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Research Article

Economic-environmental analysis of solar-wind-biomass hybrid renewable energy system for hydrogen production: A case study in Vietnam

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Abstract. Combining biomass with solar and wind energy to produce electricity and hydrogen, referred to as the Solar-Wind-Biomass Hybrid Renewable Energy System (SWB-HRES), provides optimal economic and environmental efficiency. This paper presents research findings from a case study of SWB-HRES implemented in Hoa Bac commune, Danang City, Vietnam, utilizing HOMER software for system modeling and optimization. The study aims to identify the optimal configuration for SWB-HRES with hydrogen production and assess its compatibility with grid-connected SWB-HRES without hydrogen production. A detailed analysis of greenhouse gas (GHG) emission reductions corresponding to different system configurations is also provided. The results indicate that the optimal SWB-HRES configuration for Hoa Bac includes a 15-kW solar panel, a 9-kW wind turbine, an 8.3 kW syngas generator, a 20-kW electrolyzer, a 24-kW converter, and a hydrogen storage tank with a capacity of 1 kg. This setup supports an annual electricity load of 7,300 kWh and produces 1,183 kilograms of hydrogen per year. For grid-connected HRES with hydrogen production, the solar-biomass system demonstrates superior economic and environmental efficiency compared to the wind-biomass configuration. The economic efficiency of SWB-HRES with hydrogen production matches that of SWB-HRES selling electricity to the grid when the hydrogen cost is \$4.5/kg for discontinuous syngas generator operation and \$5/kg for continuous operation. Furthermore, integrating biomass energy into HRES proves to be an effective strategy for GHG emission reduction. For the same electricity output of 62,863 kWh/year, the solar-wind HRES without hydrogen production achieves a GHG emission reduction of 33 tons of CO_2-eq, while the solar-wind-biomass HRES with hydrogen production achieves a reduction of 217 tons of CO_2-eq. Given that the performance of HRES depends on geographic location, equipment availability, and energy pricing, practical implementations should validate simulation results with experimental data collected on-site.

Keywords: Renewable energy; Hybrid energy system; Economic analysis; Hydrogen production; Energy transition; Greenhouse gas emission.

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1. Introduction

Hydrogen is one of the most promising energy sources for the future. As a sustainable fuel, it has extensive potential applications in electricity generation, transportation, industrial manufacturing, and daily life (Hoang *et al*., 2023b; Le *et al*., 2025). Projections indicate that hydrogen energy will account for approximately 11% of global energy demand by 2025 and 34% by 2050 (Hussam *et al*., 2024; Tarhan and Çil, 2021). Consequently, advancing hydrogen production technologies from renewable energy sources is crucial for the global energy transition.

Various hydrogen production methods have distinct advantages and limitations (Younas *et al*., 2022). Currently, the predominant commercial method is steam methane reforming using natural gas (Cao *et al*., 2020; El-Shafie, 2023). However, this process relies on non-renewable feedstock and fails to align with the Net Zero strategy. In contrast, the photoelectrochemical water-splitting method utilizes sunlight and specialized catalyst materials to generate hydrogen and oxygen (Agyekum, 2024; Hoang *et al*., 2023a). This approach offers several advantages, including zero emissions, high-purity hydrogen production, and seamless integration with renewable energy technologies (Hassan *et al*., 2024; Wang *et al*., 2020; Zhang *et al*., 2023). Nevertheless, significant challenges such as material stability, energy efficiency, and the high cost of specialized catalysts hinder its widespread adoption (Ahmed and Dincer, 2019; Liu *et al*., 2014).

Hydrogen production via water electrolysis is highly flexible and can be implemented at various scales (Godula-Jopek, 2015; Heidari *et al*., 2024). However, the primary challenges of this method stem from the electricity source used and its overall energy efficiency (El-Shafie, 2023). Additionally, the high initial capital costs associated with electrolysis equipment, particularly for large-scale facilities, result from the reliance on expensive materials (Badgett *et al*., 2021). When powered by renewable energy, electrolysis enables the production of carbon-neutral green hydrogen (Sanz-Bermejo *et al*., 2014). This method

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facilitates decentralized hydrogen production, making it viable for applications ranging from hydrogen refueling stations to large-scale industrial production. Furthermore, it has broad applicability across various sectors, including transportation and energy storage (Palmer *et al*., 2021; Terlouw *et al*., 2022; Widera, 2020). Electrolysis also functions as an energy storage solution, helping to stabilize the electrical grid by absorbing surplus renewable energy during periods of excess generation and supplying energy when renewable power generation is insufficient (Laimon and Yusaf, 2024; Zeng and Zhang, 2010).

In recent decades, hydrogen production from renewable energy sources such as solar and wind has garnered significant research interest (Alzahrani *et al*., 2022; Hasan and Genç, 2022; Okonkwo *et al*., 2022). Due to the intermittent nature of individual renewable energy sources, current research trends focus on expanding Hybrid Renewable Energy Systems (HRES) for hydrogen production (Demir, 2024; Swaminathan *et al*., 2024). Integrating multiple renewable energy sources enhances hydrogen production efficiency while reducing pollutant emissions (Bui *et al*., 2021; Bukar *et al*., 2024; Nasser *et al*., 2022; Taipabu *et al*., 2022), thereby lowering the cost of green hydrogen. Garcia et al. (Garcia G. and Oliva H., 2023) investigated hydrogen production in a solar-wind HRES using HOMER software and reported that hydrogen production efficiency reached 60%, surpassing the efficiency of standalone solar or wind energy systems. Similarly, Dufo-López et al. (Dufo-López *et al*., 2007) conducted a techno-economic analysis of a hybrid solar-wind renewable energy system for hydrogen production using HOMER software. Their findings demonstrated that hydrogen production efficiency in hybrid renewable energy systems is significantly higher than in systems utilizing individual renewable energy sources. In recent years, hydrogen production from biomass has attracted increasing interest from both researchers and industry (El-Shafie, 2023; Kachroo *et al*., 2024; Morya *et al*., 2022). Utilizing biomass not only helps reduce carbon emissions but also promotes a circular economy by closing the carbon cycle and minimizing the amount of organic waste requiring landfill disposal (Hosseini and Wahid, 2016; Iribarren *et al*., 2014). Biomass, which includes various plant-based materials and organic waste, is the only renewable carbon-containing raw material and holds significant potential as an alternative to fossil fuels *(*Dahmen *et al*., 2025; Lykas *et al*., 2024). Its key advantages include renewability, abundance, and ease of utilization. Throughout its lifecycle, the net CO_2 emissions from biomass are nearly zero due to the carbon sequestration effect of photosynthesis. Currently, biomass is the fourth-largest energy source globally, contributing approximately 10% of total primary energy consumption (Dahmen *et al*., 2025). The most efficient way to harness biomass energy is by converting it into fuels (Shokri *et al*., 2024).

Several technologies have been developed for hydrogen production from biomass, including thermochemical, biochemical, photoelectrochemical, and electrolytic methods (Kharisma *et al*., 2022; Kong *et al*., 2023; Saravanakumar *et al*., 2023). Biochemical conversion pathways such as fermentation and anaerobic digestion are effective for feedstocks rich in starch and sugar but face limitations in processing lignocellulosic materials (Shanmugam *et al*., 2023). Biological dark fermentation is considered a promising approach for large-scale hydrogen production (Kharisma *et al*., 2022; Rusdianasari *et al*., 2023). Additionally, biomass electrolysis, which operates at relatively low temperatures (Liu *et al*., 2020), offers several advantages, including high hydrogen purity, fast reaction rates, and lower energy consumption compared to conventional water electrolysis. This method can efficiently process biomass with high moisture content while maintaining low carbon emissions (M. Li *et al*., 2023). The energy required to produce 1 kg of hydrogen via biomass electrolysis varies depending on the feedstock, with banana peels and cucumbers requiring 35.35 kWh/kg and 42.17 kWh/kg, respectively (Umer *et al*., 2024b), while corn straw requires 30.58 kWh/kg (Li *et al*., 2022). In comparison, hydrogen production through conventional water electrolysis consumes approximately 47–63 kWh/kg (El-Shafie, 2023). As a result, biomass electrolysis demonstrates 20–45% higher energy efficiency than traditional water electrolysis, making it a promising method for cost-effective and sustainable hydrogen production (Umer *et al*., 2024b). Despite these advantages, several technical challenges must be addressed before biomass electrolysis can be commercially implemented (Dolle *et al*., 2022; Luo *et al*., 2021; Umer *et al*., 2024a). Thermochemical methods, including pyrolysis and gasification, are considered promising for large-scale hydrogen production from various agricultural and forestry waste materials (Yong and Abdul Rasid, 2022), primarily due to their higher economic efficiency compared to other alternatives (Ni *et al*., 2006). However, these methods present challenges in maintaining optimal gasification conditions and require additional processing to remove contaminants from the hydrogen product (Cao *et al*., 2020; Chozhavendhan *et al*., 2020; Dash *et al*., 2023) The removal of such contaminants remains a significant technical bottleneck for thermochemical biomass-based hydrogen production (Huang *et al*., 2025). By employing a fluidized bed gasifier combined with appropriate catalysts, hydrogen production rates of approximately 60% by volume can be achieved (Ni *et al*., 2006). Given its economic and environmental benefits, biomass gasification is regarded as a promising approach for hydrogen production. This method has garnered increasing interest from researchers, as the resulting syngas can be directly utilized in fuel cells for energy generation (R. Li *et al*., 2023).

