OPTIMIZING SOLAR-WIND-BIOMASS-HYDROGEN HYBRID RENEWABLE ENERGY SYSTEM FOR LY-SON ISLAND

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Abstract - This study investigates various configurations of Solar–Wind–Biomass–Hydrogen Hybrid Renewable Energy Systems (SWBH-HRES) for Ly Son Island. Using HOMER Pro software, the analysis identifies an optimal configuration consisting of 8 kW of photovoltaic panels, a 6 kW wind turbine, a 3.5 kW syngas generator, and a 10 kW electrolyzer. Scheduled generator operation produces 56,524 kWh of electricity and 942 kg of hydrogen annually, which outperforms the automatic control strategy, yielding only 50,423 kWh and 835 kg, respectively. The SWBH-HRES enhances energy utilization efficiency, resulting in only 1.6% excess electricity, compared to 18.3% in systems without hydrogen production. The initial capital cost is USD 19,268 for systems incorporating hydrogen production and USD 17,718 for systems without it. Hydrogen-producing systems become economically favorable at USD 5.0-5.5/kg, yielding USD 36,000 profit. Environmentally, these systems reduce GHG emissions up to 6.58 kg CO_2-eq/kWh.

Key words - Renewable energy; Hybrid renewable energy system; Optimizing hybrid renewable energy system; HOMER software; GHG emission reduction

1. Introduction

Global greenhouse gas (GHG) emissions continue to rise despite international commitments under the Paris Agreement to limit global warming to well below 2°C above pre-industrial levels. Achieving the 1.5°C target, as recommended by the Intergovernmental Panel on Climate Change (IPCC), requires reducing global CO_2 emissions by 45% by 2030 and reaching net-zero by 2050 relative to 2010 levels [1]. Transitioning from fossil fuels to renewable energy sources is critical to meeting these targets, particularly in the power generation sector, which contributes significantly to global emissions. The International Energy Agency (IEA) projects that renewable energy will contribute approximately 90% of global electricity generation by 2050 [2].

Vietnam has aligned with these global decarbonization goals through its National Power Development Plan VIII (2021–2030), which targets renewable sources to account for 30.9–39.2% of total electricity generation by 2030 and over 70% by 2050 [3]. However, the intermittency and variability of renewable resources, such as solar and wind, pose significant challenges to energy reliability [4–5]. Hybrid Renewable Energy Systems (HRES), which combine multiple renewable energy sources, represent a promising approach to improving system stability, minimizing storage requirements, and reducing overall energy costs when compared to single-source configurations [6–8].

HRES optimization has progressed through advanced simulation tools like HOMER Pro, enabling detailed techno-economic assessments of various configurations [9]. Yet, most studies to date focus on two-source systems, particularly solar–wind, with limited analysis of multi-source systems that include biomass and hydrogen. Solar–Wind–Biomass–Hydrogen Hybrid Renewable Energy Systems (SWBH-HRES) represent a more comprehensive and resilient solution by integrating diverse resources and enabling hydrogen production for both storage and revenue generation.

Despite these advantages, existing research has several limitations. Hydrogen is primarily considered a storage medium, with insufficient evaluation of alternative operational strategies. In particular, the comparative effectiveness of scheduled versus automatic hydrogen production control strategies remains underexplored. Additionally, there is a lack of optimization studies involving four-source systems that combine solar, wind, biomass, and hydrogen. Hydrogen's potential as a tradable commodity also remains inadequately assessed, especially concerning its financial viability and revenue potential in isolated or island systems.

This study aims to address these research gaps through the comprehensive optimization of a SWBH-HRES tailored for Ly Son Island, Vietnam. The key objectives are: (1) to develop a detailed system model integrating solar photovoltaic, wind, biomass syngas generators, and hydrogen production units; (2) to optimize the configuration using HOMER Pro under realistic operational constraints; (3) to compare scheduled and automatic control strategies for hydrogen dispatch; (4) to conduct a techno-economic assessment considering investment, operational costs, and hydrogen revenues; and (5) to evaluate environmental benefits via greenhouse gas emission reduction analysis.

Ly Son Island, located approximately 15 nautical miles off the coast of Quang Ngai Province, possesses high solar irradiance, seasonal wind patterns, and biomass availability from agricultural residues and municipal solid waste. These characteristics make it a suitable case study for developing SWBH-HRES optimization methodologies applicable to similar tropical island contexts.

2. Methodology and study area

2.1. Diagram of the SWBH-HRES system

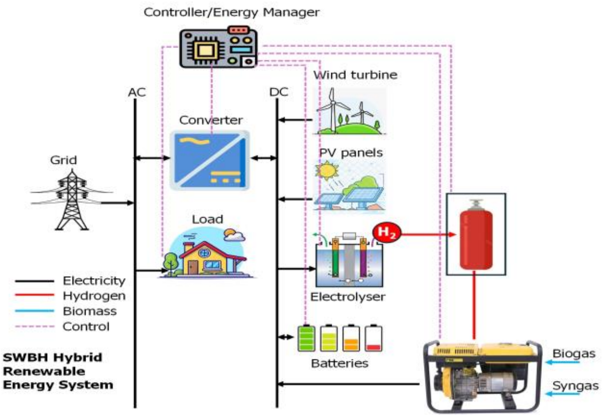


***Figure 1**. Diagram of SWBH-HRES*

Figure 1 presents the complete diagram of the SWBH-HRES hybrid renewable energy system. In the SWBH-HRES, most components such as wind turbines, solar panels, converters, hydrogen production and storage systems, and control systems are widely available on the market. These components come in various sizes, suitable for the capacity scales of different HRES configurations. However, biomass-based power generation systems remain less common, making the integration of biomass energy into HRES quite limited. This limitation arises from the bulky nature of biomass energy systems, their complex control requirements, and the challenges associated with traditional biomass storage solutions. Additionally, popular optimization software for HRES calculations, such as HOMER, does not specifically include detailed biomass modules.

