MICRO GRID SOLAR-WIND-BIOMASS HYBRID RENEWABLE ENERGY SYSTEM

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Abstract - This study evaluates the performance of a Solar-Wind-Biomass Hybrid Renewable Energy System (SWB-HRES) optimized for Hoa Bac conditions. The system comprises a 15 kW solar panel, 9 kW wind turbine, 8.3 kW syngas generator, 20 kW electrolyzer, 24 kW converter, and a 1 kg hydrogen storage tank. It supplies 7,300 kWh/year of electricity and produces 1,183 kg/year of hydrogen. When integrated with a hydrogen production grid, the solar-biomass (SB-H_2) configuration demonstrates superior economic and environmental performance, offering double the profit and half the payback period compared to the wind-biomass (WB-H_2) option. The economic viability of hydrogen production matches that of grid electricity sales when hydrogen is priced at \$4.5/kg (non-continuous engine operation) or \$5/kg (intermittent operation). Incorporating biomass significantly reduces greenhouse gas emissions: while a solar-wind system without hydrogen production cuts 33 tons CO_2-eq/year, the solar-wind-biomass system with hydrogen production achieves a reduction of 217 tons CO_2-eq/year.

Key words - Renewable energy; Hybrid renewable energy system; Hydrogen; Energy transition; GHG emission.

1. Introduction

Hydrogen is a sustainable fuel source with broad potential applications in electricity generation, transportation, industrial production, and daily life. Scientists predict hydrogen energy will meet 11% of global energy demand by 2025 and 34% by 2050 [1], [2]. Therefore, researching and developing hydrogen production technology from renewable energy is crucial in the energy transition process. A disadvantage of renewable energy is its intermittency. Combining different renewable energy sources into a hybrid renewable energy system (HRES) helps address this issue and increases hydrogen production efficiency [3-6].

Many studies have been conducted on hydrogen production from solar-wind hybrid energy systems [7-10]. The results of these studies indicate that hybrid renewable energy systems significantly enhance hydrogen production efficiency [11-13]. Based on HOMER software, research by Akyuz and colleagues shows that hydrogen production efficiency reaches 60% in hybrid renewable energy systems, higher than the efficiency levels of hydrogen production from standalone solar or wind energy [11]. The techno-economic features of the solar-wind hybrid renewable energy system with hydrogen production have also been studied by Okonkwo and colleagues using HOMER software [13]. The results indicate that hydrogen production efficiency from hybrid renewable energy systems is greater than when utilizing separate renewable energy sources.

One of the current research trends in renewable energy is expanding Hybrid Renewable Energy Systems (HRES) to hydrogen production, not just electricity generation as before [14-15]. Recently, research has widely discussed integrating the water electrolysis process within HRES for hydrogen production. This method offers numerous benefits regarding energy efficiency and reducing environmental pollution emissions [16-18], indicating that grid-connected HRES systems optimize equipment capacity within HRES, thereby reducing hydrogen production costs. For independent HRES, storing renewable energy in hydrogen demonstrates its superiority [19-20]. Hydrogen generated from the system can be blended with other renewable fuels to fuel engine-driving generators, which helps maintain the stability of HRES output [21-22].

One of the criteria for assessing the effectiveness of HRES in producing hydrogen is fuel cost. The cost of hydrogen produced from HRES depends on the potential for renewable energy, electricity prices, equipment costs, and other factors at the installation site. The cost of hydrogen produced from the HRES system combining solar and wind energy in Chile and Argentina is estimated at around 2 USD/kg [23]. However, research results in other regions indicate that the cost of hydrogen is significantly higher [24-27]: 6.2 USD/kg in the United States and 4.64 USD/kg in Morocco. The payback period for the HRES system producing hydrogen is typically no more than four years [28]. Reducing the production cost of hydrogen in hybrid renewable energy systems can be achieved by making informed choices regarding equipment components and improving system efficiency. However, experts predict that the average cost of green hydrogen will hover around 3.70 USD/kg [29], which is higher than the projected cost of hydrogen produced based on fossil fuels by 2050 (3 USD/kg) [28].

Technically, the power factor is a key indicator for evaluating the efficiency of energy production systems. It is defined as the ratio of the actual energy generated over a specific period to the maximum energy that could be produced if the system operated continuously at full capacity during that same period [30]. Accordingly, biomass has the highest power factor (35-94%) [31], followed by wind turbines (17%-40%), while solar power has a lower power factor [32].

