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Simulation and Optimization of Hybrid Energy Systems for Green Hydrogen Production in Industrial Settings

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Abstract

The global push toward Net Zero Emissions (NZE) has positioned green hydrogen as a key component in sustainable energy strategies. In Indonesia, the energy sector contributes over 40% of national emissions, prompting the need for increased renewable energy integration. However, green hydrogen production remains limited due to high costs and dependency on fossil-based electricity. This study focuses on a hydrogen production facility located in the Gresik industrial port area, which currently relies 91% on electricity from the national grid. To address this, we propose a hybrid energy system combining photovoltaic (PV) and grid power. The goal is to reduce the Levelized Cost of Energy (LCOE) while increasing the share of renewable energy in hydrogen production. A simulation-based approach was used, employing HOMER Pro software with real industrial operational data as input. Several scenarios were developed by varying PV capacity and daily load demand. The optimal configuration consisting of a 6.179 MWp PV system and a 5,000 kWh/day load resulted in the lowest LCOE of IDR 2,175/kWh, compared to the baseline of IDR 2,783/kWh. The renewable energy share also increased from 9% to 21%. Additionally, performance analysis showed that the actual PV system efficiency was 21%, slightly lower than its theoretical efficiency due to seasonal weather variations. These results indicate that higher PV integration and larger energy loads significantly improve both cost-effectiveness and renewable energy penetration. This study demonstrates a practical, data-driven approach for optimizing green hydrogen production systems in industrial environments.

Keywords: *Green hydrogen, hybrid energy system, HOMER Pro, LCOE, photovoltaic, Indonesia, Net Zero Emissions.*

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INTRODUCTION

Global climate change stands as one of the most pressing challenges of the 21st century, marked by a global average temperature increase of +1.1°C compared to pre-industrial levels (1850–1900), and is projected to exceed the 1.5°C threshold as early as the 2030s without drastic mitigation efforts [1]. Currently, atmospheric carbon dioxide (CO_2) concentrations have surpassed 419 ppm, the highest level in modern human history [2]. The consequences include a global sea level rise of 3.3 mm per year, increased frequency of extreme weather events, and economic losses due to climate-related disasters exceeding USD 300 billion in 2022 alone [3].

In response, over 140 countries, representing approximately 90% of global Gross Domestic Product (GDP), have committed to achieving Net Zero Emissions (NZE) by mid-century. The key performance indicators for these commitments include a 45% reduction in emissions by 2030 (compared to 2010 levels) and carbon neutrality by 2050 [4]. Global strategies to achieve these targets involve increasing the share of renewable energy in global electricity generation from 29% in 2021 to 88% by 2050 and raising clean energy investments to USD 4 trillion per year by 2030 [5].

As a developing country, Indonesia has also committed to an NZE target by 2060 or earlier, as outlined in its Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) and the updated Nationally Determined Contribution (NDC) submitted in 2022 [6]. Indonesia aims to reduce greenhouse gas emissions by 31.89% unconditionally and up to 43.20% with international support by 2030 and energy mix targets are set at 23% by 2025, 31% by 2050, and over 60% by 2060 [7] [9]. The energy sector, contributing 42% of national emissions, remains the primary focus of the country's decarbonization roadmap [8]. However, by 2023, the actual renewable energy share in the national mix reached only 13.1% [10]. In this context, green hydrogen has emerged as a strategic solution to support the low-carbon energy transition, serving as an energy storage medium, a transportation fuel, and a power source for hard-to-abate industrial sectors [11].

Currently, global hydrogen production capacity reaches approximately 94 million tons per year, yet more than 99% of this is generated from fossil fuels [12]. Green hydrogen, produced via electrolysis powered by renewable energy, accounts for less than 1%, primarily due to high production costs, ranging from USD 3 to 8 per kg, compared to USD 1 to 2 per kg for grey hydrogen [13].

This research focuses on a case study at an industrial company in the Gresik industrial zone, which has initiated hydrogen production via electrolysis. However, 91% of the electricity supply still comes from the national power grid, with only 9% derived from on-site solar photovoltaic (PV) systems, classifying the resulting hydrogen as grey. To label the product as green hydrogen, the company must purchase Renewable Energy Certificates (RECs) [14]. The use of Renewable Energy Certificates (RECs) allows hydrogen to be classified as green hydrogen. This raises questions about the environmental integrity of the production process, given its reliance on fossil-fueled electricity sources.

Accordingly, this study aims to design an optimal hybrid energy supply system to minimize the Levelized Cost of Energy (LCOE) using the HOMER software platform [15]. This approach is expected to deliver an efficient, cost-effective green energy system that supports Indonesia's NZE goals in a practical and sustainable manner [15].

Literature Review

As the global demand for clean and sustainable energy continues to rise, various hybrid renewable energy systems, such as those integrating solar, wind, and biomass, have been extensively studied to enhance efficiency and sustainability across multiple sectors, including industry. In the Gresik industrial port area, the implementation of such systems holds significant potential due to the site's strategic position for renewable energy deployment. One of the main focuses of this research is the technological optimization for green hydrogen production as an environmentally friendly alternative fuel.

Previous studies on hybrid renewable energy systems utilizing HOMER Pro have been conducted by several researchers. El-Maaroufi et al. [16] carried out a techno-economic analysis of an off-grid hybrid energy system combining solar, wind, and biomass in rural northern Morocco. Using HOMER software, they demonstrated that the system could substantially reduce dependence on fossil fuels at a competitive cost. This research offers valuable insights for implementing hybrid energy systems in areas with limited access to energy infrastructure. Similarly, Singh et al. [17] simulated and optimized a hybrid system incorporating solar, fuel cells, and biomass in off-grid locations. Their findings revealed strong potential for reducing operational costs and improving energy sustainability; however, the greatest challenge lies in efficiently integrating these systems under real-world conditions.