The transition to green hydrogen as a replacement for fossil fuels is an inevitable trend; however, it currently lacks a competitive price advantage in the market (Huang *et al*., 2025). The production cost of green hydrogen generally ranges from 3 to 8 USD/kg, while blue hydrogen costs between 1 and 2 USD/kg, and gray hydrogen is priced between 0.5 and 1.7 USD/kg (El-Emam and Özcan, 2019). Hydrogen production from renewable energy sources is more expensive than steam methane reforming, which costs approximately 2.08 USD/kg without carbon capture and storage (CCS) and 2.27 USD/kg with CCS (Ji and Wang, 2021). Projections suggest that by 2050, the average cost of green hydrogen will stabilize at around 3.70 USD/kg (Agyekum, 2024). The cost of green hydrogen depends on factors such as the availability of renewable energy, electricity prices, and equipment costs at the system's installation site. For example, the estimated cost of hydrogen production from solar-wind hybrid renewable energy systems (HRES) is approximately 2 USD/kg in Chile and Argentina (Armijo and Philibert, 2020), 6.2 USD/kg in the United States, and 4.64 USD/kg in Morocco (Fopah-Lele *et al*., 2021; Koleva *et al*., 2021; Mokhtara *et al*., 2021; Touili *et al*., 2018). The payback period for HRES-based hydrogen production systems is typically around four years (Akyuz *et al*., 2012). Cost reductions in HRES-based hydrogen production can be achieved through the optimal selection of system components and improvements in efficiency. Additionally, hydrogen production costs vary depending on the primary electricity source. In the context of Hong Kong, the production cost of green hydrogen from thermal power generation, solar-grid energy, and wind energy is 2.165 USD/kg, 2.132 USD/kg, and 2.060 USD/kg, respectively (Ayub *et al*., 2025). If electricity is sourced from offshore wind energy, the projected cost of green hydrogen is estimated to range between 3.60 and 3.71 EUR/kg in 2030, decreasing to approximately 2.05 to 2.15 EUR/kg by 2050 (Herdem *et al.*, 2024; Komorowska *et al.*, 2023). The cost of hydrogen production from biomass varies depending on the conversion method employed. According to (Ji and Wang, 2021), the estimated hydrogen production costs are as follows: gasification (1.77–2.77 USD/kg), direct bio-photolysis (2.13 USD/kg), indirect bio-photolysis (1.42 USD/kg), photo-fermentation (2.83 USD/kg), and dark fermentation (2.57–6.98 USD/kg). It was also estimated that hydrogen production via biomass pyrolysis costs between 8.86 USD/GJ and 15.52 USD/GJ, depending on the scale of the facility and the type of biomass used (Padro and Putsche, 1999). In comparison, hydrogen production using water electrolysis powered by wind and solar energy costs approximately 20.2 USD/GJ and 41.8 USD/GJ, respectively (Huang *et al.*, 2025). These figures indicate that biomass pyrolysis presents a more economically viable hydrogen production pathway compared to water electrolysis using renewable electricity.

From an environmental perspective, the maximum greenhouse gas (GHG) emissions over the lifecycle of biomass-generated electricity devices reach 650 g CO_2-eq/kWh, compared to 300 g CO_2-eq/kWh for solar power and 124 g CO_2-eq/kWh for onshore wind power (Abdelsalam *et al.*, 2024). However, the environmental impact of biomass must be evaluated holistically, considering its role in integrated solid waste treatment. When biomass is processed into fuel (syngas) and converted to electricity using internal combustion engines or gas turbines, the CO_2 emitted is reabsorbed by subsequent plant growth, maintaining atmospheric CO_2 equilibrium. Conversely, if biomass is not recovered and treated, it decomposes into biogas, which contains a significant proportion of CH_4—a greenhouse gas with a global warming potential over 20 times higher than CO_2. Integrating biomass into hybrid renewable energy systems can significantly contribute to sustainable energy production within the future hydrogen economy (Zhou *et al.*, 2023). To enhance energy reliability, biomass can be stored in the form of Refuse-Derived Fuel (RDF) to mitigate the intermittency of renewable energy sources such as solar and wind power in a multi-generation hybrid renewable energy system (Heidarnejad *et al.*, 2024; Phung *et al.*, 2024; Xuan *et al.*, 2023). Such systems simultaneously produce multiple forms of energy, including electricity, heat, and hydrogen, making them an effective and environmentally sustainable solution to energy challenges (Nanvaei Qeshmi *et al.*, 2025). Optimizing system components and operational parameters is crucial to maximizing performance while minimizing costs and environmental impact (Nanvaei Qeshmi *et al.*, 2025).

The combination of solar energy and biomass for hydrogen production was explored in the literature. In a study, solar energy was used to electrolyze water into hydrogen and oxygen, with the oxygen subsequently utilized to enhance the biomass gasification process for additional hydrogen production (Cormos, 2024). The evaluation results indicate that the system's overall energy efficiency improved, with an equivalent hydrogen production cost of 2.47 USD/kg (Cormos, 2024), which is only slightly higher than the hydrogen production cost from steam methane reforming with CO_2 capture (2.27 USD/kg) (Ji and Wang, 2021). Specific studies on multi-generation HRES integrating solar, wind, and biomass-based energy are presented in (Bui *et al.*, 2023; H. H. Nguyen *et al.*, 2024; V. G. Nguyen *et al.*, 2024). Despite the many potential benefits of biomass-based multi-source energy generation, several technical, economic, and environmental challenges remain to be addressed.

The above overview highlights that multi-generation HRES represent a sustainable model for future energy production. Integrating biomass into solar-wind renewable energy systems enhances energy conversion efficiency, improves economic viability, and reduces GHG emissions. Biomass within multi-generation HRES can be converted into hydrogen through several approaches:

- *Direct conversion* via biochemical, photoelectrochemical, or electrolytic methods. However, this approach is limited to specific biomass types and is not applicable to solid waste in general.
- *Indirect conversion* through gasification or pyrolysis produces syngas that can be further processed into hydrogen. While this method is applicable to various biomass sources and carbon-containing solid waste, it requires a hydrogen refining system to remove impurities from the syngas.
- *Electrolysis of water* using electricity generated from biomass. This is the simplest approach, wherein solid waste is converted into electricity, which is then integrated with other power sources in the HRES to supply energy to the grid and produce hydrogen.

To ensure the energy source for the future, the energy used is not only electricity but includes various other forms of energy. Thus, developing the hybrid solar-wind-biomass energy system is important because of the following reason:

- Integrating electricity and fuel production (polygeneration) to diversify the use of renewable energy for various purposes.
- Integrating biomass into the hybrid energy system, on one hand recovering energy from solid waste, reducing greenhouse gas emissions, and on the other hand, reducing the amount of waste that needs to be landfilled.

The fact shows that most current research focuses on electricity generation from solar and wind energy, while biomass energy has great potential but has not been effectively exploited. Therefore, research on integrating biomass energy into the hybrid solar-wind-biomass renewable energy system is very practical in the energy transition, reducing greenhouse gas emissions, and meeting the net zero roadmap. Indeed, this study employs HOMER software to evaluate the economic and environmental efficiency of various multi-generation HRES configurations that integrate solar, wind, and biomass energies for electricity and hydrogen production. Simulations are conducted based on the renewable energy conditions of ecologic Hoa Bac village, Da Nang, using input parameters that reflect current equipment costs and electricity purchase and sale prices in Vietnam. In this work, the simulation of a hybrid renewable energy system of solar, wind, and biomass energy, abbreviated as SWB-HRES, applied in Hoa Bac commune is studied. This mountainous commune is in Hoa Vang District, approximately 30 km from the center of Da Nang City. The geographic coordinates are 167.1'N and 10758'E, as shown in Figure 1. Hoa Bac is a buffer zone between the Bach Ma National Park 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 comprising 4,356 inhabitants. Hoa Bac has 2 villages of ethnic minorities, Ta Lang and Gian Bi, with 248 families, mainly of the Co Tu ethnic group. 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