Regarding the environment, greenhouse gas emissions over the life cycle of biomass power generation equipment are a maximum of 650 g-CO_2-eq/kWh, followed by solar energy with a maximum emission of 300 g-CO_2-eq/kWh. In comparison, onshore wind energy has an emission level of 124 g-CO_2-eq/kWh [28]. However, for biomass, environmental efficiency needs to be assessed more comprehensively based on the overall treatment process of solid waste. When biomass is processed into fuel (syngas) and converted into electricity via internal combustion engines or gas turbines, the greenhouse gas emitted is CO_2. This amount of CO_2 will be absorbed by the next generation of plants, thus not increasing the concentration of greenhouse gases in the atmosphere. Conversely, if biomass is not recovered and treated, it will convert into biogas in the environment. Biogas contains a significant amount of CH_4, a substance with a greenhouse effect of over 20 times greater than CO_2. A practical solution for converting biomass into energy is to process it into RDF and gasify it into syngas [33-34].

The above overview research shows that hydrogen production in HRES is a developing trend in applying renewable energy technology today. The effectiveness of hydrogen production depends on the potential of renewable energy available in the applicable area. Most published works on this issue focus on hybrid renewable energy systems combining solar and wind power. Very few works integrate biomass energy into the system. Converting biomass into electricity not only helps recover energy from solid waste but also reduces the pressure of solid waste management and decreases the emission of greenhouse gases, a problem that is becoming increasingly serious in developing countries.

Figure 1. Geographic location of Hoa Bac Commune, Da Nang City

In this project, we study the simulation of a hybrid renewable energy system of solar, wind, and biomass, abbreviated as SWB-HRES, applied in Hoa Bac commune. This is approximately 30 km from the center of Da Nang City. The geographical coordinates are 167.1'N and 10758'E (Figure 1). Hoa Bac is a buffer zone between the Bach Ma National Park nature reserve and Ba Na-Nui Chua, with an average elevation of about 200 m above sea level. Hoa Bac commune currently has a total natural area of 33,864 hectares, with 1,383 households and a population of 4,356. Hoa Bac has two villages of ethnic minorities, Ta Lang and Gian Bi, with 248 households primarily belonging to the Co Tu ethnic group.

Hoa Bac has beautiful, peaceful scenery featuring rivers and mountains. It is characterized by the pristine beauty surrounding the lush green rice fields along the winding hillside roads. The villages of the Co Tu ethnic group are nestled among the lush green mountains, allowing visitors to immerse themselves in the daily life of the local people and explore the beauty of their culture.

Most of the local population here lives through agriculture. The community-based tourism model has recently brought visitors closer to the Co Tu ethnic group. With the emergence of the homestay tourism model, some residents have shifted to service-oriented activities. These ecotourism models also help preserve the region's distinctive traditional cultural elements.

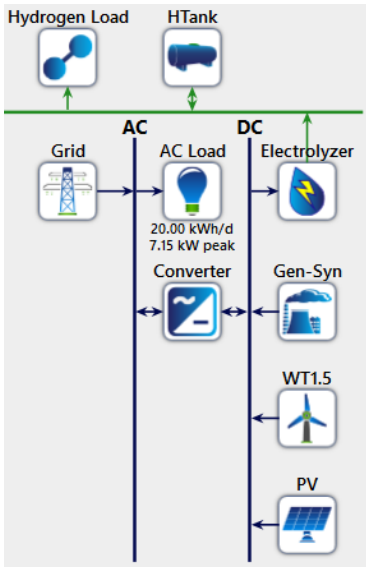
Therefore, Hoa Bac should be developed sustainably, first implementing energy transition, reducing dependence on fossil fuels, and developing renewable energy. In this study, we investigate a renewable energy model to partially replace electricity from the grid and partially replace petroleum products with green hydrogen.

2. Research Methodology

In this study, we use HOMER software to calculate the optimal selection of components for the grid-connected HRES system in Hoa Bac Commune. Figure 2a presents the SWB-HRES calculation diagram within HOMER. In this diagram, solar power, wind power, and power generated from the generator are all direct current. These power sources are converted to alternating current to supply the load through a converter. This diagram simplifies the grid synchronization system for each component of the SWB-HRES system. According to this diagram, the generator uses a mixed renewable gas fuel, including syngas and hydrogen. This fuel mixture is simplified to biogas in HOMER.

The electricity load uses alternating current and is assumed to be a cluster of households, consuming an average of 20 kWh per day with a peak power of 7.15 kW (Figure 2b). The annual hydrogen production required ranges from 1100 kg to 1200 kg. Since the hydrogen produced is stored in a tank, its flow rate does not need to meet the AC load in full. The energy used for hydrogen production is surplused by the HRES after supplying the load. Therefore, in the simulation, we can choose a maximum hydrogen load of 100%, and the average daily hydrogen load can be greater than its average value calculated for the entire year. In Vietnam, the price of electricity is calculated on a tiered basis. The average residential electricity price is approximately \$0.21 per kWh. The average selling price of renewable electricity to the EVN grid is \$0.094 per kWh.

In this HRES, we select the initial power of the solar panel array and the wind turbine array. HOMER automatically adjusts the specifications of the generator set while the power of the converter and electrolyzer is adjusted to ensure the system's output parameters. The hydrogen storage tank can hold 1 kg of hydrogen.