Unlike the previous study in the domain of green hydrogen production and storage, Zhang et al. [18] investigated a photovoltaic (PV)-based microgrid optimized for both electricity supply and hydrogen generation. Using HOMER, they identified the optimal configuration for maximizing efficiency while minimizing cost, which is highly relevant to hydrogen research in industrial areas. Furthermore, Bovo et al. [19] demonstrated how hydrogen storage can enhance the performance of multi-technology microgrids powered by renewable sources, highlighting its importance in developing sustainable energy storage solutions for industrial systems.

In terms of microgrid development and optimization with hydrogen integration, Tatar et al. [20] explored optimal microgrid design and operation that incorporates green hydrogen to support intermittent renewable energy sources. Their study emphasized that appropriate system design can ensure stable energy supply despite the variability of renewable resources. Meanwhile, Smith et al. [21] identified the challenges and opportunities of green hydrogen production via water electrolysis and emphasized the importance of electrolysis efficiency in reducing green hydrogen production costs, a particularly relevant aspect in the context of Gresik.

In the context of sustainable energy systems for industrial areas, mapped renewable energy potential for industrial applications in Gresik, providing a critical foundation for developing energy policies in the region. Their findings suggest that a combination of solar and wind energy could significantly enhance industrial energy efficiency. The feasibility of hybrid renewable energy systems for industrial use and found that such systems can reduce long-term operational costs.

The application of electrofuel technologies within a circular economy framework was examined by Rusmanis et al. [22] who proposed that electrofuels could play a crucial role in achieving net-zero emissions. Their study presented a system-level approach leveraging hydrogen as a fuel to support a low-carbon economy, which aligns closely with the focus of this thesis.

Based on the literature review above, several research gaps have been identified. First, there is a lack of location-specific studies that directly address implementation in industrial port areas like Gresik. This research aims to offer new insights into deploying renewable energy technologies in spatially constrained industrial zones. Second, many studies have not fully explored efficient energy storage options, particularly hydrogen-based systems, within hybrid configurations for industrial applications in areas with limited energy access. Third, although the potential use of electrofuels has been widely

Table 1. configurations and their corresponding Cost of Energy (COE) values in various countries for green hydrogen production.

Reference	Country	Method	Objective	Novelty	LCOE (USD/kWh)	Green Energy Mix	Research Gap
Maaroufi et al. [16]	Morocco	HOMER Pro	Off-grid rural electrification	Integration of PV (50%), biomass (30%), hydro (20%)	0.21	PV, Biomass, Hydro	Does not consider winter season resilience
Singh et al. [17]	India	HOMER Pro	Optimization of fuel cell–biomass system	Combination of fuel cell (25%), biomass (35%), PV (40%)	0.18	PV, Biomass, FC	Does not evaluate variable demand
Zhang et al. [18]	China	HOMER + Optimization	Microgrid PV with hydrogen load	Addition of hydrogen as a major component	0.25	PV	Does not consider hydrogen demand dynamics
Bovo et al. [19]	Italy	Technical simulation	Integration of industrial-scale hydrogen-based energy storage	No long-term economic analysis	0.27	PV, H2, Grid	—
Amiruddin et al. [23]	Indonesia	Energy storage simulation	Evaluation of optimal multi-technology storage scenario	PV (60%), wind (25%), hydro (15%)	—	PV, Wind, Hydro	Does not account for extreme intermittency