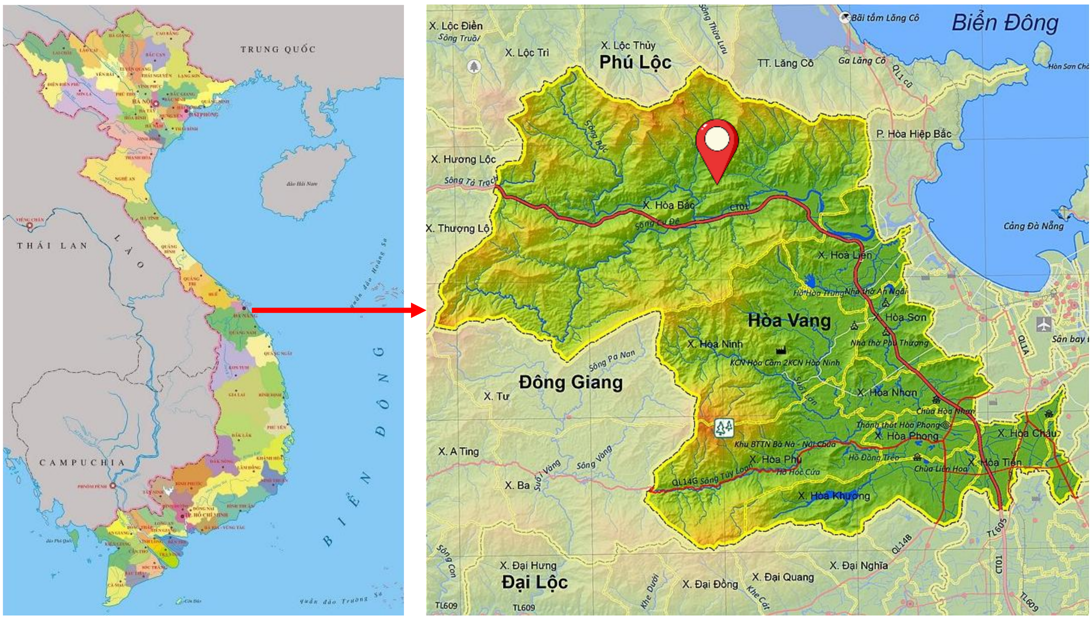


Fig. 1 Geographic location of Hoa Bac Commune, Hoa Vang District, Da Nang City

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. Methodology

2.1. Schematic diagram for the SWB-HRES system

Figure 2 presents the diagram of the SWB-HRES renewable energy system. Biomass is processed into RDF fuel pellets, which are then gasified into syngas in the gasifier (Alzahrani *et al.*, 2022; Garcia G. and Oliva H., 2023). After passing through the filtration system, the syngas is directed to a gas storage tank. When solar power and wind power generation exceed the load capacity, the surplus power is supplied to the water electrolysis unit to produce hydrogen and oxygen. Oxygen enriches the air as an oxidizing agent provided to the gasifier (Xuan *et al.*, 2023). Hydrogen is stored in metal hydride tanks to fuel motorcycles. The remaining hydrogen is kept in a storage tank or directed to the syngas storage tank to blend into fuel supplied to the generator's internal combustion engine. When the solar and wind power generation is lower than the load capacity, the internal combustion engine generates electricity to ensure a continuous and stable power supply. Thus, the internal combustion engine-generator unit acts as an energy storage system in this system. The electrical energy obtained from various sources is integrated into the power grid through a converter. Hydrogen is stored in metal hydride canisters at low pressure and temperature for use in motorcycles. Thus, this

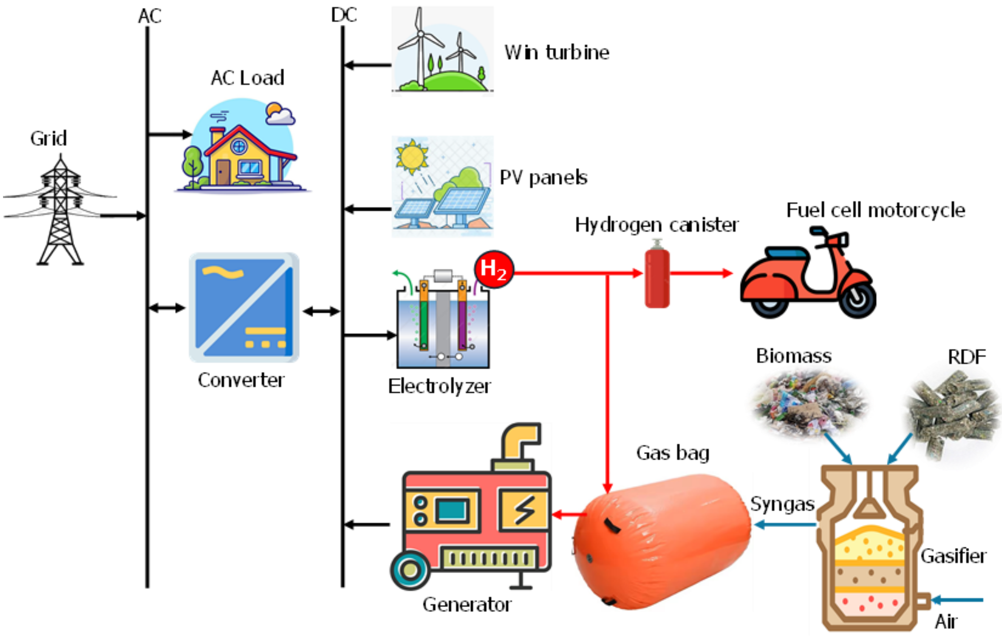


Fig. 2 Diagram of the hybrid SWB-HRES renewable energy system

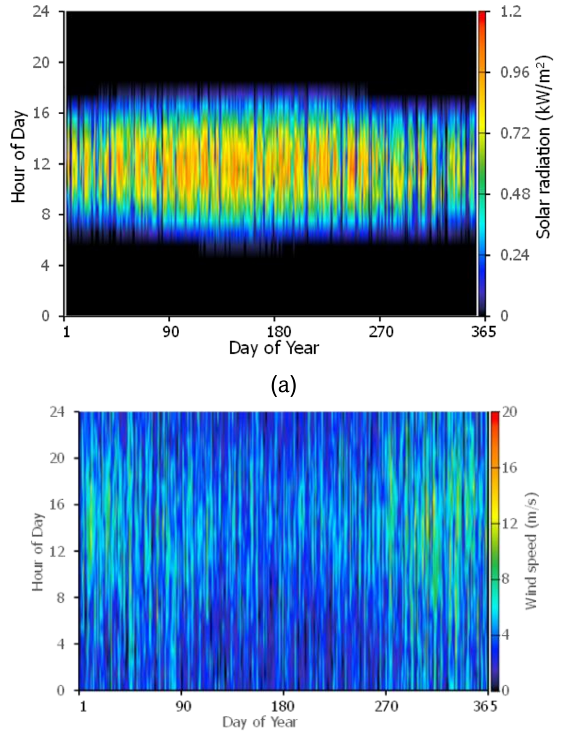


Fig. 3 a) Solar radiation in Hoa Bac Commune; b) Average wind speed in Hoa Bac Commune

SWB renewable energy system can be seen as a poly-generation system that provides electricity and fuel.

Figure 3a and Figure 3b present solar radiation and the average wind speed in Hoa Bac Commune, extracted from NASA's climate database. The maximum solar radiation occurs at noon in summer, around 1.2 kW/m^2. The peak average wind speed is about 20 m/s during the last months of the year. In general, solar radiation is high in the year's middle months, but wind energy is low.

2.2 Research tools

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 4a 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, as illustrated in Figure 4b. The required hydrogen production annually ranges from 1,100 kg to 1,200 kg. Since the produced hydrogen is stored in a tank, its flow rate does not need to meet the requirements fully, like the AC electrical load. The energy used for hydrogen production is surplus energy from the HRES after supplying the load. Therefore, in the simulation, we can set the maximum hydrogen load to 100%, and the average daily hydrogen load can be selected to be greater than its annual average value. In Vietnam, the price of electricity is calculated on a tiered basis. The average residential electricity price is approximately \$0.21/kWh. The average selling price of renewable electricity to the EVN grid is \$0.094/kWh. In this HRES, we select the initial power of the solar panel array and the average 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 specifications. The hydrogen storage tank can hold 1 kg of hydrogen.