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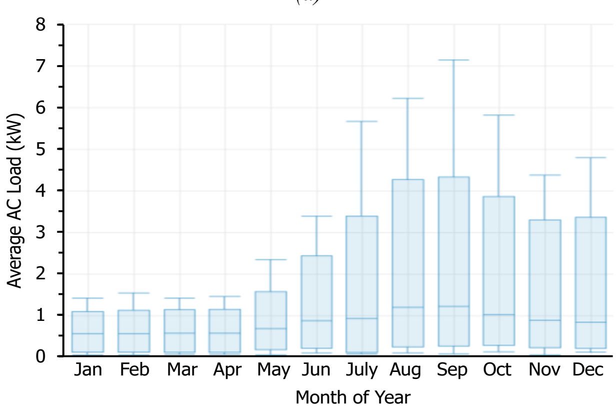


(b)

Figure 2. *Diagram of the layout of SWB-HRES components connected to the grid (a) and variations in load power by hour of the day and by day of the year (b)*

In the illustrated hybrid renewable energy system (SWB-HRES), the electrolyzer serves as a critical component for hydrogen production. It operates on the DC side of the system and receives electrical energy generated from renewable sources, including photovoltaic panels (PV), wind turbines (WT1.5), and the syngas generator (Gen-Syn). This energy is converted via the converter to match the required input for the electrolyzer.

The electrolyzer utilizes this electricity to perform water electrolysis, splitting water molecules into hydrogen and oxygen. The produced hydrogen is then stored in the hydrogen tank (H Tank). It can be used to meet the hydrogen load, thereby supporting energy needs in transportation, electricity generation, and other applications.

This process not only enables energy storage but also contributes to greenhouse gas emission reduction and aligns with the system's goal of promoting sustainable energy transformation in the Hoa Bac region.

3. Simulation Results

3.1. The influence of the HRES configuration on the economic efficiency of the system

The values in Table 1 and Table 2 were derived from a combination of:

Simulation results using the HOMER software, which models hybrid renewable energy systems based on input parameters such as solar irradiance, wind speed, biomass availability, and load demand specific to the Hoa Bac region.

Technical specifications from manufacturers and literature for components such as photovoltaic panels, wind turbines, syngas generators, electrolyzers, and converters.

Empirical data collected from previous pilot projects and feasibility studies conducted in similar rural and semi-urban contexts in Vietnam.

Explanations of Parameters:

S (kW), W (kW), B (kW): Represent the installed capacities of solar, wind, and biomass systems, respectively.

P_total (kW): Total installed power capacity of the system.

P_electrolyzer (kW): Rated power of the electrolyzer used for hydrogen production.

P_converter (kW): Capacity of the converter used to manage AC/DC transitions.

E (kWh/year): Total electricity generated annually by the system.

H_2 (kg/year): Annual hydrogen production based on the electricity supplied to the electrolyzer.

E excess/surplus (kWh/year): Represents unused or excess electricity that is not consumed or stored, indicating system efficiency.

These configurations were selected to evaluate the performance of different combinations of renewable sources, with and without biomass integration, and their impact on electricity and hydrogen output. The values reflect optimized scenarios balancing technical feasibility, economic efficiency, and environmental impact.

- HRES without generator

When the system relies solely on solar power without a generator, the electrolyzer can only produce hydrogen during the day. To achieve the same hydrogen output as other continuous production methods, the solar panels' peak power and electrolyzer capacity must be significant. Table 1 shows that, in this case, the peak capacity of the solar panels is 52 kW, and the capacity of the electrolyzer is 30 kW. When solar power is replaced with wind power, hydrogen production can occur at all hours of the day, reducing the wind turbine capacity to 37.5 kW, and the electrolyzer capacity remains unchanged at 18kW. When the system uses solar power combined with wind power, the system's peak capacity is 44.5 kW, with the electrolysis tank having a capacity of 24 kW. To ensure the same electricity and hydrogen production, the system's total capacity ranges from 37.5 kW (wind power) to 52 kW (solar power), a difference of 14.5 kW.

Table 1. *The capacity of the equipment and electricity, hydrogen output according to different configurations of SW-HRES*

S (kW)	W (kW)	P_{total} (kW)	$P_{electrolyzer}$	$P_{converter}$	E (kWh/year)	H_2 (kg/year)	E excess (kWh/year)
52	0	52	30	23	62927	1143	48
0	37.5	37.5	30	23	61529	1152	38
25	19.5	44.5	24	24	62249	1169	12

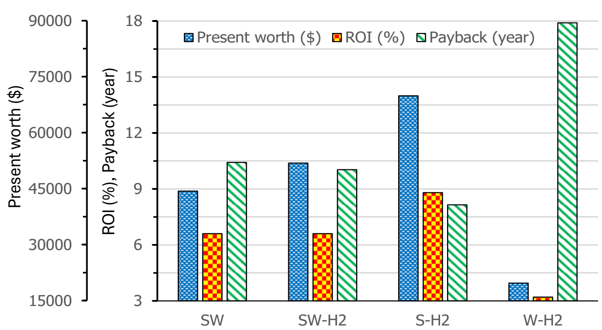
Table 2. *Power capacity of equipment and production of electricity hydrogen according to different configurations of SWB-HRES*