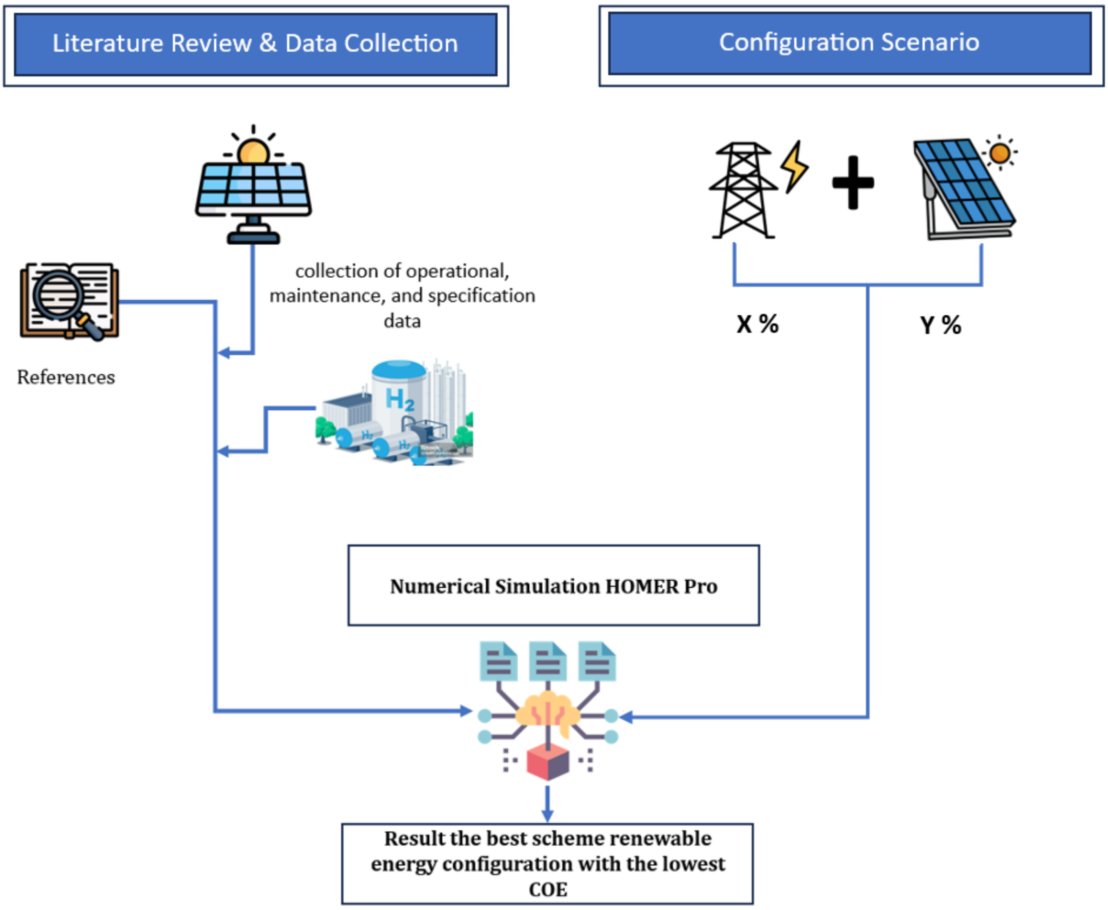


Figure 1. Overview of research schematic.

Table 2. Spesification of H_2 Plant

No	Parameter	Unit 1	Unit 2	Unit
1	Maximum production capacity of existing electrolyze after accounting for maintenance downtime	11.8	11.8	Ton/year
2	Historical hydrogen (H_2) production of the existing electrolyzer	11.8	11.8	Ton/year
3	Maximum H_2 requirement for generator cooling	11.8	11.8	Ton/year
4	Net demineralized water consumption per kg of H_2	0.01	0.01	m^3/kg H_2
5	Actual and nameplate power consumption of electrolyzer and BOP	63.8	63.8	kWh/kg H_2
6	Output hydrogen pressure from hydrogen plant	10	10	Bar
7	H_2 storage capacity	87.5 m^3	87.5 m^3	m^3
8	Availability of injection pipeline for H_2 into the tank	No	No	yes / no
9	Availability of loading area for hydrogen tank truck around the hydrogen plant	Yes	Yes	yes / no
10	Operating age of electrolyzer and BOP	12	12	Years
11	Design lifetime of electrolyzer and BOP	20	20	Years
12	Maintenance frequency history of electrolyzer	PM – 6 months	PM – 6 months	In Operating Hours
13	Operating age of the affiliated power plant connected to the electrolyzer	32	32	Years
14	Design lifetime of the affiliated power plant connected to the electrolyzer	40	40	Years
15	Historical capacity factor of the affiliated power plant (2023)	40.24	40.24	% CF (2023)
16	Historical availability factor of the affiliated power plant (2023)	94.56	94.56	% AF (2023)
17	Excess demineralized water production capacity (excluding power generation needs) available for green H_2 production	150	150	m^3/day
18	Price of demineralized water	225	225	IDR/m^3
19	Power source	SGT	SGT	UAT/SST
20	Single line diagram document	Attached	Attached	-
21	REC Price	58.29	58.29	IDR/kWh
22	Nearest TR network specification and distance	380 V, 60 m	380 V, 60 m	Voltage, meter
23	Estimated residual value of existing hydrogen plant assets	89.987.055,837.32		IDR

discussed, their economic and technical feasibility in real industrial energy systems remains underexplored.

This literature review highlights the significant contributions of previous studies to the development of hybrid renewable energy systems and green hydrogen production. While considerable progress has been made, particularly through simulations and system optimization using HOMER Pro, notable gaps remain especially regarding implementation in industrial port environments such as Gresik. Future research that integrates cutting-edge technologies with deeper economic analysis will be crucial in addressing these gaps. Here is a summary of research findings on renewable energy configurations and their corresponding Cost of Energy (COE) values in various countries for green hydrogen production. Based on personal analysis, the novelty of the following journals is as Table 1.

METHODS AND ANALYSIS

This chapter explains the research methods used in this study. The main goal is to analyze and simulate a hybrid renewable energy system to support green hydrogen production. The methodology includes steps such as data collection, system modeling, scenario development, and simulation. The research scheme is illustrated in the Figure 1.

This research begins with a comprehensive literature review, including analyses of both national and international journals, in order to gain an in-depth understanding of the issues addressed in this study. In parallel, data were collected on the technical specifications, operational performance, and maintenance requirements of the existing photovoltaic (PV) and hydrogen (H_2) production units.

The microgrid simulation process consists of several critical stages. First, the electrolysis load was calculated based on the projected hydrogen production needs. Subsequently, selected renewable energy sources were configured as input scenarios for the microgrid model. These configurations were simulated using HOMER Pro software to determine the most optimal system design. The best configuration was selected based on the lowest Levelized Cost of Energy (LCOE) obtained from the various simulation scenarios.

Data collection included both quantitative and qualitative information gathered from academic journals, technical reports, and expert opinions. All data were normalized to ensure comparability across different units and measurement scales. The simulation stage involved designing system configurations either hybrid or standalone, based on the availability of renewable energy sources. Key input parameters included electricity demand profiles, solar irradiance, wind speed, biomass availability, investment and operational costs, and system lifetime.