3. Results ad discussion

3.1. General cases of HRES Solar-Wind-Biomass

Table 1 presents the amount of electricity and hydrogen produced in the SWB-HRES. In the case of HRES without

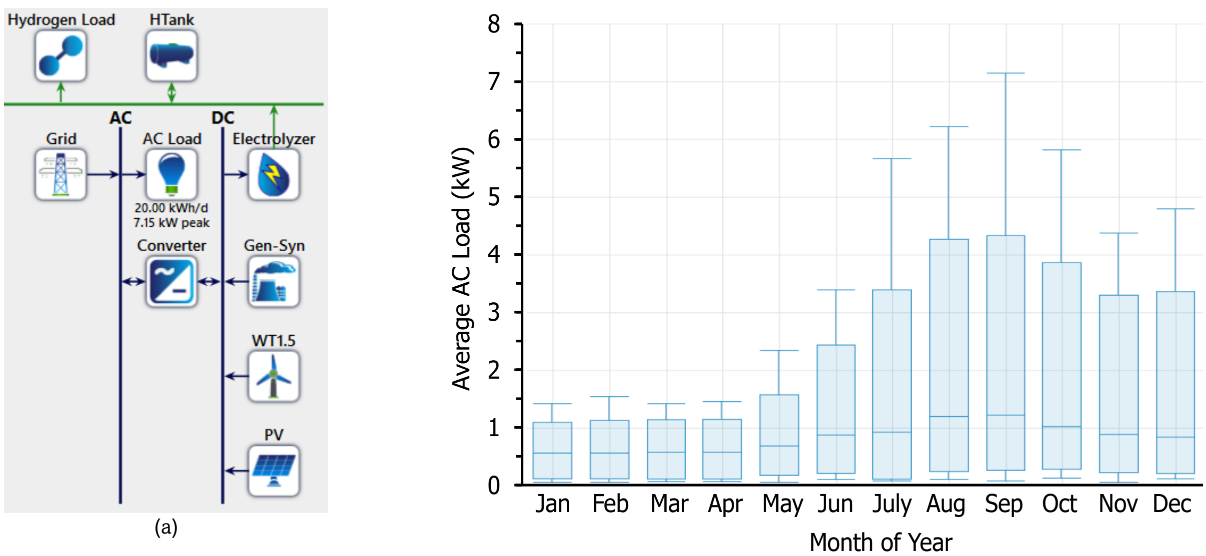


Fig. 4 Diagram of the layout of SWB-HRES; a) Components connected to the grid; b) Variations in load power by hour of the day and by day of the year (b)

Table 1
Electricity and hydrogen production

Scen.	PV (kWh/ year)	WT (kWh/ year)	Gen. (kWh/ year)	H_2	Purcha. (kWh/ year)	Sold (kWh/ year)
SWB-H_2	18152	14767	72708	2093	0	790
SWB	18152	14767	72708	0	0	92728

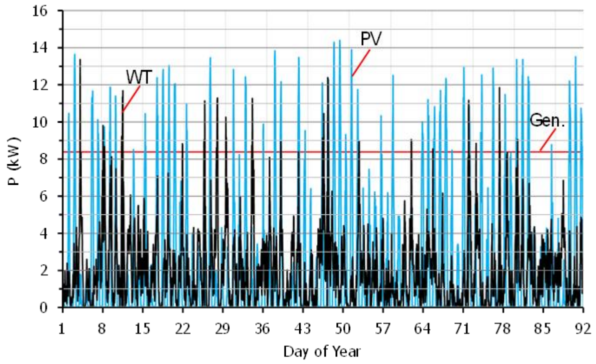


Fig. 5 Variation of PV, WT, and Generator power over the days in the first three months of the year

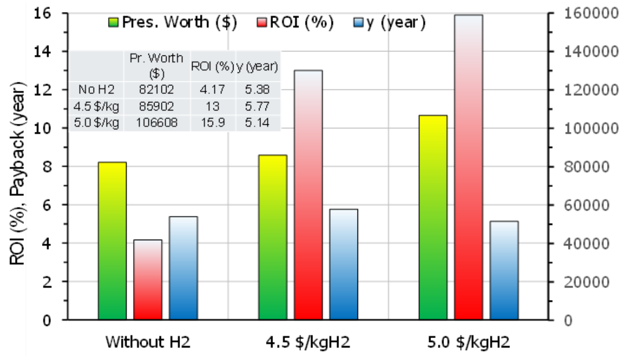


Fig. 6 Assessing the economic effectiveness of the extreme case when the generator operates continuously based on hydrogen cost

hydrogen production, we select the configuration of a 15kW peak PV and a 9kW wind turbine (case SWB). In the case of HRES with hydrogen production (SWB-H2), a 20 kW electrolyzer was added in the case of SWB-H2, in which HOMER optimizes the generator output at 8.3 kW. The converter capacity is 22 kW (case SWB) and 24 kW (case SWB-H2). The system produces 105,627 kWh/year. In the case of SWB, the system sold to the grid 92,728 kWh/year. In the case of SWB-H2, the system sold 790 kWh/year to the grid and produced 2,093 kg of hydrogen per year.

Figure 5 introduces the chart of the variations in power output from generation sources in the SWB system during the first three months of the year. Solar and wind power fluctuate according to weather conditions, while the generator output remains stable at 80% of maximum capacity. This is an extreme hypothetical case, as engines powered by biomass-derived fuel are challenging to operate continuously in practice due to their dependence on sources like syngas and biogas.

Figure 6 demonstrates that, in this extreme case, when the price of hydrogen ranges between \$4.5/kg and \$5/kg, the hydrogen-producing HRES achieves a higher present worth and return on investment (ROI) compared to the HRES without hydrogen production. Additionally, the payback period for the hydrogen-producing HRES is comparable to that of the non-hydrogen-producing HRES. Therefore, for HRES to operate nor mally, we can schedule the engine's operation or adjust the engine's power and operating time according to the AC load. If we schedule the engine's operation, it isn't easy to accurately guarantee when the generator needs to manage to supplement the load. Therefore, automatically adjusting the engine according to the AC load will be more reasonable. In this case, we adjust the power of the converter.

Figure 7a illustrates the variation in average electricity output by month throughout the year from solar, wind, biomass, and grid sources. Solar power dominates in the year's middle months, wind power in the latter months, and biomass compensates to meet load requirements. Figure 7b shows the variation in power output from these sources over the days in July. Solar power only operates during the day, while solar output is interrupted at night. Wind power shows a lower degree of fluctuation. Biomass power, when active, only fluctuates slightly to compensate for load power. The electrical output component of the PV is 18,152 kWh, and the WT is 14,767 kWh, which does not change according to the power of the converter. However, the electricity generated by the generator increases from 16,463 kWh when the converter power is 4 kW to 29,938 kWh when the converter power is 6 kW to compensate for the

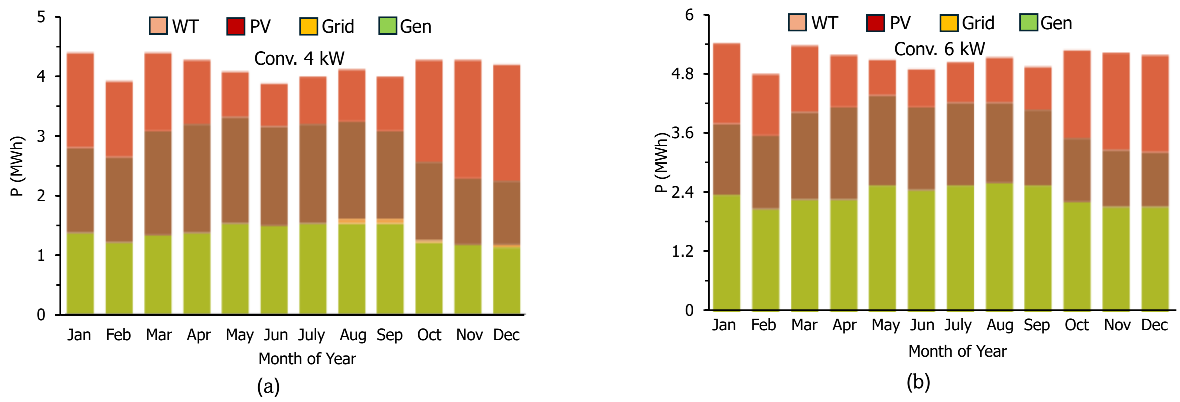


Fig. 7 Electricity generation components by month throughout the year for a converter power; a) 4 kW; b) 6 kW

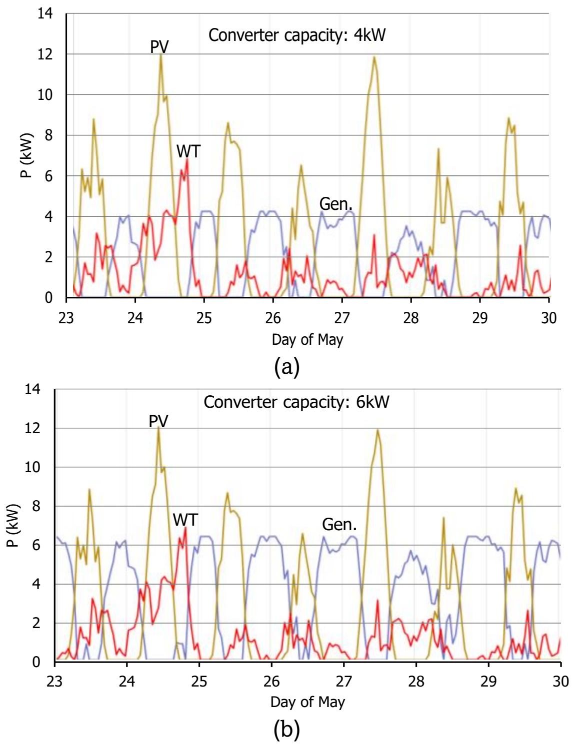


Fig. 8 Variation in the power of PV, WT, and Gen. over the last weeks of May with converter power, a) 4 kW, b) 6 kW