S (kW)	W (kW)	B (kW)	P_{total} (kW)	$P_{electrolyzer}$	$P_{converter}$	E (kWh/year)	H2 (kg/year)	E surplus (kWh/year)
20	0	8.3	28.3	18	6	62529	1181	5
0	19.5	8.3	27.8	18	6	62827	1173	65
15	9	8.3	32.3	18	6	62863	1183	32

ROI (%) stands for Return on Investment, a financial metric used to evaluate the profitability of an investment.

Role in the Analysis: In the context of this study, ROI (%) is used to assess the economic efficiency of various SW-HRES configurations, both with and without hydrogen production. It provides a standardized measure to compare how effectively each configuration converts investment into profit. A higher ROI indicates a more economically attractive option.

As shown in Figure 3, the S-H_2 configuration (solar + biomass + hydrogen production) yields the highest ROI at 8.8%, demonstrating superior profitability compared to other configurations. This metric complements other indicators such as present worth and payback period, offering a comprehensive view of each system's financial performance.

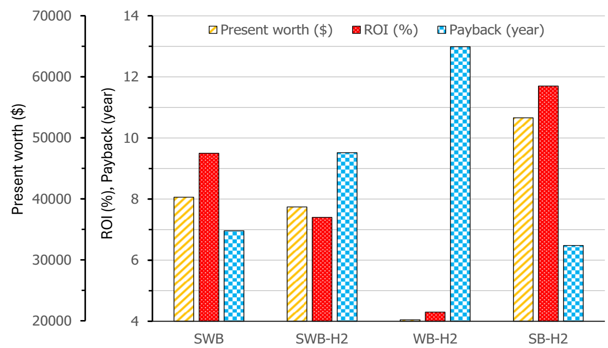


c	Present worth ($)	ROI (%)	Payback (year)
SW	44414	6.6	10.42
SW-H2	51919	6.6	10.03
S-H2	69952	8.8	8.15
W-H2	19765	3.2	17.9

Figure 3. *Analysis of the economic efficiency of SW-HRES configurations with hydrogen production and without hydrogen production*

Figure 3 compares the economic efficiency of SW-HRES configurations with and without hydrogen production. The results indicate that in the case of grid-connected HRES that combines solar and wind energy, the wind electricity option with hydrogen production has the lowest economic efficiency, with a present worth of only 19765$ and a return on investment of only 3.2% per year. At the same time, the payback period extends to 17.9 years. The SW option with and without hydrogen production has comparable economic efficiency regarding ROI and payback. The option with the highest economic efficiency is solar electricity combined with hydrogen production. This option yields a present worth of 69952$, a return on investment of 8.8% per year, and a payback period of 8.15 years. Thus, in the case of grid-connected HRES with hydrogen production without a syngas engine, the option with only solar energy provides the highest economic efficiency.

- HRES, including syngas generator



Scenario	Present worth ($)	ROI (%)	Payback (year)
SWB	40304	9.5	6.96
SWB-H2	38706	7.4	9.52
WB-H2	20237	4.3	12.99
SB-H2	53309	11.7	6.48

Figure 4. *Analysis of the economic efficiency of SWB-HRES configurations with and without hydrogen production*

Table 2 summarizes the power capacity of the equipment and the electricity and hydrogen production generated over the year. When HRES includes a syngas generator, the system's total capacity varies slightly from 28.3 kW for the WB system to 32.3 kW for the SWB system, a difference of 4 kW. This difference is very low compared to the 14.5 kW in the case without the syngas generator. This result indicates that the syngas generator plays a crucial role in stabilizing the power capacity of the HRES system, thereby reducing the capacity of solar panels or the capacity of the wind turbine to achieve the same amount of electricity and hydrogen production.

Figure 4 compares the economic efficiency of SWB-HRES configurations with and without hydrogen production. The results indicate that in the case of grid-connected HRES combining solar, wind, and biomass energy, the SB option that includes hydrogen production has the lowest economic efficiency. The present worth of this option only reaches 20237$, with a return on investment of only 4.3% per year, while the payback period extends to 12.99 years. The SWB option, both with and without hydrogen production, is equivalent in present worth, but due to higher initial investment, the ROI is lower, and the payback period is longer. The SB option with hydrogen production offers the highest economic efficiency. This option has a present worth of 53309$, a return on investment of 11.7% per year, and a payback period of 6.48 years. Compared to the WB option with hydrogen production, the profit of the SB-H_2 option doubles, and the investment payback period is halved. Thus, in the case of grid-connected SWB-HRES with hydrogen production, the option that only uses solar energy combined with biomass offers the highest economic efficiency.