Table 3. Operational and Maintenance Parameter

No	Parameter	Unit 1	Unit 2
1	Number of H_2 Plants owned (units)	1	1
2	Capacity of each H_2 Plant (Nm^3/hour)	15	15
3	Annual production of each H_2 Plant (tons/year)	11,810232	11,810232
4	Installed PV capacity (existing PV system)	50.6 kWp	
5	Electrical capacity of each H_2 Plant (kW)	86	86
6	Capacity of each H_2 Plant (Nm^3/hour)	15	15
7	Consumption (kW/Nm^3)	5.7	5.7
8	Daily production load of H_2 Plant (%)	100%	100%
9	Daily H_2 production load (Nm^3/day)	360	360
10	Daily H_2 production load (kg/day)	32.3	32.3
11	Daily electricity demand (kWh)	2.064	2.064
12	Average Energy consumption of H_2 Plant (Actual Measurement) (kWh/day)	2.175	2.175
13	Energy consumption of H_2 Plant (Based on Nameplate) (kWh/day)	3.957,3	3.957,3
14	Energy produced by PV (kWh/day)	223.33	
15	Energy from REC (Renewable Energy Certificate) (kWh/year)	659.000	

HOMER Pro was used to perform technical and economic optimization with the aim of minimizing LCOE while ensuring system reliability. The final evaluation considered parameters such as LCOE, Net Present Cost (NPC), and system reliability indices, enabling the identification of the most feasible and cost-effective renewable energy system configuration to support hydrogen production.

Technical Specifications and Electrical Load Measurements of the H_2 Plant

Data collection was conducted at an energy company located in Indonesia, where one of its activities includes producing hydrogen for internal use. Based on data gathered over a three-month period, several operational, maintenance specification parameters of the H_2 plant were obtained, as presented in Tables 2 and 3.

RESULTS AND DISCUSSIONS

Based on the collected data, the electricity load (in kWh) of the H_2 plant supplied by the PLN grid and solar PV is shown in Figure 2. Currently, 91% of the plant's electricity demand is supplied by the grid, while only 9% comes from PV. As a result, the renewable energy fraction in the hydrogen production process remains relatively low, leading to the consequence of REC (Renewable Energy Certificate) payments for 91% of the electricity drawn from the grid.

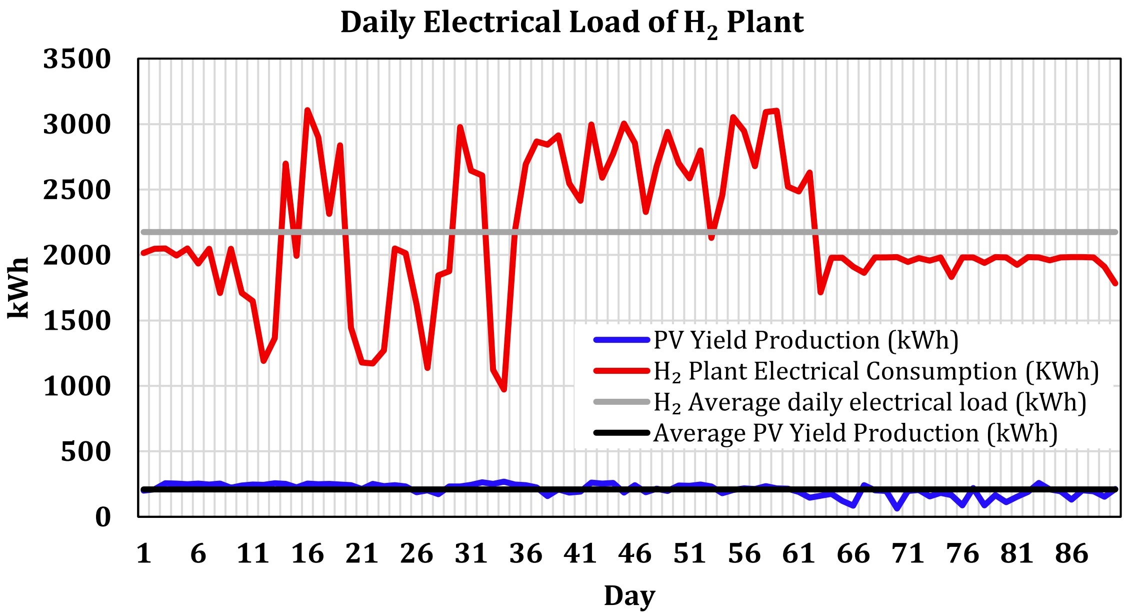


Figure 2. Electrical load data of the hydrogen (H_2) plant, supplied by both the state electricity grid (PLN) and the installed solar photovoltaic (PV) system.

Another analysis conducted was to assess the potential of solar energy. In 2023, the company installed a 50.6 kWp solar PV system, which supplies approximately 9% of the total electrical load for the hydrogen (H_2) plant. The PV system covers an area of 248.49 m^2, with annual solar irradiation of 1566.7 kWh/m^2. After two years of operation, performance efficiency was evaluated as equation (1).

$$E\ pv\ (theoretical) = Irradiasi\ \times\ A\ (pv\ area) \quad (1)$$

$$E\ pv\ (theoretical) = 1566{,}7\ kWh/m^2\ x\ 248{,}49\ m^2$$

$$E\ pv\ (theoretical) =\ 389312{,}41\ kWh/\text{year, atau } 32442{,}70 \text{ kWh/month}$$

The actual monthly energy output measurement for the existing PV system with a capacity of 50.6 kWp is shown in Figure 3, with an average monthly energy production of 6813.52 kWh as presented in Figure 4. The actual efficiency is calculated based on equation (2).

$$Eff\ = E\ pv\ (actual)/E\ pv\ (theoretical) \quad (2)$$

$$Eff\ = 6813{,}52\ \text{kWh}\ /32442{,}70\ \text{kWh} = 21\%$$

In December, higher rainfall reduces sunlight hours, which affects the energy produced. The PV system operates for a shorter time, resulting in lower energy output compared to other months. During October to December, increased rainfall in the Gresik area also affected the PV peak hours, which shifted earlier from around 11 a.m. during July to September to around 9–10 a.m. This performance is slightly lower than the nameplate efficiency of 21.2%, and can serve as a benchmark for further solar PV development in the facility. Currently, the company has 30,800 m^2 of unutilized space.