Thus, researching and developing components for biomass-based power generation systems is essential, both to support the broader adoption of SWBH-HRES and to contribute to updating and expanding the capabilities of HRES optimization software.

This study investigates the optimization of key parameters in the SWBH-HRES to improve energy efficiency, economic viability, and environmental sustainability.

2.2. Study Area

The case study was conducted on Ly Son Island, located at 15.382°N, 109.098°E. Ly Son is an island district of Quang Ngai Province, situated approximately 15 nautical miles off the mainland, accessible from Sa Ky Port (Figure 2). The island covers an area of about 10 km² and has a population of over 21,000 residents. Among them, approximately 60% of households depend on fishing as their primary source of income, while 30% are engaged in agricultural activities.

Ly Son experiences a tropical monsoon climate typical of oceanic regions, characterized by high temperatures and humidity. The island receives an average of approximately 2,430 sunshine hours annually, with peak solar irradiance occurring between 10:00 AM and 2:00 PM. The average wind speed is around 1.5 m/s, peaking during the northeast monsoon season (October to June) at 5–10 m/s, and occasionally reaching up to 30–40 m/s, especially in October. These climatic conditions endow Ly Son Island with considerable renewable energy potential, which is essential for facilitating its sustainable development. Figure 3a and b illustrate the average solar irradiance and wind speed on Ly Son Island, based on NASA datasets.

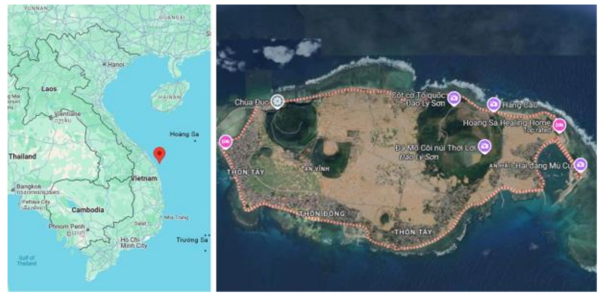


***Figure 2**. Geographic location of Ly Son Island*

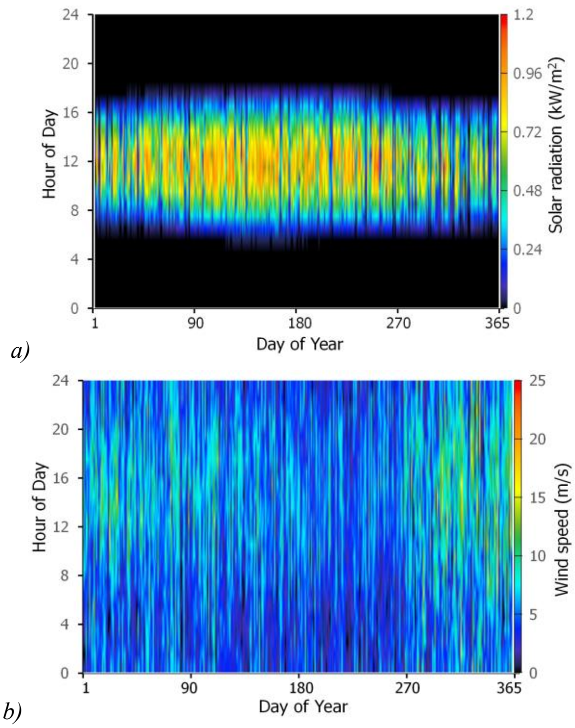


***Figure 3**. Solar radiation (a) and average wind speed (b) on Ly Son Island*

Municipal solid waste in the district mainly consists of household refuse and agricultural by-products. The collected waste is transported to a centralized solid waste treatment facility, which has a maximum capacity of 25 tons/day. On average, 22–25 tons/day are processed, with peak volumes reaching 26–30 tons/day.

Ly Son Island is connected to the national grid via a 22 kV submarine cable. However, due to limited grid capacity, the integration of renewable energy sources has become necessary. In this study, HOMER software was employed to optimize the configuration of a on-grid HRES for Ly Son Island, with 30 kWh/day demand and 3.01 kW peak load. Two scenarios were considered: one without hydrogen production and one with hydrogen integrated into the system.

3. Results and discussion

3.1. Stand-alone SWB-HRES system

3.1.1. System without Battery Storage

To ensure a reliable electricity supply to the load, the system is configured with a 2 kW solar PV array, a 2 kW wind turbine, a 3.5 kW syngas generator, and a 2.75 kW converter (Figure 4). The system produces approximately 14,115 kWh of electricity annually, while the annual load demand is 10,950 kWh.