3.2. Comparison of standalone HRES and grid-connected HRES with hydrogen production

In this study, the SWB-HRES system was designed and simulated using HOMER software, which includes detailed modeling of load profiles, resource variability, and component interactions. The following aspects were considered to ensure stable operation in standalone mode:

Load Matching and Energy Balance: The system configuration was optimized to meet a daily AC load of 20.00 kWh/day with a peak demand of 7.15 kW, ensuring that generation from solar (PV), wind (WT1.5), and biomass (Gen-Syn) could reliably supply the required energy.

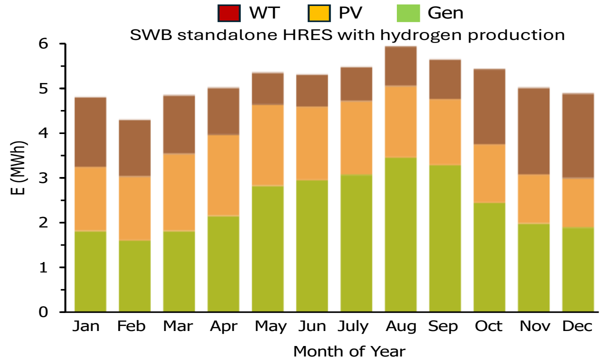
Converter and Storage Integration: The inclusion of a 24 kW converter and a hydrogen storage tank allows for effective energy management between AC and DC components. It provides backup capacity during periods of low renewable generation.

Hydrogen Buffering: The electrolyzer and hydrogen tank act as a buffer system, converting excess electricity into hydrogen during surplus periods and supplying energy during deficits, enhancing system resilience.

Simulation of Resource Variability: Hourly simulations over a full year were conducted to account for fluctuations in solar irradiance, wind speed, and biomass availability. The system maintained energy supply without critical shortfalls, confirming its reliability.

Excess Energy and Curtailment: The system design includes provisions for handling excess energy (as shown in Tables 1 and 2), which further supports stable operation by preventing overloads and ensuring efficient utilization.

In the independent SWB-HRES and grid-connected cases, the devices S, W, and B output power remains unchanged, as shown in Table 2. The system generates 62863 kWh of electricity and 1183 kg of hydrogen annually. The amount of electricity exchanged with the grid in the grid-connected case is negligible (purchasing 6 kWh/year and selling 247 kWh/year). Figures 5a and 5b illustrate the variation in electricity production by month throughout the year for the independent SWB-HRES and grid-connected cases. In both cases, the total annual electricity production from wind, solar, and generator accounts for 23.5%, 28.9%, and 47.6%, respectively. When the HRES generator serves as a backup energy system to compensate for the shortfall in solar and wind energy relative to the load, we set the maximum hydrogen load at 100% in this simulation. Therefore, the minimum load of the internal combustion engine operating in the independent HRES system must be maintained to ensure power delivery to the electrolyzer. This level is set at 90% to ensure that the annual electricity output provided by the generator in the independent HRES system is equivalent to when it operates in the grid-connected HRES.



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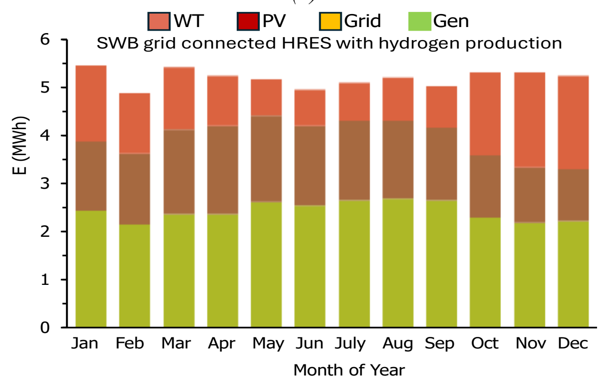
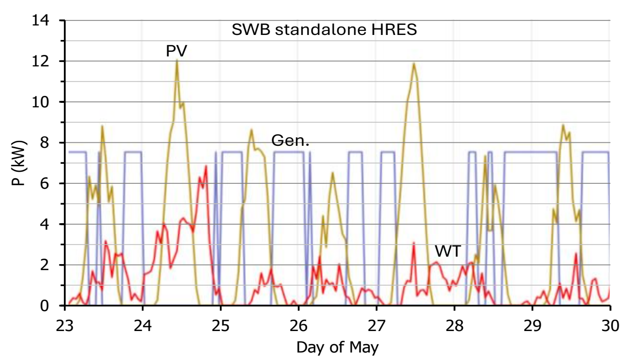


(b)

Figure 5. *Electricity production from the different components of the SWB-HRES combined with hydrogen production in the case of off-grid (a) and grid-connected (b)*