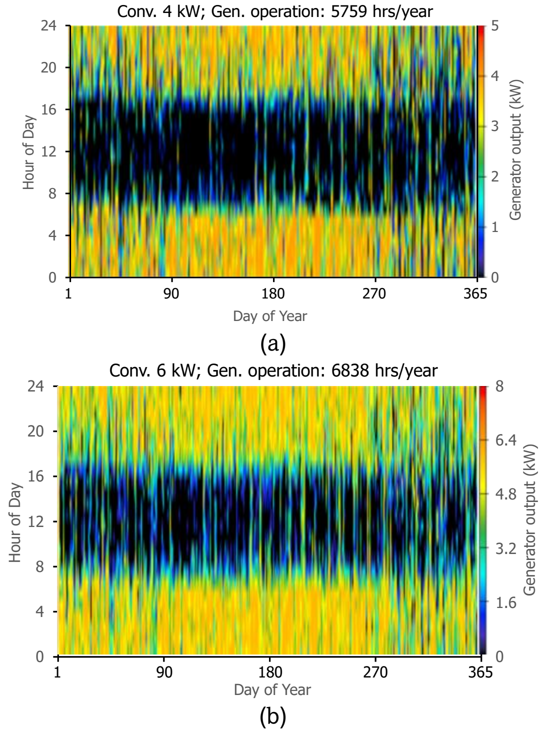


Fig. 9 Variation of generator power output by hour throughout the year for converter capacity, a) 4 kW, b) 6 kW

power when solar energy and wind energy are lower than the inverter's power.

Figure 8 illustrates that the generator operates only when the combined solar and wind power output falls below the converter's capacity. The generator's maximum electrical output matches the converter's capacity, corresponding to scenarios where solar and wind power contributions are zero. Under these conditions, the syngas generator functions as an energy storage device. For this purpose, a reliable supply of syngas fuel is essential, which is not feasible with conventional biomass energy applications. In this case study, biomass is converted into RDF to enable storage and utilization based on demand schedules. To ensure efficient operation, the gasification system must be equipped with an automated smart control system capable of dynamically managing fuel conversion and energy generation processes.

When the converter capacity is increased, not only does the generator's capacity increase, but its operating time also extends. As illustrated in Figure 9, a converter capacity of 6 kW results in longer daytime operating hours for the generator compared to a 4-kW converter capacity. Specifically, the generator operates for 5,759 hours and 6,838 hours for the 4-kW and 6-kW converter capacities, respectively. This extended operating time leads to higher maintenance costs for the engine and accelerates its wear and tear, ultimately shortening its lifespan and increasing equipment replacement costs. In the SWB-HRES system, the operation of the syngas generator is influenced by the availability of biomass feedstock. Therefore, in practical applications, it is essential to optimize the generator's operation schedule, which can be achieved using the advanced scheduling options available in HOMER software. Additionally, a sensitivity analysis should be conducted to evaluate the generator's performance under varying operating periods, ensuring optimal efficiency and cost-effectiveness.

The electricity generated by the system is primarily used to supply AC loads, with any surplus directed to the electrolysis cell for hydrogen production. As illustrated in Figure 10 (above), hydrogen output reaches its peak during periods of maximum solar radiation, specifically between 11:00 AM and 1:00 PM. Conversely, hydrogen production is minimal at night, as the generator predominantly supplies power to the electrolysis cell during this time. The generator's power output establishes a consistent baseline for hydrogen production, as depicted in Figure 10. The results indicate that optimizing the electrolyzer

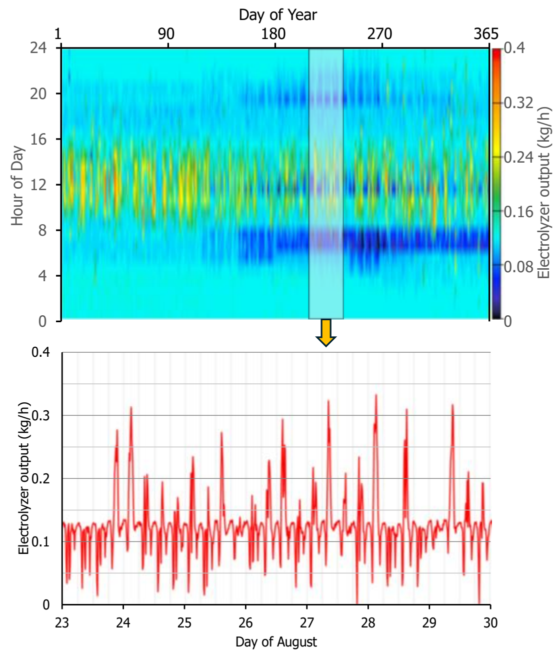
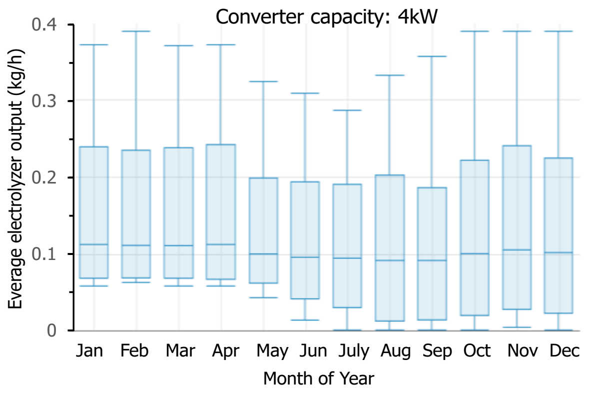
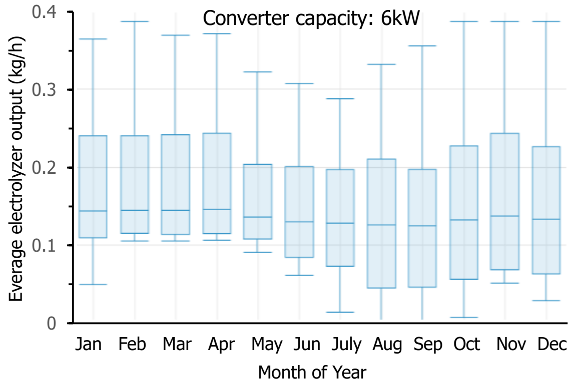


Fig. 10 Variation of hydrogen production by hour throughout the year (above) and by day in August (below)



(a)



(b)

Fig. 11 Variation in hydrogen output by month over the year for converter power ratings, a) 4 kW, b) 6 kW

capacity requires maintaining hydrogen production throughout both daytime and nighttime. To achieve this, scheduling the generator to operate during nighttime hours is recommended to enhance the system's cost-effectiveness. This approach would reduce the required capacity of the electrolyzer and simultaneously lower the engine's maintenance costs.

Figure 11a and Figure 11b illustrate the average hydrogen output for converter power levels of 4 kW and 6 kW. The overall trend in hydrogen output variation throughout the year remains consistent regardless of the converter capacity. However, the average annual hydrogen production by the HRES increases from 900 kg/year with a 4-kW converter to 1,183 kg/year with a 6-kW converter. Both the wind turbine and syngas generator are capable of producing either AC or DC electric power; in this case study, they generate DC power. A converter is required to transform DC power into AC power to supply AC loads and enable electricity sales to the grid. Any surplus power is allocated for hydrogen production. Therefore, the converter can be conceptualized as a "valve" that regulates and splits the energy flow between the hydrogen production system and the AC load.

With the HRES configuration, increased hydrogen production enhances the economic feasibility of the system.

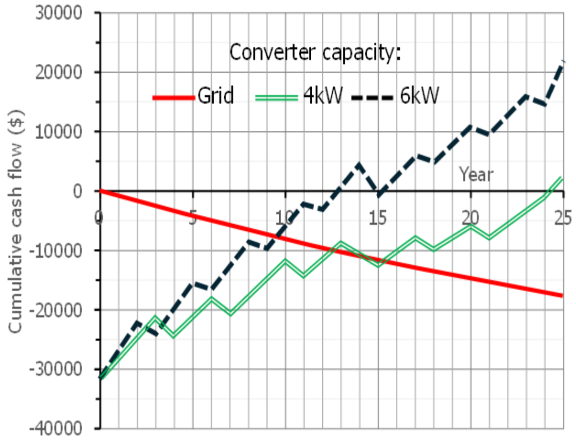


Fig 12 Comparison of cumulative cash flow in the case of 4 kW and 6 kW inverter capacity

Figure 12 compares the cumulative cash flow for converter capacities of 4 kW and 6 kW. When relying solely on grid electricity, the initial investment is zero, and annual electricity costs accumulate based on consumption, reaching $17,258 after 25 years. In contrast, the HRES achieves a cumulative return of $2,238 after 25 years for the 4-kW converter and $21,448 for the 6-kW converter. The payback period is determined by the intersection point between the present cash flow curve of the HRES and that of the grid electricity scenario. As shown in Figure 12, the payback period is 12.66 years for the 4-kW converter and 9.52 years for the 6-kW converter. Therefore, to maximize the economic efficiency of the HRES, the electricity output from the generator cluster should be optimized to achieve the highest possible production levels.