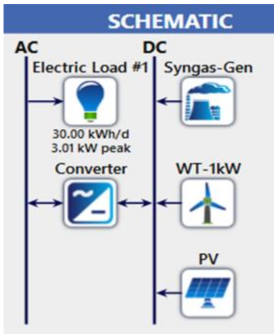
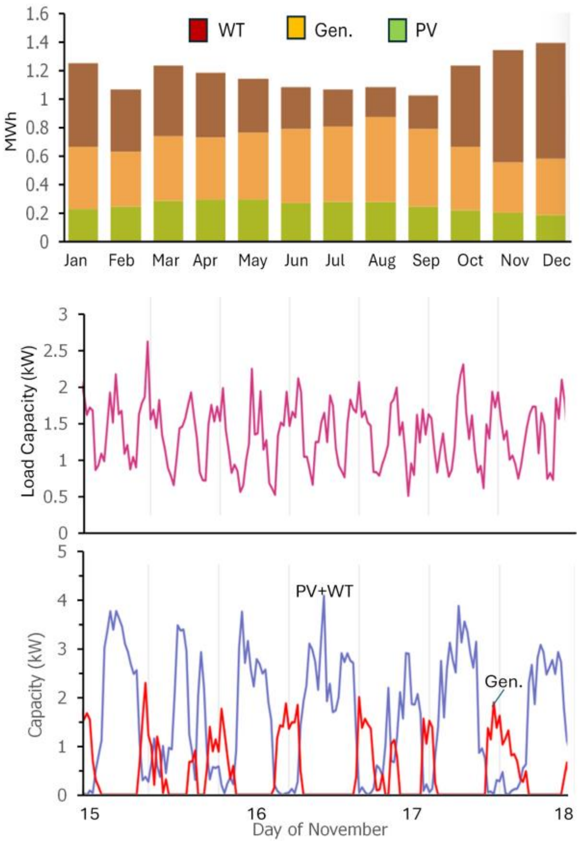


Figure 4. *Schematic of stand-alone SWB-HRES without energy storage*

This results in excess electricity, which accounts for 18.3% of the total generated energy converter (Figure 5a).



a)

b)

Figure 5. *Stand-alone SWB-HRES without energy storage: (a) Solar, wind, and biomass power contribution; (b) Time-series data of load demand, combined solar-wind power, and biomass power generation in mid-November*

In this configuration, the generator set functions as a power-balancing unit. Figure 5b illustrates the time-series variations of load demand, combined solar-wind output, and generator power. The generator is only activated when the solar-wind power output is insufficient to meet the load demand. Therefore, the engine control system relies on monitoring the power difference between generation and consumption.

Moreover, the engine must be maintained in a standby mode, and its output power frequently fluctuates during operation. This operating pattern affects the engine's lifespan and reduces overall energy efficiency, as the engine often works under partial-load conditions.

3.1.2. System with battery storage

Figure 6 presents the schematic of the stand-alone SWB system with battery storage. Compared to Figure 4, this configuration includes a 19 kWh battery. As shown in Figure 7a, the generator only operates when the battery's state of charge (SOC) falls below the predefined minimum (20% in this case). Under other conditions, the battery is charged using excess energy from the hybrid system when generation exceeds load demand.

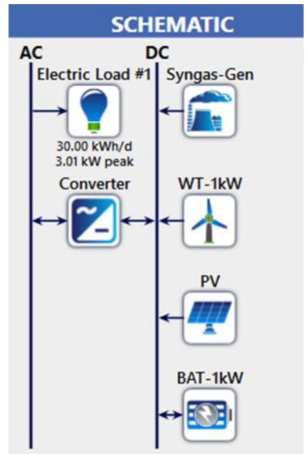
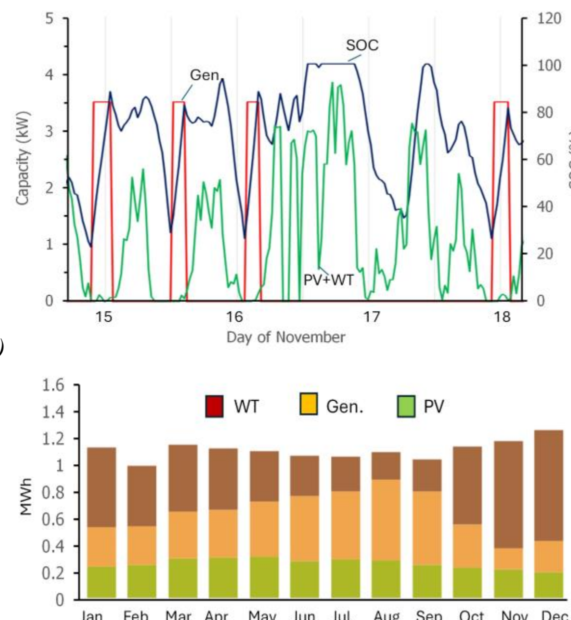


Figure 6. *Schematic of stand-alone SWB-HRES with energy storage*

Excess electricity accounts for 8.35% of the total generated energy (Figure 7b, which is lower than that of the system without energy storage. With the addition of battery storage, the engine operates in an on-off mode. Its operating time is reduced compared to the system without storage. When operating, the generator runs at rated capacity, allowing for better fuel utilization.