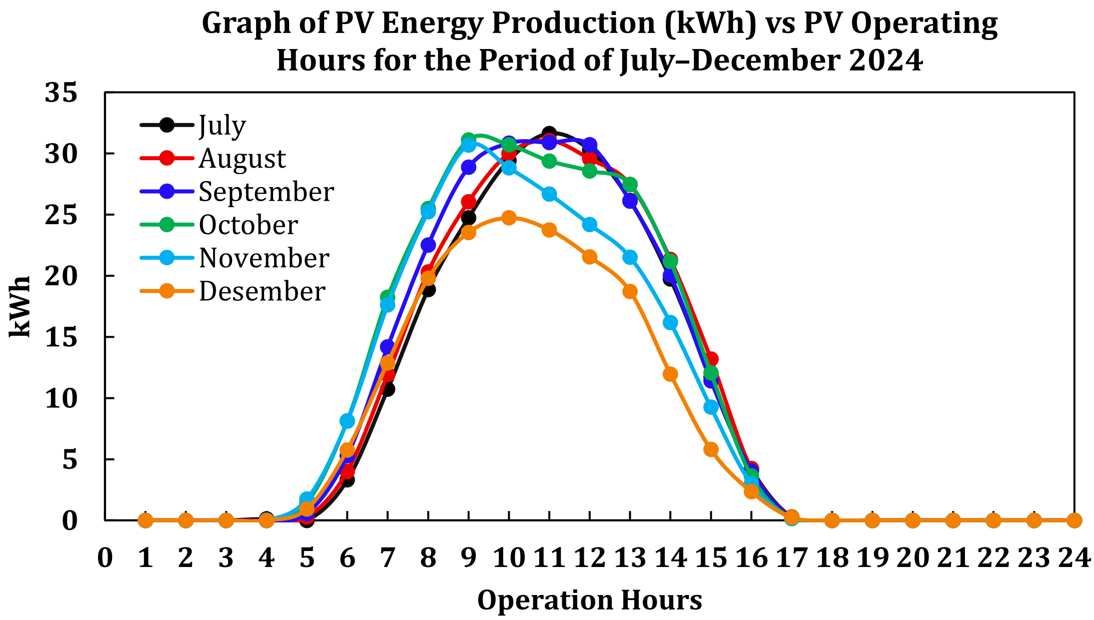


Figure 3. Daily PV Energy Output (kWh) during the Period of July to December 2024.

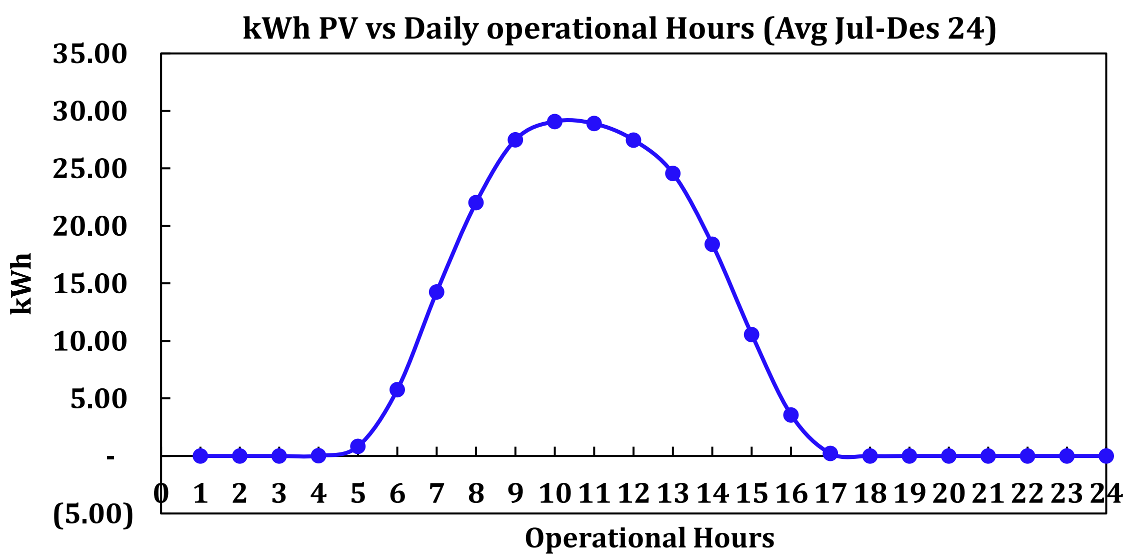


Figure 4. Daily PV Energy Output (kWh)

Based on the measured efficiency, the additional solar PV system could potentially generate up to 10,133,415.6 kWh/year with 6,17 MWp of PV.

Numerical Simulation Results

This study employs three scenario schemes by varying the installed capacity of the photovoltaic system (kWp) and the load on the hydrogen (H_2) electrolyzer unit. These configurations and the corresponding HOMER input parameters are presented in Table 4.

The technical and economic input parameters for the HOMER Pro simulation are presented in Table 5. The technical parameters are based on direct field measurements, while the economic parameters are obtained from actual contracts or maintenance costs, as reflected in the company's financial modules. Therefore, all input data are derived from real-world industrial sources.

Three different hybrid system configurations were analyzed to determine the optimal solution based on the cost of energy (COE) and energy mix are shown in Table 6.