3.2. Impact of the HRES configuration on the economic efficiency of the system

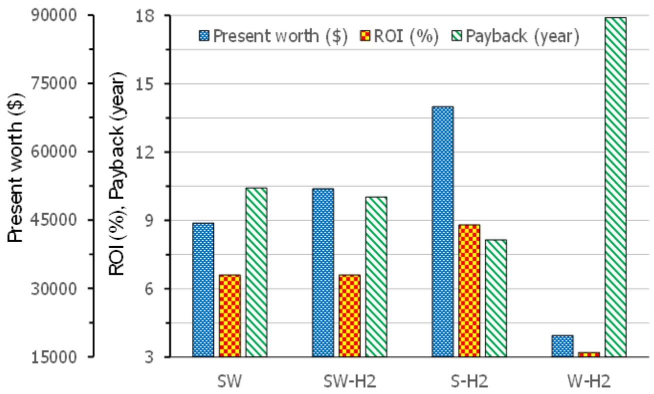
3.2.1. HRES without generator

When the system only has solar power without a generator, the electrolyzer can only produce hydrogen during the day; thus, the solar panels' peak and electrolyzer capacity must be significant to achieve the same hydrogen output as other continuous production methods. Table 2 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 to 18kW unchanged. 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.

Figure 13 compares the economic efficiency of SW-HRES

Table 2
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



Scenario	Present worth ($)	ROI (%)	Payback (year)
SW	44414	6.6	10.42
SW-H_2	51919	6.6	10.03
S-H_2	69952	8.8	8.15
W-H_2	19765	3.2	17.9

Fig. 13 Analysis of the SW-HRES configurations' economic efficiency with and without hydrogen production

Table 3
Power capacity of equipment and production of electricity hydrogen according to different configurations of SWB-HRES

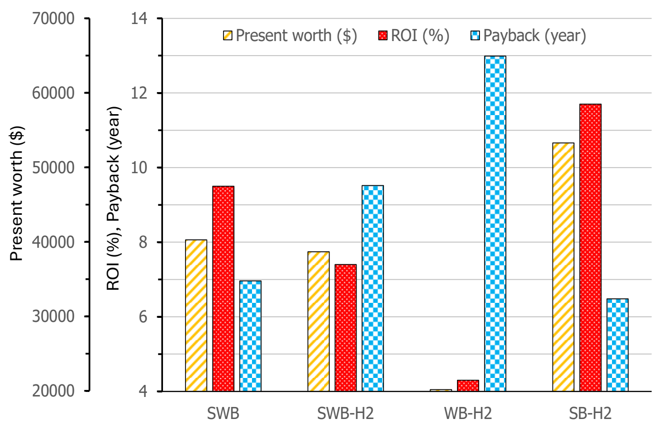
S (kW)	W (kW)	B (kW)	P_{total} (kW)	$P_{electrolyzer}$ (kW)	$P_{converter}$ (kW)	E (kWh/year)	H_2 (kg/year)	E excess (kWh/year)
20	0	8.3	28.3	18	6	62529	1181	5
0	19.5	8.3	27.8	18	6	62827	1173	65
15	9	8.3	32.3	18	6	62863	1183	32

configurations with and without hydrogen production. The results show that in the case of a grid-connected HRES combining only solar and wind energy, the wind power option with hydrogen production has the lowest economic efficiency, with a present worth of only $19,765, a return on investment of just 3.2% per year, and a payback period extending to 17.9 years. The solar-wind configuration, both with and without hydrogen production, demonstrates similar economic efficiency in terms of ROI and payback period. Among the analyzed configurations, the solar power combined with hydrogen production option achieves the highest economic efficiency. This configuration yields a present worth of $69,952, an ROI of 8.8% per year, and a payback period of 8.15 years. Therefore, for a grid-connected SW-HRES system integrated with hydrogen production but excluding a syngas engine, the S-H2 configuration (solar power with hydrogen production) emerges as the most economically viable option. The similar results were also reported in the previous studies (Jahangir and Cheraghi, 2020; Alhijazi *et al.*, 2023).

Table 3 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.

3.2.2. HRES with syngas generator

Figure 14 compares the economic efficiency of SWB-HRES configurations with and without hydrogen production. The economic efficiency analysis based on the price of HRES components found in Vietnam. The results show that the SB option with hydrogen production has the lowest economic efficiency in the case of grid-connected HRES involving solar,



Scenario	Present worth ($)	ROI (%)	Payback (year)
SWB	40304	9.5	6.96
SWB-H2	38706	7.4	9.52
WB-H_2	20237	4.3	12.99
SB-H2	53309	11.7	6.48

Fig. 14 Analysis of the SWB-HRES configurations' economic efficiency with and without hydrogen production

wind, and biomass energy. The present worth of this option only reaches $20,237, with a return on investment of only 4.3% per year, and the payback period extends to 12.99 years. The SWB option with hydrogen production and the one without is equivalent in present worth. However, the ROI is lower due to a larger initial investment and longer payback period. The SB option with hydrogen production provides the highest economic efficiency. This option has a present worth of $53,309, 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 profits of the SB-H2 option double, and the investment payback period is halved. Thus, in the case of grid-connected SWB-HRES with hydrogen production, the option consisting solely of solar energy combined with biomass offers the highest economic efficiency. The similar results could be found in the literature (Kumar and Channi, 2022; Dodo *et al.*, 2022).

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

In both cases of the SWB-HRES being off-grid and grid-connected, the power of the devices S, W, and B remains unchanged, as shown in Table 3. The system generates 62,863 kWh of electricity and 1,183 kg of hydrogen annually. The amount of electricity exchanged with the grid in the grid-connected case is negligible (buying 6 kWh/year and selling 247 kWh/year). Figure 15a and Figure 15b show the variation in electricity production by month throughout the year for both the off-grid and grid-connected SWB-HRES scenarios. In both cases, the total annual production of wind, solar, and generator electricity accounts for 23.5%, 28.9%, and 47.6%, respectively. When the HRES generator system serves as a backup energy system to compensate for solar and wind energy shortages compared to the load, we set the maximum ultimate hydrogen load at 100%, so the minimum load for the internal combustion engine operating in the off-grid HRES system must be maintained to ensure power is supplied to the electrolyzer. This level is set at 90% to ensure the annual electricity production provided by the generator in the off-grid HRES system is equivalent to that when it operates in the grid-connected HRES.

Figure 16a and Figure 16b compare the variation in power output from generation sources in independent SWB-HRES and grid-connected systems during the last week of May. The power output from wind and solar energy remains consistent across both configurations. In the independent HRES setup, the generator operates at 90% of its maximum capacity, resulting in 4,021 operating hours per year with 850 starts. In contrast, the grid-connected system adjusts the generator's electrical power output to align approximately with the average maximum AC load, which is lower than the generator's output in the

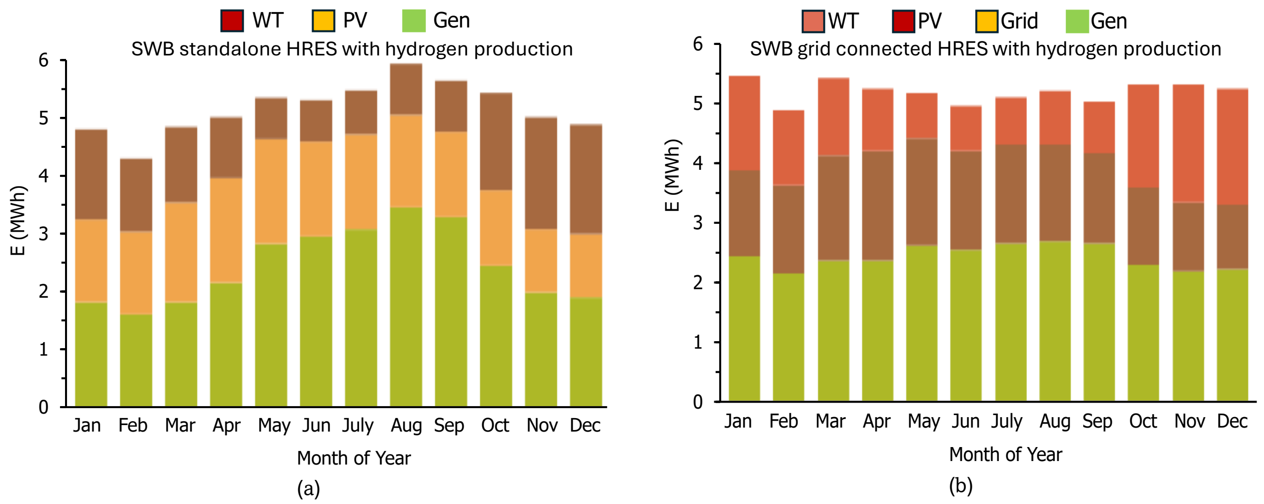


Fig. 15 Electricity production from different components of the SWB-HRES combined with hydrogen production in various cases, a) off-grid, b) grid-connected