The control system is simplified, as only SOC monitoring is required to start the generator and switch it to rated power operation.



a)

b)

Figure 7. *Stand-alone SWB-HRES with energy storage: (a) Time-series data of load, combined solar-wind power, biomass power, and battery SOC in mid-November; (b) Power contribution from solar, wind, and biomass*

3.2. Stand-alone Solar-Wind-Biomass hybrid renewable energy system with hydrogen production (SWBH-HRES)

3.2.1. System with automatic load-following generator control

In this configuration, surplus electricity generated by the HRES is diverted to hydrogen production, with priority given to fulfilling the load demand (Figure 8). The generator-engine unit acts as a dispatchable source to balance the system power.

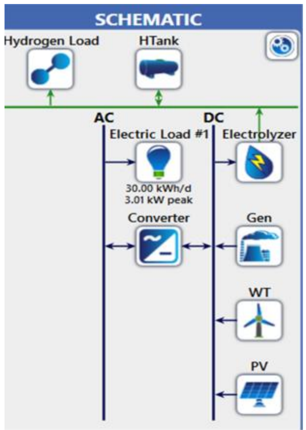


Figure 8. *Schematic of Stand-alone SWBH-HRES system*

Unlike conventional stand-alone systems where the generator follows load variation, the engine in this setup operates at rated capacity and switches on or off based on system conditions (Figure 9b, c).

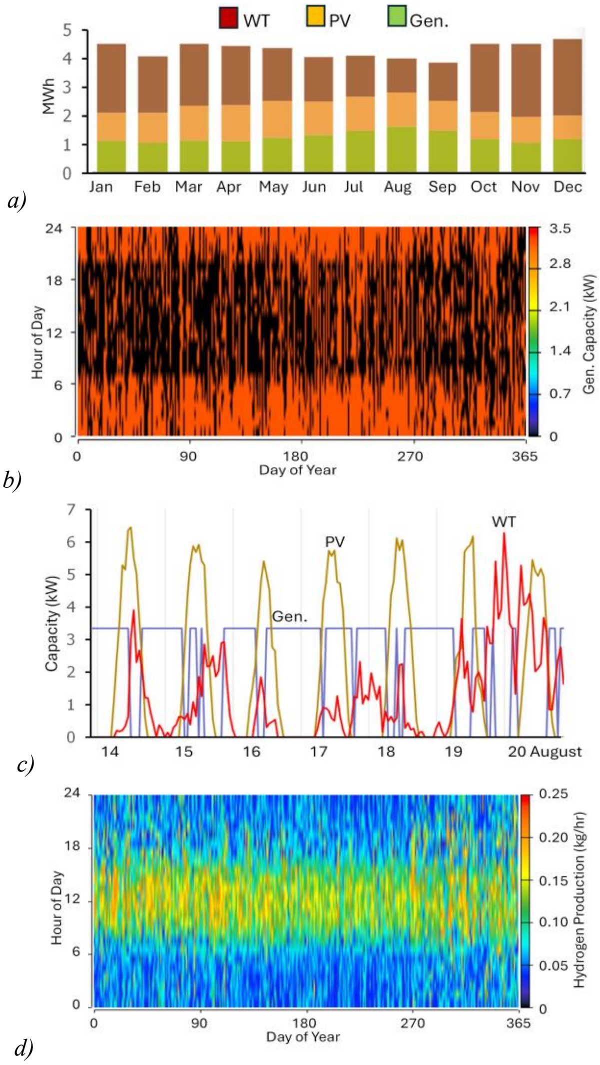


Figure 9. *Stand-alone SWBH-HRES and automatic load-following generator control: (a) Electricity generation by source; (b) Generator power variation by hour and season; (c) Solar, wind, and generator output in mid-August; (d) Hydrogen production by hour and season*

The SWBH-HRES consists of an 8 kW solar PV array, a 6 kW wind turbine, a 3.5 kW generator, a 3.63 kW converter, and a 10 kW electrolyzer. Annual output includes 50,423 kWh of electricity and 835 kg of hydrogen (Figure 9a, d).Due to electrolyzer capacity constraints, only 1.6% of the total generation is lost as unused surplus during peak production periods.

The generator control strategy is triggered when the combined solar and wind power is insufficient to meet the load. Upon activation, the generator runs at full rated power, enhancing fuel efficiency and minimizing specific emissions.

3.2.2. System with scheduled generator operation

In this scenario, the HRES utilizes excess renewable energy for hydrogen production, enabling full system utilization. Solar and wind generation remain dependent on climatic conditions, while biomass-fueled electricity generation is dispatchable, allowing operation based on fuel availability and engine maintenance needs. Figure 10a presents a pre-set daily operation schedule, where the syngas engine runs at night and remains offline during daytime periods of high solar output for maintenance purposes.