Table 4. Energy system configuration schemes

No	Homer Method	Energy Schema Configuration	H_2 Plant Load (kWh/hour)
1	Search Space	Existing (Grid + PV 50 kWp)	90.6
2	Search Space	Grid + PV 430 kWp	90.6
3	Search Space	Grid + PV 6.179 kWp	5000

Table 5. HOMER economic parameter input

Alernative Energy Componen	Capex (Rp/kW)	Capex (Rp/kW)	Capex (Rp/kW)	Opex (Rp/kW-Yr)	Replace -ment (Rp)	Lifetime (year)
	50.6 kWp	430 kWp	6179 kWp			
Solar PV System	**14.222.222**	**12.196.276**	**9.147.207**	284,444	Equal CAPEX	12
`PV	4.772.727	4.092.855	3.069.641			
Inverter	2.170.566	1.861.370	1.396.028			
Protrction, cabling, accesosrries	5.491.518	4.709.255	3.531.941			
Commisioning, Testing	1.787.411	1.532.795	1.149.597			
Grid	2.800	2.800	2.800	-	-	-

Table 6. Result of Configuration Scheme simulation

No	Configuration Scheme	NPC (Rp)	COE (Rp/kWh)	Energy Mix (kWh)		Renewable Fraction (%)
				PV	Grid	
1	Existing (Grid + PV 50 kWp)	30.274.286.000	2.783	77.021	719.722	9%
2	Grid + PV 430 kWp	26.942.910.000	2.321	662.379	483.183	57.8%
3	Grid + PV 6,179 kWp	1.300.000.000.000	2.175	9.545.956	34.780.790	21%

The initial step in the HOMER simulation process is to input the electrical load profile of the H_2 plant. Figure 5 shows an example of the load input in HOMER for simulation scenario 3, featuring an hourly load of around 5,000 kWh.

Among the three configurations analyzed, the best Cost of Energy (COE) was obtained from configuration scheme 3, with a COE of 2,175 Rp/kWh and a Net Present Cost (NPC) of Rp 1,300,000,000,000. This configuration increased the renewable energy fraction to 20.9%, primarily supported by photovoltaic (PV) sources. As the optimal configuration, the following presents the detailed simulation results of option 3, including the cost summary, electrical performance, and renewable energy penetration as shown in Figure 6.

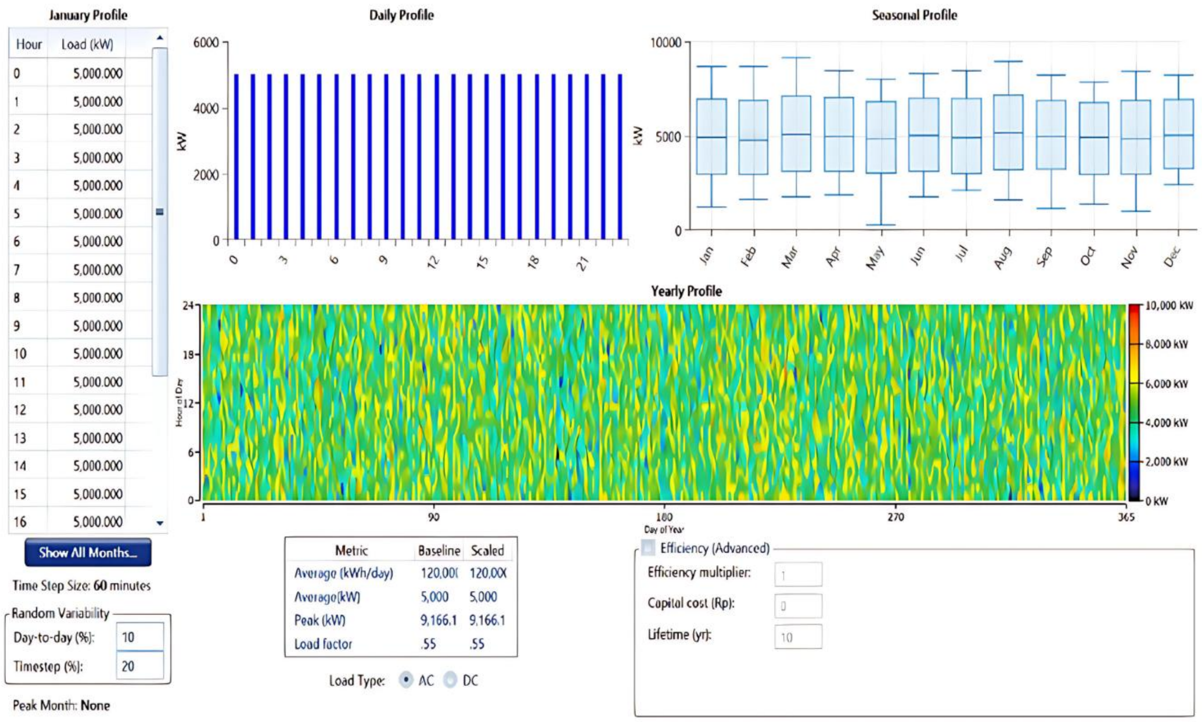
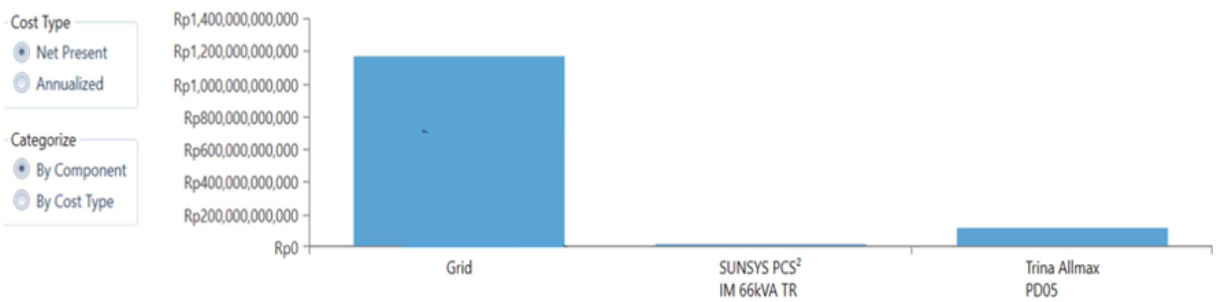