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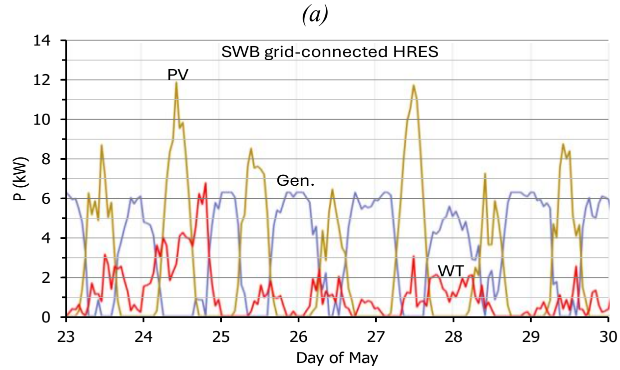

(b)

Figure 6. *Variations in power output from wind, solar energy, and generators in the last days of May for the independent SWB-HRES (a) and grid-connected (b)*

Figures 6a and 6b compare the variations in power output of the generation sources in the independent and grid-connected SWB-HRES during the last week of May. The power output from wind and solar energy is the same in both cases. In the independent HRES case, the generator operates at 90% of its maximum capacity. In this case, the engine's operating hours are 4021 hours/year with 850 starts. For the grid-connected system, the generator's active power during operation is approximately equal to the average peak power of the AC load, which is lower than the engine's power in the independent HRES case. The total operating hours of the generator per year is 6838 hours with 470 starts. Increasing the operating time of the engine will increase operating costs due to reduced equipment replacement time.

Figures 7a and 7b compare the variation in electrical power of the generator throughout the hours of the year. As explained above, the electrical power in the case of an HRES connected to the grid varies according to the load, while in the case of an independent HRES, the engine power is only at the set nominal level during operation or at 0 when the machine is turned off.

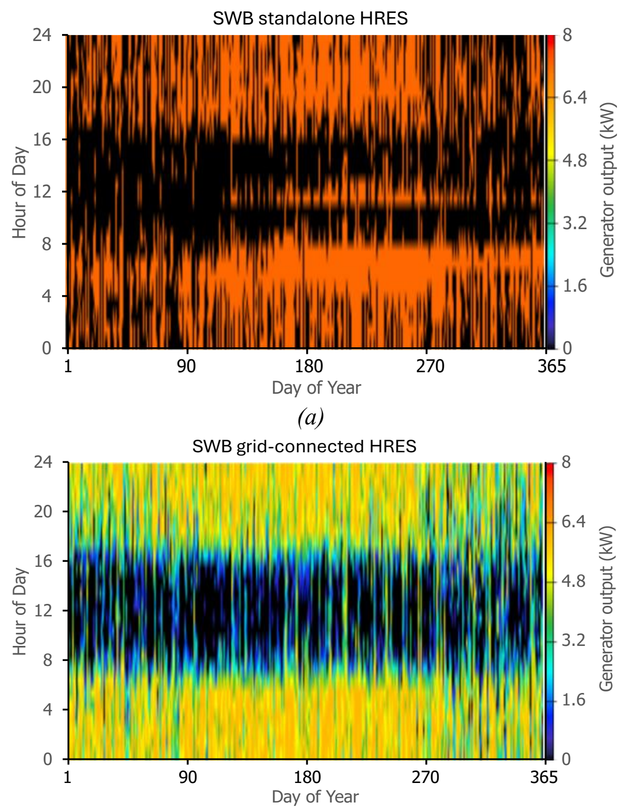

Figure 7. *Variation of generator power output by hour throughout the year for the independent SWB-HRES (a) and grid-connected (b)*

Figures 8a and 8b compare the variations in hydrogen production during the last days of May for the grid-independent and grid-connected HRES. We see that in the grid-connected HRES, the level of fluctuation in hydrogen production is lower than that of the grid-independent HRES. Although both cases have the same average annual hydrogen production, if the system requires a stringent (low maximum ultimate hydrogen load), the grid-connected HRES is more suitable than the grid-independent case.

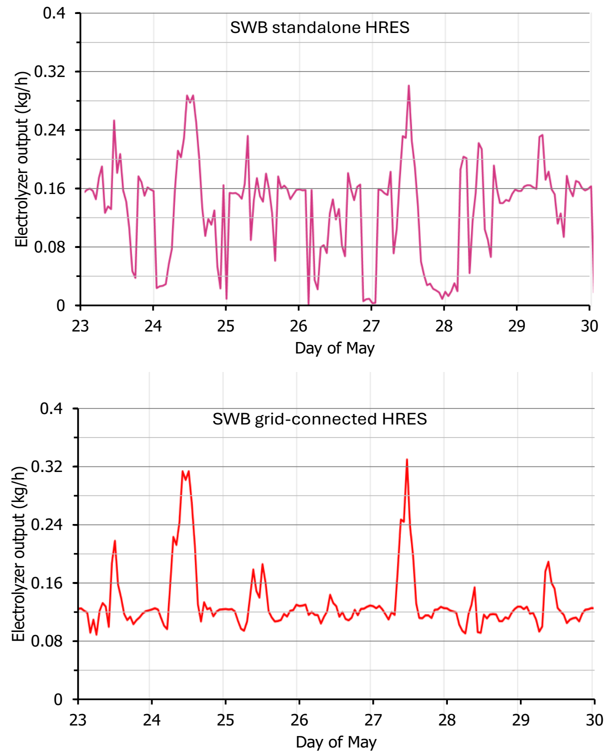

Figure 8. *Variations in hydrogen production during the last days of May for SWB-HRES in standalone (a) and grid-connected (b) modes*