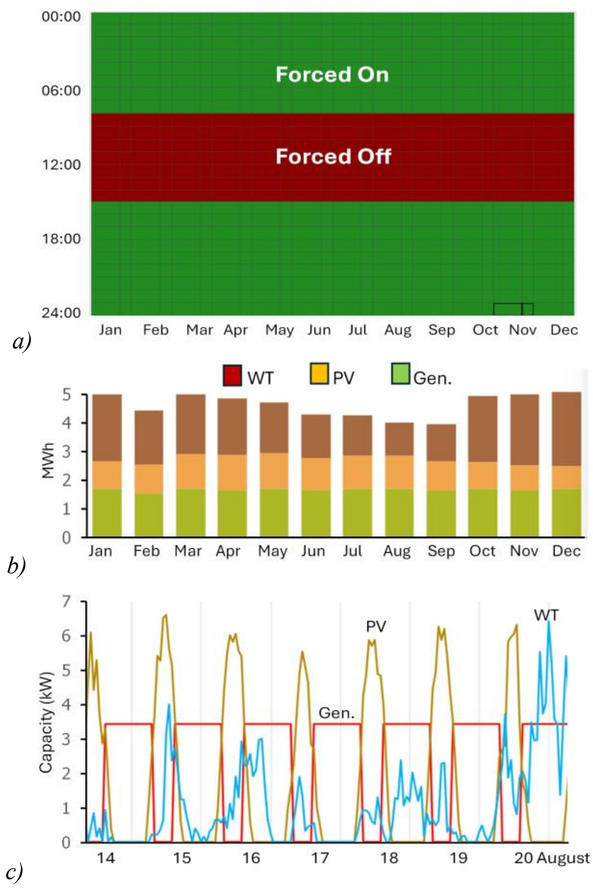


Figure 10. *Stand-alone SWBH-HRES with scheduled generator operation: (a) Generator operation schedule; (b) Electricity generation by source; (c) Solar, wind, and generator output in mid-August*

Using the same system specifications as previously described, scheduled operation results in 56,524 kWh/year of electricity and 942 kg/year of hydrogen production (Figure 10b).

In this case, the generator control system is simplified further. The engine is started according to a predefined time schedule and operates immediately at rated capacity. This control strategy requires only a single-mode governor, enabling stable and efficient operation with minimal control complexity (Figure 10c).

3.3. Grid-tied SWB-HRES with and without hydrogen production

3.3.1. Without hydrogen production

When connected to the grid, the HRES operates in parallel with the national electricity system. This configuration is similar to existing grid-tied rooftop solar systems. The SWB-HRES functions similarly: when the system's electricity output exceeds the load demand, the surplus energy is exported to the grid; conversely, when the generation is insufficient, the grid supplies the deficit (Figure 11).

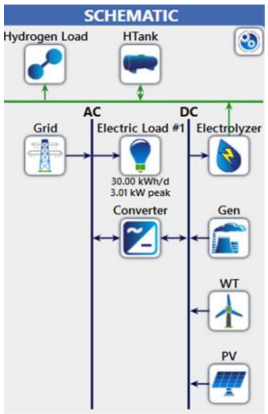


Figure 11. *Schematic of on-grid SWB-HRES*

When a generator is included in the HRES, its output can be regulated, as it serves as a dispatchable power source. The operation of the generator-engine unit can be optimized to improve the system's economic performance. Figure 12 shows the system under a grid selling price of \$0.05/kWh, while Figure 13 demonstrates generator output when the price increases to \$0.07/kWh. HOMER software optimizes generator operation to ensure that revenue from energy sales exceeds operational and replacement costs.

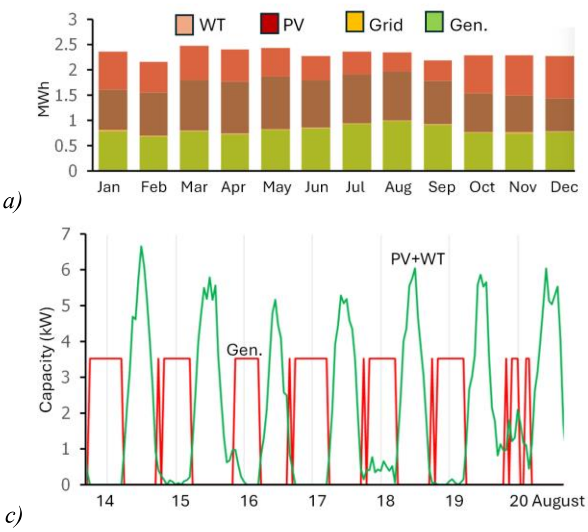


Figure 12. *On-grid SWB-HRES: (a) Electricity production by source; (b) Time-series of combined solar-wind power and generator output in mid-August, with a grid selling price of \$0.05/kWh*

Simulation results indicate that at \$0.05/kWh, approximately 60% of the electricity is exported to the grid, while at \$0.07/kWh, this proportion increases to 74% of the total electricity generated.