Figure 5. Electrical load input in Homer Pro Simulation



Component	Capital (Rp)	Replacement (Rp)	O&M (Rp)	Salvage (Rp)	Total (Rp)
Grid	Rp0.00	Rp0.00	Rp1,170,000,000,000	Rp0.00	Rp1,170,000,000,000.00
SUNSYS PCS² IM 66kVA TR	Rp9,984,602,727.27	Rp5,070,869,887.00	Rp2,720,407,046.79	Rp0.00	Rp17,190,071,536.28
Trina Allmax PD05	Rp56,685,241,779.00	Rp41,558,822,603.47	Rp24,013,269,790.89	Rp0.00	Rp117,456,284,949.06
System	Rp66,669,844,506.27	Rp46,629,692,490.47	Rp1,200,000,000,000	Rp0.00	Rp1,300,000,000,000.00

Figure 6. Cost summary for the optimal configuration: Grid + 6.179 MWp PV

The breakdown of energy productivity from each energy source is shown in Figure 7, which provides a detailed overview of the energy mix for the Grid + 6.179 kWp PV . The total annual energy production is approximately 44.326.746 kWh/year, which is consumed by the hydrogen (H_2) plant. Based on the simulation results, 20.9% of the load can be supplied by PV sources, while the remaining 79.1% is covered by the grid. A daily overview of energy demand and supply is illustrated in the energy balance shown in Figure 8.