3.3. Economic and environmental effectiveness analysis of HRES

3.3.1. Effects of hydrogen cost

The economic and environmental efficiency of the HRES system is compared between the SWB-HRES option that produces hydrogen and the case where hydrogen is not made while maintaining the same electricity generation output of the system. The initial investment for the hydrogen-producing SWB-HRES system is higher than that of the non-hydrogen-producing system due to the necessity of an electrolyzer and hydrogen storage tank. For the non-hydrogen-producing SWB-HRES system, part of the electricity generated serves the load, with any surplus sold to the grid. HOMER simulation results indicate that, in this case, the payback period for the investment is 6.96 years, with an ROI of 9.5%, and present worth 40304$ (Figure 9). If the price of hydrogen is 4.5/kg, the payback period is longer, and the present worth, the ROI is lower than those of the non-hydrogen-producing case. If the price of hydrogen is 5$/kg, the payback period for this system is 9.52 years, longer than that of the non-hydrogen-producing system, but the ROI is 10.6% higher than that of the non-hydrogen-producing system. With a hydrogen price of 5.5$/kg, the present worth of HRES with hydrogen production is about 10000$ higher than that of the non-hydrogen-producing system. According to The International Council of Clean Transportation [35], the average cost of green hydrogen fluctuates between

3.5 USD/kg and 5.5 USD/kg. Therefore, the SWB-HRES with hydrogen production is economically feasible.

In the case of SB-HRES with hydrogen production (Figure 4), when the hydrogen price is 5$/kg, the present worth and the ROI of the system are higher than those of the SWB-HRES non-hydrogen-producing system. In view of the economy, the SB-HRES with hydrogen production operating in the case study site is the most preferable.

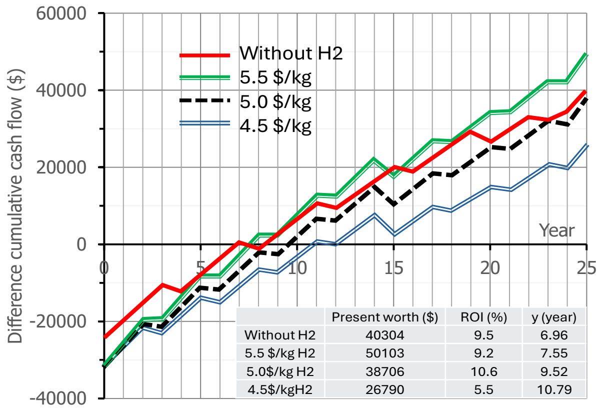

Figure 9. *The impact of hydrogen unit price on the economic effects of SWB-HRES*

3.3.2. Environmental Effective Analysis

The environmental efficiency is assessed compared to the option of using grid electricity. The level of reduction in greenhouse gas emissions depends on the configuration and products of HRES. When HRES uses a fuel engine from biomass, the efficiency of GHG emission reduction needs to account for the amount of CH_4 it consumes. When HRES produces hydrogen, the GHG reduction efficiency must also consider replacing petroleum products with the amount of hydrogen generated by the system. The following section will analyze the efficiency of GHG emission reduction in various scenarios:

- GHG emissions when using grid electricity: The average CO_2 emission level in electricity generation in Vietnam is 521 g/kWh. Therefore, to produce an amount of electricity of 62863 kWh/year, equivalent to HRES, Vietnam's electricity generation system emits 33 tons of CO_2 into the atmosphere yearly.

- Case of the SW system not producing hydrogen: When the HRES only has solar and wind power, does not use generators running on fuel recovered from biomass, and does not produce hydrogen, the reduction in CO_2 emissions into the atmosphere is equivalent to the CO_2 emissions generated from grid electricity production, meaning a reduction of 33 tons of CO_2.

- Case of the SW system producing hydrogen: In this case, the amount of electricity generated by the system is used to supply a load of 7,300 kWh/year, with the remainder used for hydrogen production. The reduction in CO_2 emissions from using renewable electricity for the load is 4 tons/year. Regarding energy, 1 kg of hydrogen equals 3 kg of gasoline. The CO_2 emissions from using gasoline for internal combustion engines are 2 kg/liter, comparable to 2.5 kg of CO_2/kg of gasoline. Therefore, using 1 kg of hydrogen instead of gasoline reduces CO_2 emissions by 7.5 kg. Using 1,183 kg of hydrogen produced by the system annually to replace gasoline lowers CO_2 emissions by 9 tons annually. Thus, the total annual reduction in CO_2 emissions that the system provides compared to using grid electricity is 13 tons of CO_2.