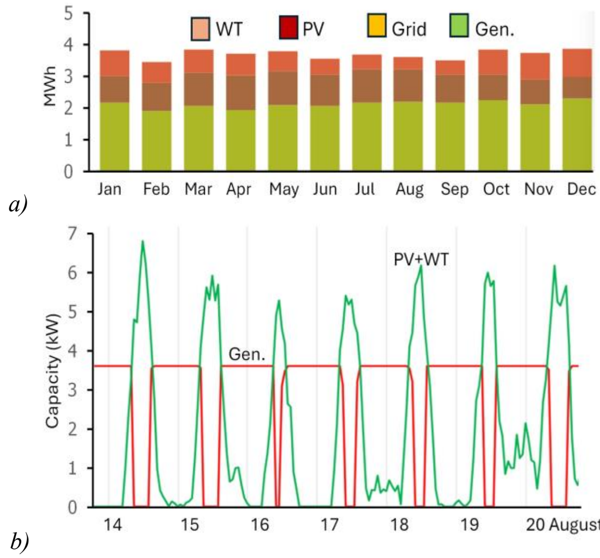


Figure 13. *On-grid SWB-HRES: (a) Electricity production by source; (b) Time-series of solar-wind and generator output in mid-August at a grid selling price of \$0.07/kWh*

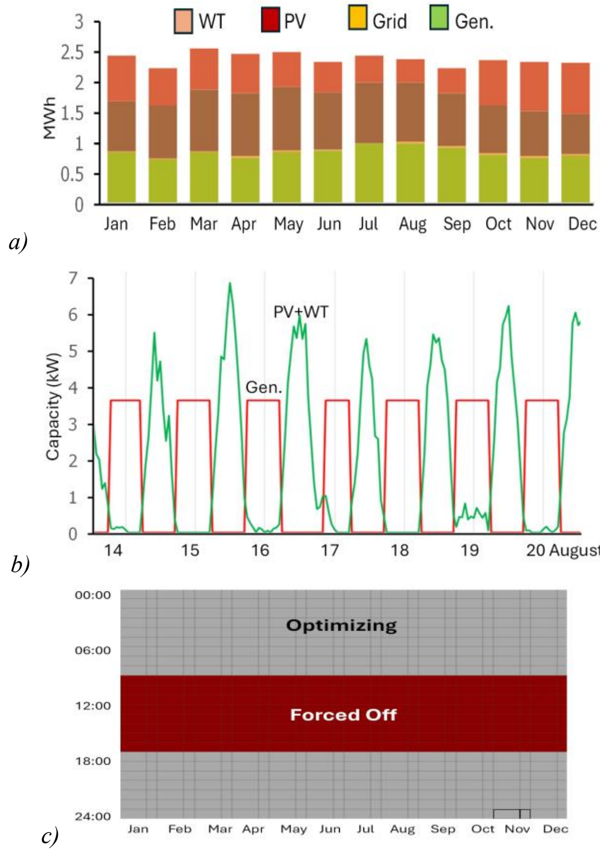


Figure 14. *On-grid SWB-HRES: (a) Electricity production by source; (b) Time-series of solar-wind and generator output in mid-August; (c) Generator operation schedule*

Additionally, generator operation can be scheduled based on peak tariff periods and maintenance cycles. Figure 14 illustrates a scenario where the generator operates only during nighttime, remaining offline during the day. This strategy enables adjustment of the grid export ratio depending on biomass fuel availability and engine maintenance conditions. When the generator runs only from 17:00 to 07:00, the proportion of electricity exported to the grid remains at 60%.

From a control perspective, the generator automatically starts when the combined solar and wind power falls below its rated capacity. Conversely, when the renewable generation exceeds this capacity, the generator is shut down. When active, the engine operates at rated output, thereby enhancing fuel utilization efficiency.

3.3.2. With hydrogen production

Figure 15 presents the schematic diagram of the on-grid hybrid renewable energy system with hydrogen production (SWBH-HRES). When the SWBH-HRES is connected to the grid and configured for hydrogen production, the generated electricity can either be sold to the grid or supplied to the electrolyzer. Accordingly, the energy optimization problem in this case is analyzed based on the relationship between the grid electricity selling price and the hydrogen market price. The technical specifications of the system are identical to those of the non-hydrogen production configuration described above, with the addition of a 10 kW electrolyzer and a hydrogen storage tank with a 1 kg capacity. The total electricity generated by the HRES remains the same as that of the system without hydrogen production. The engine also runs at night based on a fixed schedule (Figure 16a). The key difference lies in the allocation of electricity: instead of being fully sold to the grid, a portion is redirected to the electrolyzer. The system produces approximately 950 kg of hydrogen annually (Figure 16b).

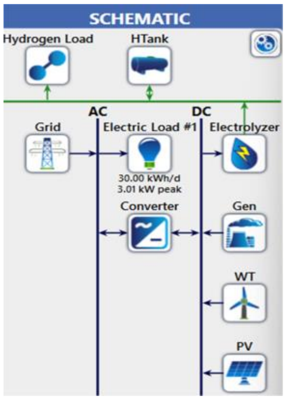


Figure 15. *Schematic of on-grid SWBH-HRES*

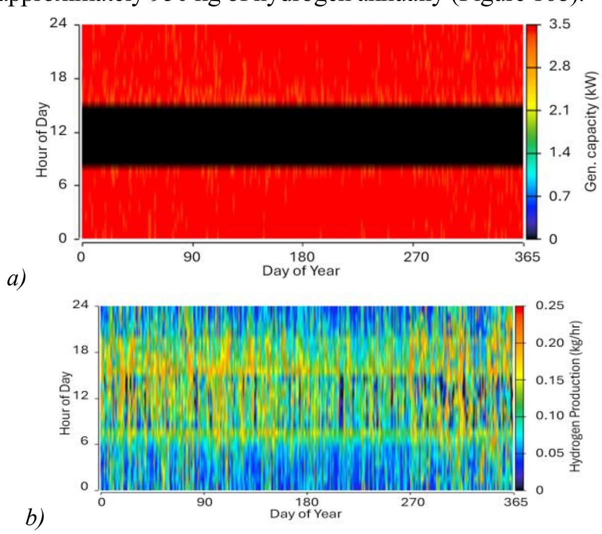


Figure 16. *On-grid SWBH-HRES; (a) Engine power variation by hour of day and day of year; (b) Hydrogen production variation by hour of day and day of year*

