	1,686,568 (57.4%)	1,768,663 (38.3%)	1,364,873 (51.1%)	283,822 (20%)	261,291 (17.6%)	372,716 (23.5%)
Renewable Fraction	0%	100%	-	-	41,8%	25.4%	43.8%
LCOH ($/kg H_2)	-	-	16.6	411	-	153	178
Total Fuel Consumption							
Diesel (L)	343,058	-	-	-	177,918	236,421	172,193
Stored Hydrogen (kg)	-	-	37,387	1,323	-	2,495	1,815
CO_2 Production (kg/year)	897,295	-	-	-	465,720	616,860	450,736

For hydrogen production, the PV-HESS scenario achieves the lowest Levelized Cost of Hydrogen (LCOH) at \$16.6/kg H_2, whereas the other hydrogen-producing scenarios range from \$153 to \$411/kg H_2. This discrepancy arises from limitations in HOMER's calculation methodology, where LCOH is determined by dividing the system's annualized cost by the annualized hydrogen mass (Eq. 10). In multi-component systems, most energy is allocated to electricity demand rather than hydrogen production, inflating LCOH values. A more detailed analysis would therefore be required to estimate hydrogen production costs with higher accuracy.

Fuel consumption patterns align with CO_2 emissions, particularly in DG-based configurations. The baseline DG-only scenario consumes 343,058 liters of diesel annually, resulting in 897,295 kg of CO_2 emissions. In comparison, hybrid systems substantially reduce emissions: PV-DG-BESS by 48.1% (431,575 kg/year), PV-DG-HESS by 31.3% (280,435 kg/year), and PV-DG-BESS-HESS by 49.8% (446,559 kg/year). From an economic perspective, the PV-DG-BESS configuration emerges as the most cost-effective, with the lowest TNPC (\$5,387,226.63) and LCOE (\$0.293/kWh). The inclusion of DG in hybrid systems, such as PV-DG-BESS-HESS, also reduces TNPC and LCOE compared to 100% renewable configurations, despite the additional cost of HESS. Conversely, the PV-HESS configuration exhibits the highest TNPC (\$10,474,595.04) and LCOE (\$0.5855/kWh), reflecting the high investment required for hydrogen-based storage.

Overall, the PV-DG-BESS configuration represents the most practical solution for Enggano Island, as it combines economic competitiveness with significant emission reductions. It thus provides a balanced pathway toward sustainable and reliable electricity supply in remote areas. Although a detailed sensitivity analysis was not within the scope of this study, it is expected that a ±20% variation in hydrogen price or electrolyzer efficiency would primarily affect the economic indicators such as NPC and LCOE. A higher hydrogen price or lower efficiency would increase the total system cost, thereby reducing the competitiveness of HESS compared to BESS-only systems. Conversely, lower hydrogen prices or improved efficiency would reduce NPC, making hydrogen integration more attractive. However, these variations are unlikely to change the overall trend observed in this study—that HESS provides environmental benefits but requires higher initial investment than conventional BESS-based configurations.

4.3. Uncertainties and Limitations

This study highlights the techno-economic and environmental potential of hybrid renewable energy systems with hydrogen integration; however, several uncertainties and limitations remain. First, the system's performance is sensitive to fluctuations in diesel prices, hydrogen production costs, and electrolyzer efficiency, which may vary significantly in remote island contexts. Second, hydrogen infrastructure deployment faces challenges due to high capital costs, storage requirements, and limited supply chain readiness in Indonesia. Third, although HOMER provides a robust optimization platform, it does not capture certain technical aspects such as frequency regulation, voltage stability, or DG start-stop dynamics, which may affect real-world operation.

Fourth, another important limitation relates to the Levelized Cost of Hydrogen (LCOH). The wide variation observed in this study (ranging from ~16.6 to >400 USD/kg) reflects both scale dependency and HOMER's simplified costing assumptions. For small-scale systems, fixed capital costs of electrolyzers, storage tanks, and FC are distributed over low hydrogen output, resulting in inflated unit costs. Conversely, at higher utilization, these costs are spread across larger production volumes, yielding more moderate values. Therefore, the reported LCOH values should be regarded as indicative rather than definitive. More refined techno-economic models that consider scale effects, degradation rates, and alternative cost structures are recommended for future research.

Fifth, the socioeconomic feasibility of hydrogen storage depends on community acceptance, financing mechanisms, and policy support—factors beyond the scope of this study. Recognizing these limitations underscores the need for future research that integrates detailed technical modeling, market-based cost scenarios, and stakeholder engagement, while also reinforcing the practical value of this study as a baseline for renewable energy planning in remote islands.

