

LOWERING THE COSTS OF BIO-HYDROGEN PRODUCTION FROM EMPTY FRUIT BUNCH (EFB) WITH SOLAR GASIFICATION – TECHNO-ECONOMIC AND THERMODYNAMIC ANALYSIS

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ABSTRACT

Hydrogen production from empty fruit bunches (EFBs) is proposed here using a gasification system powered by solar energy and biomass, generating bio-hydrogen through combined steam methane reforming, along with electricity using an organic Rankine cycle. For EFB input of 1,286 kg/hr, the hourly production is 28.5 kW of electricity and 36 kg of hydrogen. The overall design efficiency is 60.37%, and the equivalent energetic efficiency is 46.33%. Finally, an economic analysis is conducted, showing an 8-year payback period. The system's environmental friendliness is highlighted by the hydrogen production cost, which is as low as USD1.21/kg. Although the carbon dioxide (CO₂) emissions in this study are relatively high, the CO₂ from EFB does not increase the environmental concentration. Importantly, the hydrogen yield from EFB is relatively high at 23.83 H₂ g/kg feed.

Keywords: bio-fuels, bio-hydrogen, empty fruit bunches, energy system, exergy and energy analysis.

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INTRODUCTION

Malaysia is the second largest producer of palm oil (Yeng et al., 2024) utilising less than 17% of its total land area, supplies 47% of the world's palm oil (Abbasi et al., 2023). In 2022, just in one year, over a million tonnes of empty fruit bunches (EFBs) were discarded in Nigeria (Obada et al., 2023), and around 88 million tonnes in Malaysia (Rajakal et al., 2024). Under unfavourable decomposition conditions, EFB releases greenhouse gases such as nitrous oxide and methane, equivalent to emitting 0.23 t of carbon dioxide (CO₂)/t of EFB (Vela Garcia, 2021). Thus, just in Malaysia and Nigeria, EFB disposal annually results in approximately 20.47 million tonnes of CO₂ emissions, causing environmental pollution and resource wastage. The EFB can be looked at as a

renewable energy source and can help to overcome the current reliance on fossil fuels (Song et al., 2022) which is clearly incompatible with the future requirements for green energy (Fan et al., 2024).

Hydrogen is a clean energy source that falls within the category of green energy sources (Yuksel et al., 2022). Two main sources of green hydrogen are water electrolysis and biomass gasification (Castro et al., 2022). The former requires renewable electricity to provide the necessary energy, while the latter offers a higher conversion efficiency and lower costs compared to traditional hydrogen production methods (Safarian et al., 2019). Biomass pyrolysis and biomass gasification are two primary methods for producing hydrogen from biomass, with the latter considered at present the most efficient and economically viable method (Nguyen et al., 2024). Hydrogen can be produced from EFB and other palm oil waste through various thermochemical and biochemical processes (Ruya et al., 2020). Additionally, other researchers have produced value-added fuels from

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the palm oil waste including methanol (Im-orb et al., 2020), bio-methanol and bio-dimethyl ether (Im-orb & Arpornwichanop, 2022), methane and electricity (Saritpongteeraka et al., 2022). It is clear that bio-hydrogen production from EFB is viable. Additionally, none of the models for solar biomass gasification mentioned above have considered EFB as the feedstock for gasification.

The use of solar energy can be divided into two main groups. They are solar photovoltaic and solar thermal energy. The process of solar thermal technology involves gathering sunlight and storing its energy as heat. A solar collector is the primary component of a solar thermal system. Generally speaking, a solar collector is a device that uses a specially coated and reinforced glass tubing to capture sunlight (Nirmala et al., 2022). Many researchers have explored the use of solar energy to convert various types of biomasses into energy, including yellow grease (Naveen et al., 2021), rice husks, beech wood and plastic waste (Naveen et al., 2023). Among all hydrogen production technologies, the cost of hydrogen produced via electrolysis is the highest. The cost of solar-powered electrolysis ranges from USD3.34 to USD17.30/kg, while wind-powered electrolysis ranges from USD3.56 to USD10.82/kg (Parkinson et al., 2019). In contrast, biomass-based hydrogen production costs range from USD1.48 to USD3.00/kg (Al-Qahtani et al., 2021), whereas hydrogen production from geothermal energy is the cheapest among green methods, ranging from USD1.08 to USD4.38/kg (Farhana et al., 2024). To address this cost disparity, this article proposes a solar-assisted EFB gasification system for hydrogen production, aiming to reduce the cost of biomass-based hydrogen production to a level comparable with coal-based hydrogen production.