3.4. Economic and environmental efficiency comparison of HRES system options

3.4.1. Economic efficiency

The economic efficiency of the HRES system is influenced by hydrogen pricing and the average equipment cost per kW of capacity (Table 1). The total initial investment for the HRES system without hydrogen production is $17,718, while the total initial investment for the HRES system with hydrogen production is $19,268. The system's operational lifetime is 25 years.

Table 1. *Equipment costs used in the simulation*

Components	Capital ($)	Rep. ($)	O&M	Life time
PV	700	600	5 ($/year)	25 years
Wind turbine	1000	900	10 ($/year)	20 years
Generator set	600	500	0.03 ($/op. hour)	15000 hours
Converter	300	300	0 ($/year)	15 years
Electrolyzer	300	300	5 ($/year)	15 years
Hydrogen tank	200	200	0 ($/year)	25 years

The economic efficiency of the HRES system configuration is evaluated through cumulative profit compared to using grid electricity. Profit is calculated as the difference between the cumulative cash flow of the investigated option and the cumulative cash flow of the grid electricity option. The point where the cumulative profit curve intersects the horizontal axis represents the investment payback period. The cumulative profit at the final year of the project lifecycle (present worth) is the total profit generated throughout the project's lifetime.

Additionally, the economic efficiency is assessed through Return on Investment (ROI), which is calculated as follows:

$$ROI = \frac{\sum_{i=0}^{R_{proj}} (C_{i,ref} - C_i)}{R_{proj}(C_{cap} - C_{cap,ref})} \quad (1)$$

Trong đó:

$C_{i,ref}$: Annual cash flow of the reference case (grid electricity);

C_i : Annual cash flow of the project;

R_{proj} : Project lifetime;

C_{cap} : Initial investment capital of the project;

$C_{cap,ref}$: Initial investment capital of the reference case.

ROI accounts for bank interest rates and inflation rates. In this research case, the bank loan interest rate for renewable energy investment is estimated at 6% per year, and the inflation rate is estimated at 4% per year. Therefore, ROI can be considered the net interest rate that investors receive.

Figure 17a compares the cumulative profit of three waste-to-energy module configurations: on-grid without hydrogen production, on-grid with hydrogen production, and off-grid with hydrogen production. The reference case is the grid electricity option. In the calculation, the average electricity purchase price from the grid is $0.12/kWh, and the selling price to the grid is $0.094/kWh. Clearly, the economic efficiency of the hydrogen production project depends on the price of green hydrogen. According to the International Council on Clean Transportation, the actual average price of green hydrogen ranges from $3.5/kg to $5.5/kg. In this calculation, we selected the green hydrogen price at $5/kg.

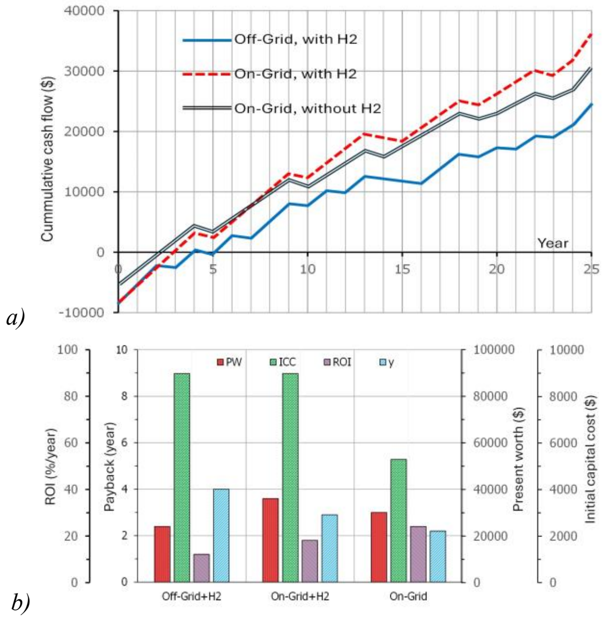


Figure 17. *Cumulative profit (a) and economic efficiency (b) of waste-to-energy module options*

The HOMER simulation results in Figure 17b show that the on-grid system without hydrogen production provides the best economic efficiency. With this option, the total profit is \$30,000, ROI = 24%/year, and the investment payback period is 2.2 years. For the on-grid system with hydrogen production, the total profit is \$36,000, ROI = 18%/year, and the investment payback period is 2.9 years. For the off-grid system with hydrogen production, the total profit is \$24,000, ROI = 12%/year, and the investment payback period is 4 years.

Figure 17b compares the economic indicators of the waste-to-energy module options with a green hydrogen price of \$5/kg. At this price, the on-grid module with hydrogen production has a slightly lower ROI and a slightly higher payback period than the on-grid module without hydrogen production. If the green hydrogen price is set between \$5-5.5/kg, the economic efficiency of these two options is equivalent. Thus, in the case of a waste-to-energy system with hydrogen production, the optimal configuration is the on-grid system.