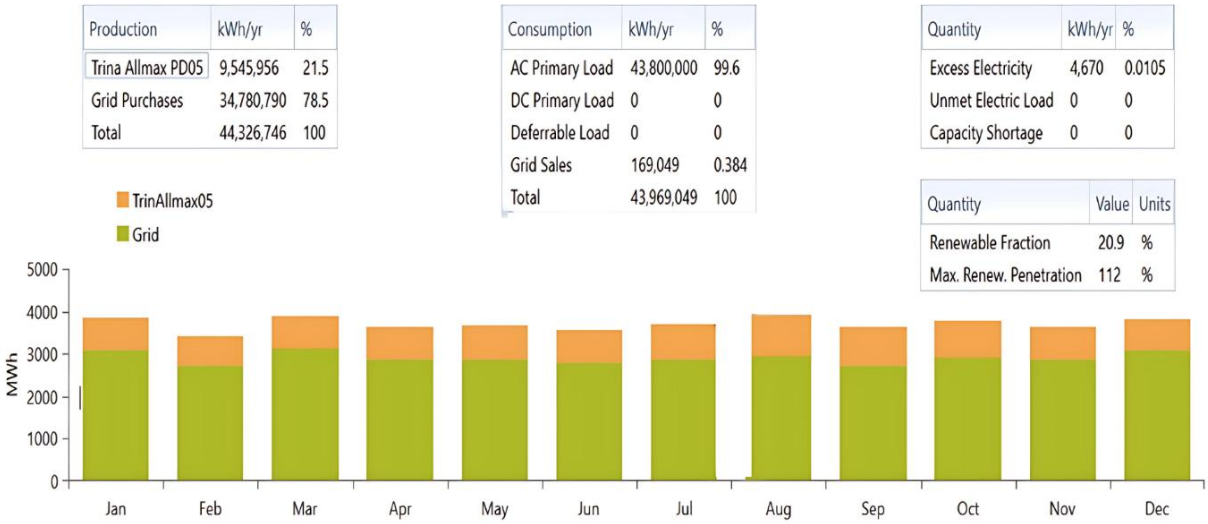


Figure 7. Energy mix of the best configuration: Grid + 6.179 kWp PV

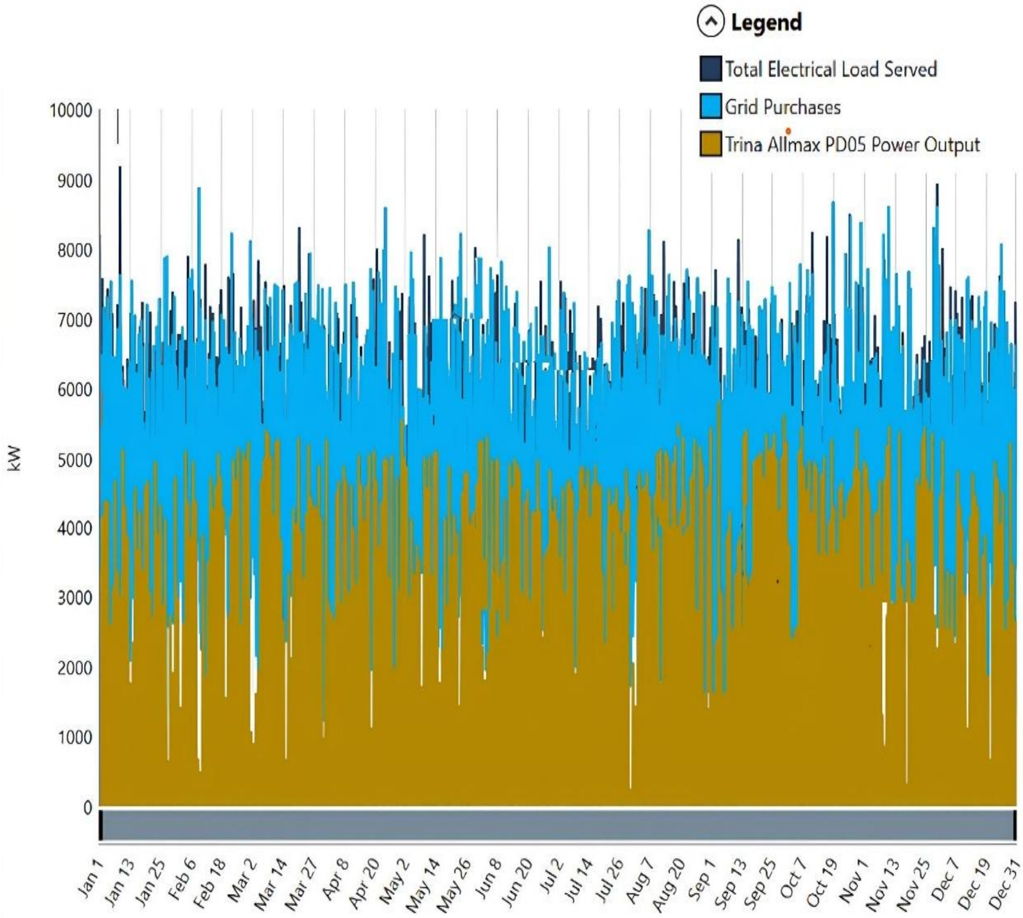
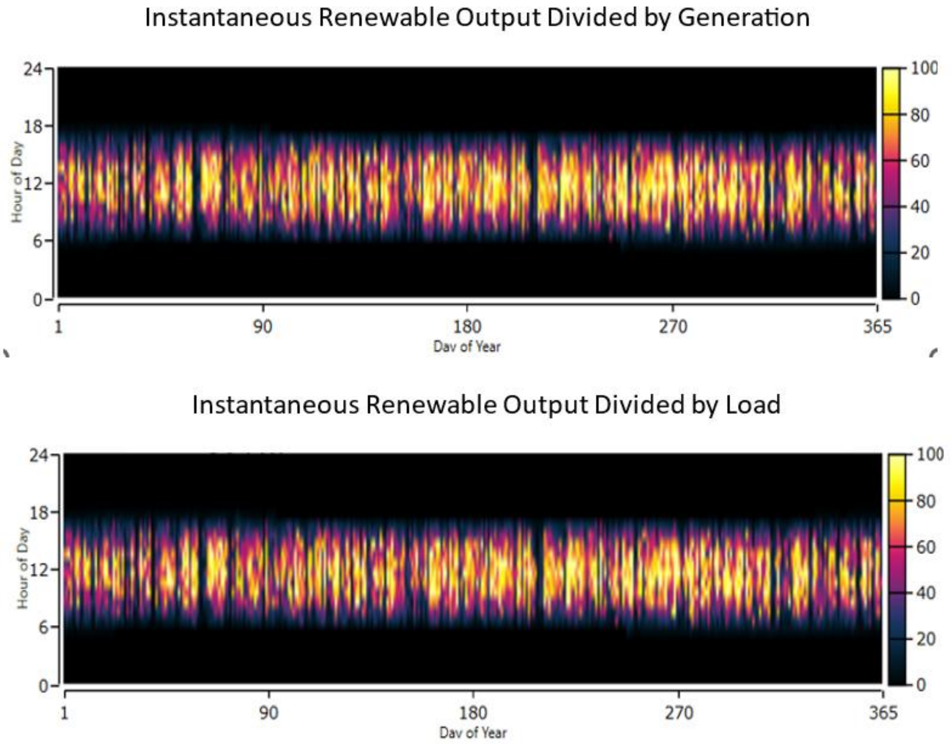


Figure 8. Energy demand 5000 kWh/hour and supply balance for the Grid + 6.179 kWp PV



Energy-based metrics	Value	Units
Total renewable production divided by load	21.7	%
Total renewable production divided by generation	21.5	%
One minus total nonrenewable production divided by load	100	%

Figure 9. Energy mix of configuration system Grid + 6.179 kWp PV

The renewable penetration is illustrated in Figure 9. As shown, the highest electricity production from renewable sources occurs between 06:00 AM and 05:00 PM. This pattern is due to solar irradiation being available for only about 8 hours per day, limiting PV output to that time window. In contrast, the hydro source provides continuous and non-intermittent power supply, as the pump operates 24 hours a day without interruption.

CONCLUSIONS

This study presents a comprehensive analysis and simulation of a hybrid renewable energy system to support green hydrogen production in an industrial setting in Gresik, Indonesia. Using real operational data and HOMER Pro simulations, several important conclusions have been drawn.

First, in terms of energy efficiency, the performance of the existing solar PV system was evaluated with an actual efficiency of approximately 21%, slightly below its nameplate rating. The findings confirm that seasonal variations, particularly during the rainy season, reduce sunlight availability and affect PV output and peak operation hours. Nevertheless, the potential for system expansion is significant, with over 30,000 m^2 of available land that could support the installation of 6.179 MWp PV to improve efficiency.

Second, from a cost-effectiveness standpoint, the simulation results show that increasing PV capacity and optimizing energy demand significantly reduce the Levelized Cost of Energy (LCOE). The best scenario (Scenario 3), which utilized a 6.179 MWp PV system combined with grid electricity and a 5,000 kWh/hour load, achieved the lowest

LCOE at IDR 2,175/kWh compared to the baseline of IDR 2,783/kWh resulting in substantial cost savings over time.

Third, the renewable energy integration improved considerably. The proposed hybrid system increased the renewable energy fraction from the initial 9% (existing condition) to 21%. This shift represents a meaningful step toward industrial decarbonization and aligns with Indonesia's national targets for increasing renewable energy share and reducing emissions in the energy sector.

Overall, this study demonstrates that a hybrid energy system integrating photovoltaic and grid electricity can enhance energy efficiency, reduce operational costs, and increase renewable penetration for hydrogen production. The approach provides a practical and scalable model for other industrial areas seeking to transition toward green hydrogen under real-world constraints.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article.

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