Although this analysis is site-specific to Enggano Island, the comparative insights between PV-DG-BESS and PV-DG-BESS-HESS configurations are broadly transferable to other off-grid islands in Indonesia with similar conditions, such as high diesel dependence, limited grid access, and strong solar potential. While exact cost figures may differ, the methodological framework and observed trends remain relevant for renewable energy planning in remote communities.

5. CONCLUSION

This study assessed the techno-economic and environmental performance of a PV-DG-BESS-HESS hybrid system for Enggano Island, Indonesia, using HOMER Pro optimization. The results show that incorporating hydrogen storage improves system reliability and reduces CO_2 emissions, although it increases investment costs compared to conventional PV-DG-BESS systems. The least-cost configuration was achieved through Net Present Cost (NPC) minimization, yielding an optimal balance between affordability and sustainability under local demand conditions.

Beyond Enggano, these findings highlight the potential role of hydrogen in supporting renewable energy integration in other remote islands with similar socioeconomic and infrastructural characteristics. Policy support will be critical to address hydrogen infrastructure challenges and financing barriers. Future research should incorporate dynamic technical modeling (e.g., voltage and frequency stability), broader sensitivity analyses, and socioeconomic assessments to strengthen the practical applicability of hydrogen-based hybrid energy systems.

Authors' Contributions: Arbye S. was responsible for conceptualizing the study design and writing the original draft. Fransisco Danang Wijaya contributed to the methodology, simulation analysis, and manuscript review. Jimmy Trio Putra handled data curation, model validation, and technical editing. Arief Budiman supervised the research, conducted formal analysis, and provided critical revisions to the manuscript. All authors reviewed and approved the final version of the manuscript.

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Declaration of AI Use: The authors declare that artificial intelligence (AI) tools, were used solely for language editing, grammar refinement, and structural adjustments of the manuscript. The AI tools were not employed for generating scientific content, data analysis, or interpretation of results. All intellectual and conceptual contributions in this work are entirely those of the authors, who have carefully reviewed and validated the final manuscript to ensure its accuracy and integrity.

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List of Abbreviations:

HRES – Hybrid Renewable Energy System

PV - Photovoltaic

DG - Diesel Generator

FC – Fuel Cell

BESS - Battery Energy Storage System

HESS - Hydrogen Energy Storage System

NPC - Net Present Cost

LCOE - Levelized Cost of Electricity

RF - Renewable Fraction

LCOH - Levelized Cost of Hydrogen

TNPC - Total Net Present Cost

Appendix A. Support Data

Table A.1 Size of Each Component in the PV-BESS, PV-HESS, and PV-BESS-HESS Configurations.

Configuration Architecture	Component	Size
PV-Battery-Converter	Generic Flat Plate PV	2,039 kW
	System Converter	255 kW
	Generic 1 kWh Lead Acid	3,912 strings
PV-Electrolyzer-Hydrogen Tank -FC- Converter	Generic Flat Plate PV	2,776 kW
	System Converter	225 kW
	Electrolyzer	600 kW
	Hydrogen tank	300 kg
	FC	190 kW
PV-Battery-Electrolyzer -Hydrogen Tank-FC- Converter	Generic Flat Plate PV	1,838 kW
	System Converter	243 kW
	Electrolyzer	30 kW
	Hydrogen tank	5 kg
	FC	100 kW
	Generic 1 kWh Lead Acid	4,234 strings

Table A.2 Size of Each Component in the PV-DG-BESS, PV-DG-HESS, and PV-DG-BESS-HESS.

Configuration Architecture	Component	Size
PV-DG-Battery-Converter	*Generic Flat Plate PV*	*544 kW*
	System Converter	*177 kW*
	DG	*250 kW*
	Generic 1 kWh Lead Acid	*730 Strings*
PV-DG-Electrolyzer-Hydrogen Tank -FC- Converter	*Generic Flat Plate PV*	*436 kW*
	System Converter	*122 kW*
	DG	*280 kW*
	Electrolyzer	*40 kW*
	Hydrogen tank	*10 kg*
	FC	*80 kW*
PV-DG-Battery-Electrolyzer -Hydrogen Tank-FC- Converter	*Generic Flat Plate PV*	*654 kW*
	System Converter	*178 kW*
	DG	*260 kW*
	Electrolyzer	*40 kW*
	Hydrogen tank	*15 kg*
	FC	*20 kW*
	Generic 1 kWh Lead Acid	*488 Strings*