3.4.2. Environmental Efficiency

Environmental efficiency is assessed in comparison with the grid electricity scenario (reference case). The reduction in GHG emissions depends on the configuration and output products of the waste-to-energy module. For modules equipped with engines running on biomass-derived fuels, the calculation of GHG reduction efficiency must include methane (CH_4) consumption. In cases where the module produces hydrogen, the efficiency assessment must also account for the replacement of gasoline with the hydrogen generated by the system. The following section presents an analysis of GHG emission reduction efficiency under different scenarios.

The data used for the GHG emission analysis are as follows:

- The average CO_2 emission factor for electricity generation in Vietnam is 0.521 kg CO_2 per kWh.

- GHG emission reduction via engines running on biomass-derived fuel: The overall efficiency of the generator engine is approximately 20%. Biomass is assumed to be converted into biogas, which contains an average of 60% CH_4 and 40% CO_2 by volume. The average calorific value of biogas is 35 MJ/kg, and approximately 0.5 kg of biogas is consumed to generate 1 kWh of electricity. Since this biogas originates from biomass, it would otherwise be released into the atmosphere if not utilized. Given that the global warming potential (GWP) of CH_4 is 20 times greater than that of CO_2, the GHG reduction, in CO_2-equivalent terms, achieved through electricity generation from biomass-derived fuel is estimated at 6.12 kg CO_2-eq/kWh.

- GHG emission reduction through hydrogen substitution for gasoline: In energy terms, 1 kg of hydrogen is equivalent to 3 kg of gasoline. The CO_2 emission factor for gasoline combustion is approximately 2 kg per liter, equivalent to 2.5 kg CO_2 per kg of gasoline. Therefore, using 1 kg of hydrogen in place of gasoline results in a reduction of 7.5 kg CO_2.

The levels of GHG emission reduction associated with different waste-to-energy configurations are summarized in Table 2. The results indicate that the off-grid waste-to-energy module without hydrogen production achieves the highest GHG emission reduction at 6.58 kg CO_2-eq/kWh, while the on-grid module without hydrogen production yields the lowest reduction at 6.16 kg CO_2-eq/kWh. When hydrogen production is included, the difference in emission reduction between off-grid and on-grid systems is marginal. The CO_2 emission reductions for off-grid and on-grid modules with hydrogen production are 6.35 kg CO_2-eq/kWh and 6.31 kg CO_2-eq/kWh, respectively. For on-grid modules, incorporating hydrogen production results in greater GHG emission reductions compared to modules without hydrogen production. Conversely, for off-grid modules, systems without hydrogen production achieve greater reductions.

Table 2. *CO_2 Emission reduction under various SWB-HRES configurations*

	Off-Grid	**On-Grid**	**Off-Grid+H2**	**On-Grid+H2**
Gen. (kWh/year)	5475	27594	30222	27594
AC Load (kWh/year)	5475	5475	5475	5475
Purchase (kWh/year)	0	2476	0	2478
Sold (kWh/year)	0	23215	0	0
H_2 (kg/year)	0	0	527	527
CO_2-eq (ton/year)	36	170	192	174
CO_2 reduc (kg/kWh)	6.58	6.16	6.35	6.31

4. Conclusion

This study analyzed and optimized various configurations of SWBH-HRES for Lý Sơn Island. The findings offer substantial technical, economic, and environmental contributions.

Technically, the optimal configuration consists of an

8 kW photovoltaic array, a 6 kW wind turbine, a 3.5 kW syngas generator, and a 10 kW electrolyzer. Under a scheduled control strategy, this system produces 56,524 kWh of electricity and 942 kg of hydrogen annually, outperforming the automatic control approach, which yields 50,423 kWh of electricity and 835 kg of hydrogen. The integration of hydrogen production significantly enhances energy utilization efficiency, reducing excess electricity to just 1.6%, compared to 18.3% in systems without hydrogen production.

Economically, the initial capital cost of the hydrogen-producing system is USD 19,268, compared to USD 17,718 for the non-hydrogen configuration. The analysis indicates that on-grid systems with hydrogen production become economically viable when hydrogen prices range from USD 5.0 to 5.5 per kilogram, yielding a total profit of USD 36,000, a return on investment (ROI) of 18% per year, and a payback period of 2.9 years. While systems without hydrogen production exhibit a higher ROI (24% annually) and a shorter payback period (2.2 years), hydrogen-producing systems provide greater total profit over the project lifespan.

Environmentally, the systems demonstrate considerable GHG emission reductions. The off-grid system without hydrogen production achieves the highest CO_2 emission reduction at 6.58 kg CO_2-eq/kWh. For on-grid systems, incorporating hydrogen production results in greater emission reductions compared to their non-hydrogen counterparts (6.31 vs. 6.16 kg CO_2-eq/kWh).

Overall, this research provides valuable insights for the development of hybrid renewable energy systems, with strong applicability to island and remote regions similar to Lý Sơn. The findings serve as a foundation for the design, operation, and management of SWBH-HRES, particularly in relation to internal combustion engine control strategies and hydrogen production optimization, thereby contributing to sustainable energy development and GHG emissions mitigation.

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