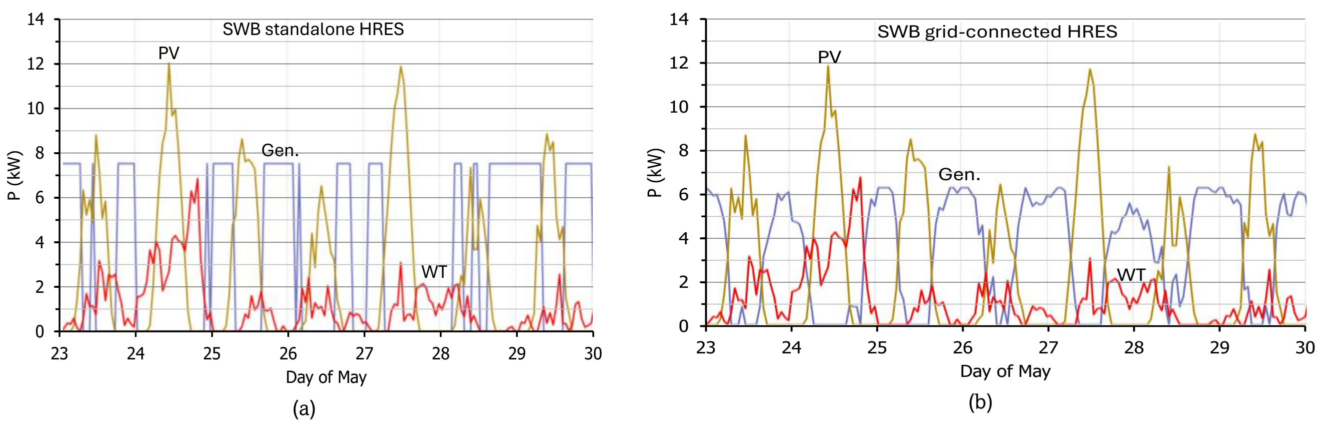


Fig. 16 Variations in electricity generation from wind, solar, and generators during the last days of May, a) SWB-HRES independent system, (b) grid-connected system

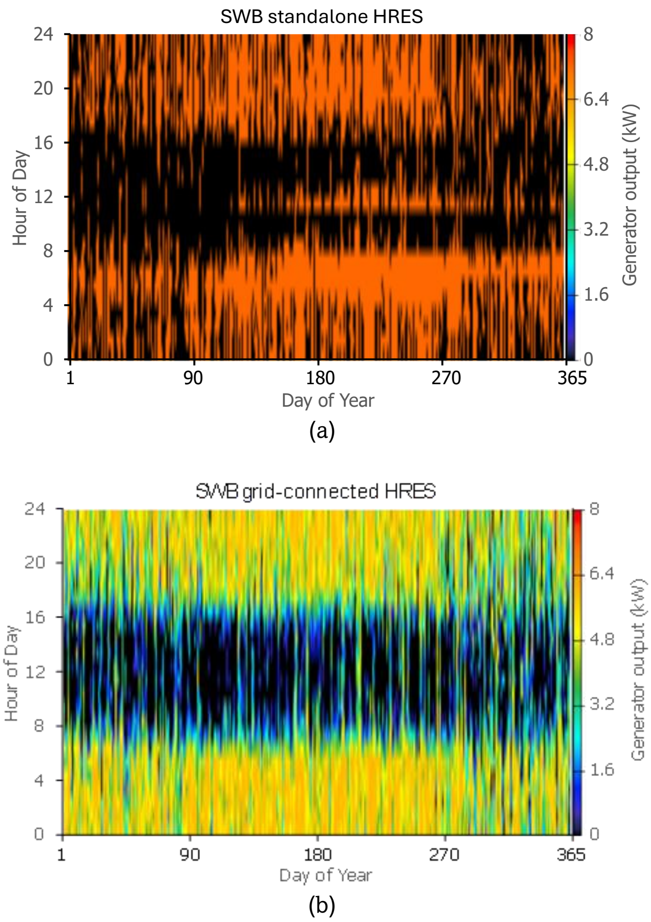


Fig.17 Variation in power output of the generator by hour throughout the year of the SWB-HRES, a) stand-alone, b) grid-connected

independent HRES configuration. In the grid-connected system, the generator operates for 6,838 hours annually with only 470 starts. While extending the generator's operating time in the grid-connected HRES increases operational costs due to shorter equipment replacement intervals, the surplus power can be sold to the grid, compensating for these costs. Additionally, the reduced number of starts positively impacts the engine's lifespan by minimizing wear and tear caused by frequent start-stop cycles. Therefore, the grid-connected HRES offers greater economic and operational benefits compared to the independent HRES.

Figure 17a and Figure 17b illustrate the annual variations in the generator's electrical power output for grid-connected and off-grid HRES configurations. In the grid-connected HRES, the generator's power output fluctuates based on the load demand, whereas in the off-grid HRES, the generator operates exclusively at its preset rated capacity when active, or remains at zero when turned off. As discussed earlier, from an economic perspective, the grid-connected HRES demonstrates superior performance compared to the independent HRES. However, from a technical standpoint, operating the generator at its rated capacity is more advantageous in terms of fuel efficiency compared to partial-load operation. Therefore, in practical applications, it is essential to carefully analyze and balance the trade-offs between economic and technical benefits to optimize system performance.

Figure 18a and Figure 18b compare the variations in hydrogen production during the final days of May for grid-independent and grid-connected HRES configurations. The results reveal that fluctuations in hydrogen production are lower in the grid-connected HRES compared to the grid-independent HRES. Although the average annual hydrogen production remains the same for both configurations, the grid-connected HRES is better suited for applications requiring stable hydrogen loading conditions, particularly in scenarios with low maximum ultimate hydrogen demand. Conversely, if hydrogen is considered a supplementary product of the HRES, the flow rate of hydrogen becomes less critical. In this case, the independent HRES offers an effective solution for utilizing surplus electricity production without relying on batteries for energy storage. This approach enhances the cost-effectiveness of the system by reducing storage infrastructure requirements.

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 $40,304, as illustrated in Figure 19.

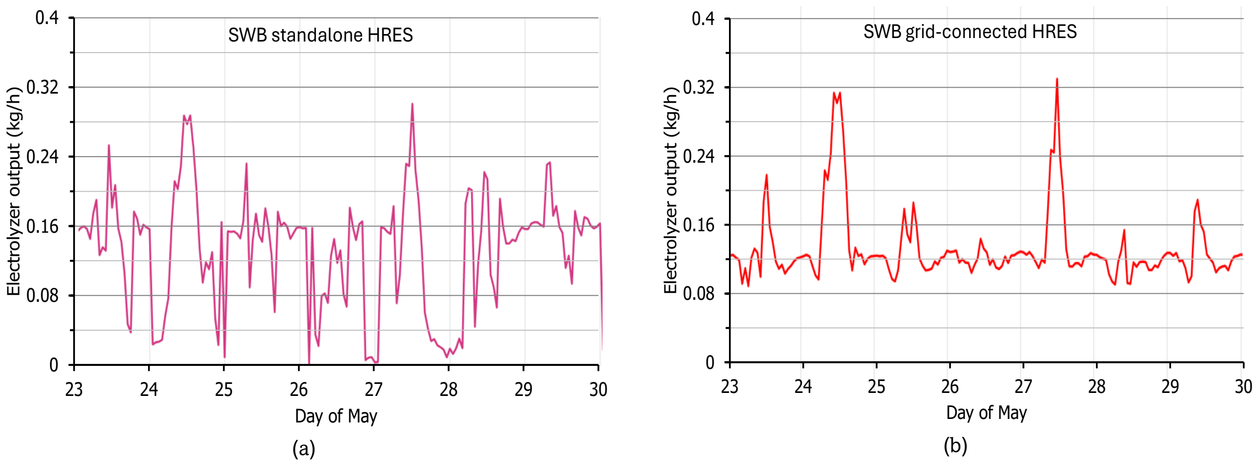


Fig. 18 Variation of hydrogen production on the last days of May for SWB-HRES, a) standalone mode, (b) grid-connected model