- Case of the SWB system not producing hydrogen: In this case, the syngas generator produces 33042 kWh of electricity per year. The overall efficiency of the generator engine group is about 20%. Assume that the engine runs on biogas that averages 60% CH_4 and 40% CO_2 by mass. The average calorific value of biogas is 35 MJ/kg. Each year, the engine consumes 17 tons of biogas. This amount of biogas is generated from biomass, which would be released into the atmosphere if not consumed. The greenhouse effect of CH_4 is 20 times that of CO_2. Thus, the amount of greenhouse gases in CO_2 equivalent due to the CH_4 in biogas released into the atmosphere is 204 tons. The annual reduction in GHG emissions equivalent to the CO_2 the system provides is 237 tons.

- In the case of the SWB system producing hydrogen: In this case, in addition to reducing emissions of 204 tons of CO_2 equivalent to the power plant, the system also helps to reduce 9 tons of CO_2 each year by replacing gasoline with 1183 kg of hydrogen and reduces 4 tons of CO_2 per year due to the energy load using renewable energy. Therefore, the total reduction in CO_2 emissions each year is 217 tons.

- In the case of the SB system producing hydrogen: In this case, the generator produces 38391 kWh of electricity each year, resulting in a corresponding reduction in CO_2 emissions of 237 tons when the engine uses fuel recovered from biomass. This system's total reduction in CO_2 emissions annually (including the reduction due to using biomass, due to the load using renewable energy, and using replacement hydrogen) is 250 tons.

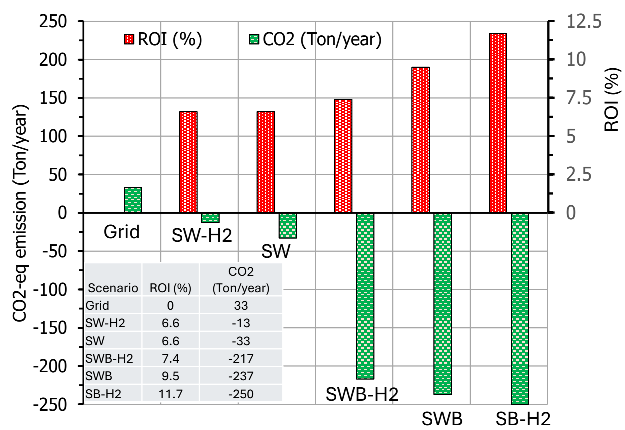

Figure 10. *Comparison of the economic and environmental efficiency of SWB-HRES options*

Figure 10 compares the economic and environmental effectiveness of the HRES options combining PV, WT, and biomass with hydrogen production and without hydrogen production. Return on investment and CO_2-eq emission reduction are selected as the comparison parameters. The results indicate that the SB-H_2 option, the solar-biomass HRES combined with hydrogen production, has superior economic and environmental performance. If the system does not produce hydrogen, the SWB option, the solar-wind turbine-biomass HRES, is the best choice for both the economy and the environment.

4. Conclusions

The findings of this study lead to the following conclusions:

The hybrid renewable energy system (SWB-HRES), integrating solar, wind, and biomass sources, enables hydrogen production and supports energy transition in electricity generation, transportation, and solid waste management, contributing to the sustainable development of Hoa Bac.

The optimized SWB-HRES configuration includes a 15kW solar panel, a 9kW wind turbine, an 8.3kW syngas generator, a 20kW electrolyzer, a 24kW converter, and a hydrogen storage tank with a 1kg capacity. This system supplies 7,300 kWh of electricity annually and produces 1,183 kilograms of hydrogen per year.

Among the hydrogen-producing grid-connected options, the combination of solar energy and biomass (SB-H_2) demonstrates the highest economic efficiency. Compared to the wind-biomass (WB-H_2) option, SB-H_2 yields double the profit and reduces the investment payback period by half.

The highest economic and environmental performance is achieved by the HRES configuration that excludes hydrogen production. However, when hydrogen production is included, the solar-biomass combination remains the most effective in both economic and environmental terms.

The economic viability of hydrogen production in the SWB-HRES system is comparable to selling electricity to the grid when hydrogen is priced at $4.5/kg (if the engine operates intermittently) and $5/kg (if the engine operates continuously).

Integrating biomass energy into HRES significantly reduces greenhouse gas emissions. For an annual electricity output of 62,863 kWh, the solar-wind system without hydrogen production reduces emissions by 33 tons of CO_2-equivalent. In contrast, the solar-wind-biomass system with hydrogen production achieves a reduction of 217 tons of CO_2-equivalent.

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