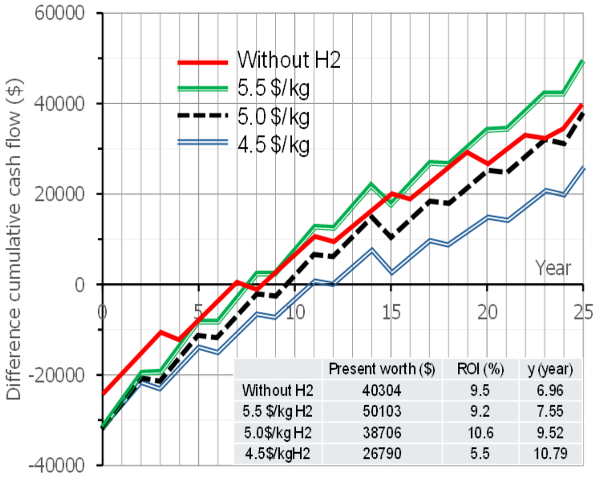


Fig. 19 The impact of hydrogen unit price on the economic effect of SWB-HRES

The cost of hydrogen produced by the HRES with hydrogen production was analyzed and compared to that of the HRES without hydrogen production. In the case of the HRES without hydrogen production, excess electricity is sold to the grid. Consequently, the sensitivity analysis of cost variables depends on the energy price specific to each country. The energy contained in 1 kg of hydrogen is equivalent to that in 3 liters of gasoline, which costs approximately $3. Therefore, if the price of green hydrogen is $3/kg, it becomes comparable to the cost of fossil fuels for heat energy production. 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 $10,000 higher than that of the non-hydrogen-producing system. According to The International Council of Clean Transportation (Navarrete and Zhou, 2024), 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, as shown in Figure 14, when the price of hydrogen is $5/kg, the present worth and 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. The similar finding in economic analysis of SWB-HRES was also reported in a study of (Li *et al*., 2020).

The environmental efficiency is assessed in comparison to the option of using the power grid. Reducing greenhouse gas emissions depends on the configuration and products of the HRES. When the HRES has an engine powered by biomass, the GHG reduction efficiency must also account for the amount of CH_4 it consumes. When the HRES produces hydrogen, the GHG reduction efficiency needs to consider replacing gasoline with the amount of hydrogen generated by the system. The following section will analyze the GHG emission reduction efficiency for different scenarios: GHG emissions when using grid electricity, the average CO_2 emissions for electricity generation in Vietnam are 521 g/kWh. Therefore, to generate 62,863 kWh/year, equivalent to HRES, the Vietnamese electricity generation system emits 33 tons of CO_2 annually into the atmosphere. For the case of the SW system not for producing hydrogen, when the HRES has only solar and wind power, does not utilize generators powered by 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 by grid electricity production, meaning a reduction of 33 tons of CO_2. In the case of the SW system for producing hydrogen, the amount of electricity generated by the system is used to supply a load of 7,300 kWh/year, with the remainder used to produce hydrogen. The reduction in CO_2 emissions from using renewable electricity to supply the load is 4 tons/ year. Regarding energy, 1 kg of hydrogen equals 3 kg of gasoline. The CO_2 emissions when using gasoline for internal combustion engines is 2 kg/litter, equivalent to 2.5 kg of CO2/kg of gasoline. Therefore, using 1 kg of hydrogen as a substitute for gasoline reduces CO2 by 7.5 kg. Using 1,183 kg of hydrogen produced by the system annually to replace gasoline reduces CO_2 emissions by 9 tons annually. Thus, the total reduction in annual CO_2 emissions that the system provides compared to using grid electricity is 13 tons of CO_2.

For the case of the SWB system not producing hydrogen: The syngas generator produces 33,042 kWh of electricity yearly. The overall efficiency of the generator engine cluster is approximately 20%. Assuming the engine runs on biogas that contains an average of 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, so if it is not consumed, it will be released into the atmosphere. The greenhouse effect of CH_4 is 20 times that of CO_2. Therefore, the equivalent CO_2 emissions from the amount of CH_4 released into the atmosphere from biogas are 204 tons. The total GHG emissions reduction equivalent to CO_2 the system provides each year is 237 tons. In the case of the SWB system that produces hydrogen, in addition to reducing emissions of 204 tons of CO_2 from the power plant, the system also helps reduce 9 tons of CO_2 each year by replacing gasoline with 1,183 kg of hydrogen and reduces 4 tons of CO_2 per year due to loads 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, the generator produces 38,391 kWh of electricity each year. Therefore, the corresponding reduction in CO_2 emissions when the engine uses fuel recovered from biomass is 237 tons. This system's total reduction in CO_2 emissions annually (including the reduction from using biomass due to the load using renewable energy and the use of substitute hydrogen) is 250 tons.

3.4 Economic and environmental effectiveness analysis of HRES

Figure 20 compares the economic and environmental effectiveness of HRES options that combine PV, WT, and biomass with and without hydrogen production. Return on investment and CO_2-eq emission reduction have been chosen as the comparison parameters. The results indicate that the SB-H2 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. In general, while numerous studies have investigated green hydrogen production using renewable energy sources, the majority have focused predominantly on solar and wind energy. Although biomass is considered as potential renewable source in producing power and hydrogen, integrating biomass energy into HRES remains challenging due to its inherent complexity

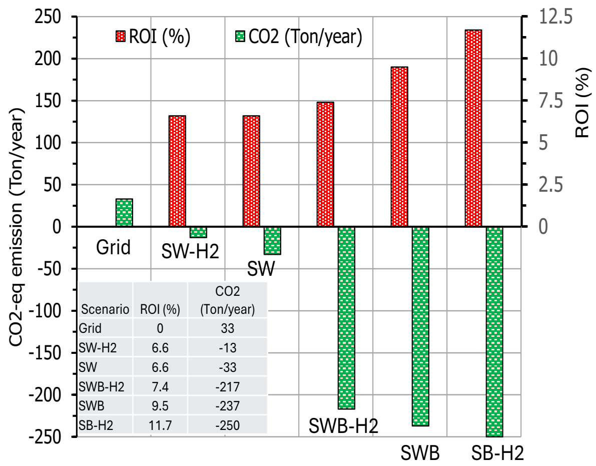


Fig. 20 Comparison of the economic and environmental effectiveness of the SWB-HRES options

(Baghel et al., 2024). In our study, biomass is converted into RDF, enabling efficient storage and utilization to complement other renewable sources such as solar and wind. A comprehensive analysis of the environmental impacts associated with integrating biomass into HRES for hydrogen production has rarely been reported in the existing literature. Our research addresses this gap by providing a detailed assessment of these environmental factors. Additionally, our findings emphasize the competitiveness of hydrogen pricing, demonstrating that hydrogen production costs can align favorably with revenues obtained from electricity sales to the grid. Furthermore, as highlighted in the introduction, the efficiency of HRES integrated with hydrogen production significantly depends on resource availability and fuel prices, thus varying according to specific implementation sites. Similar case studies conducted in Vietnam remain scarce in current literature. Therefore, this research contributes significantly toward developing an optimized multi-generation HRES tailored specifically to a practical location. Additionally, this study is conducted in Vietnam, where the energy transition is in progress, but lacking fundamental research on solar-wind-biomass integrated HRES with hydrogen production. Consequently, our findings will significantly support strategic planning for renewable energy applications, thereby contributing toward achieving Vietnam's net-zero goal.

4. Conclusion

In this study, the hybrid renewable energy system utilizing solar, wind, and biomass energy (SWB-HRES) produces hydrogen, contributing to energy transformation in electricity generation, transportation, and solid waste management, which aligns with Hoa Bac's sustainable development. The optimized SWB-HRES system includes a 15-kW solar panel, a 9kW wind turbine, an 8.3kW syngas generator, a 20-kW electrolyzer, a 24-kW converter, and a 1kg hydrogen storage tank. It supplies electricity for a load of 7,300 kWh/year and produces 1,183 kilograms of hydrogen/year. In the case of the SWB-HRES hybrid grid for hydrogen production, the solar power combined with biomass SB-H2 option provides the highest economic efficiency. Compared to the WB-H2 option, the profits of the SB-H2 option double, and the payback period for the investment is half. The economic and environmental efficiency is highest with HRES solar-wind turbine-biomass systems that do not produce hydrogen. When HRES combines hydrogen production, combining solar energy and biomass yields the best economic and environmental results. The economic efficiency of the SWB-HRES in producing hydrogen is equivalent to the SWB-HRES selling electricity to the grid when the cost of hydrogen is $4.5/kg if the engine does not operate continuously and $5/kg if the engine is not continuously operating. Integrating biomass energy into HRES is an effective solution for reducing GHG emissions. When producing the same amount of electricity, 62,863 kWh/year, HRES solar-wind turbines without hydrogen production reduce emissions by 33 tons CO_2-eq per year. In contrast, HRES solar-wind turbine-biomass systems that produce hydrogen reduce emissions by 217 tons CO_2-eq.

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