Solar gasification involves the use of a hyperbolic reflector, which can produce temperatures of above 1,000°C (D. Xu, et al., 2023), which is adequate for biomass gasification temperature of 600°C–1,000°C (Abanades et al., 2021). Direct normal irradiation (DNI) is a key parameter for solar gasification. Studies on biomass solar gasification have achieved gasification temperatures under different DNI levels, including 850°C at 766 W/m² (Assareh et al., 2023), 800°C at 850 W/m² (Anvari et al., 2019), 1,073°C at 800 W/m² (Wang et al., 2019) and 877°C at 751 W/m² (Bai et al., 2019).

Even though the gasification temperatures reported above are high, the values of DNI reported above are higher than the mean value of DNI for Malaysia which is 600 W/m² (Mohammad et al., 2020). It is important that the representative value of DNI is used in the study of solar gasification in order to arrive at a realistic cost for bio-hydrogen production.

Table 1 compares the hydrogen production from EFB and related poly-generation systems in this

study with those reported by other researchers. Although several studies have investigated EFB gasification for hydrogen production, most focus primarily on technical performance and lack comprehensive economic and thermodynamic analysis. Many studies only construct basic models without detailing energy sources, and few consider the combustion of EFB and palm oil shell (POS) as inputs. Detailed assessments of hydrogen production, as well as strategic and environmental analysis, are also rare. Furthermore, few studies examine the scalability and economic feasibility of these systems for practical industrial applications. This study fills these gaps by integrating techno-economic and thermodynamic analysis, offering a more comprehensive perspective on EFB-based hydrogen production.

In Table 1, abbreviations are used to streamline references to key areas of analysis: En stands for energy (focusing on the energy efficiency and output of systems); Ex represents exergy (evaluating the quality and utilisation of energy within the system); Ec denotes economic (assessing cost-effectiveness and financial viability); Env refers to environmental considerations (emphasising the system's impact on ecological sustainability) and SCWG stands for supercritical water gasification.

This study proposed a combined approach of solar energy gasification and biomass combustion gasification. Malaysia, in particular, has abundant solar energy due to its geographical location (Mohammad et al., 2020). To reduce the cost of hydrogen production or provide a low-cost alternative to coal gasification for hydrogen production, this article introduces a novel solar biomass EFB gasification system integrated with an organic rankine cycle (ORC) system for the production of hydrogen and electricity. Thermodynamic analysis of the system is first conducted to perform an exergy loss analysis. This is followed by an economic feasibility study by calculating the payback period of the system and its environmental costs by assessing the hydrogen output and CO₂ equivalent emissions.

MATERIALS AND METHODS

System Description

The solar gasification unit (SG), biomass combustion (BC), steam methane reforming (SMR) and ORC are the four main components of the unique design system, as shown in Figure 1.

In order to convert EFB biomass into syngas, the SG or BC units need solar energy as a heat source. Hydrogen is created in the SMR when steam reacts with syngas methane and carbon monoxide. Heat for the SMR is produced by burning unreacted

TABLE 1. THE COMPARISON OF EFB HYDROGEN PRODUCTION SYSTEM STUDIES

Source	Pro	System	Analysis				References
			En	Ex	Ec	Env	
Palm tree residues	H ₂	Gasification	✓	✓			Kayıoğlu and Demirtaş (2023)
BC-EFB	H ₂	SMR	✓	✓			Ruya et al. (2020)
EFB	H ₂	SCWG					Vargas-Mira et al. (2019)
EFB	H ₂	SMR					Sinaga et al. (2020)
EFB	H ₂	SMR			✓		Rahmi et al. (2019)
EFB	H ₂	SMR	✓	✓			Laguna et al. (2018)
SG-BC	H ₂	SMR	✓	✓	✓	✓	This study

Note: EFB - empty fruit bunch; BC - biomass combustion; SG - solar gasification; SMR - steam methane reforming; SCWG - supercritical water gasification; En - energy; Ex - exergy; Ec - economic; Env - environmental considerations.

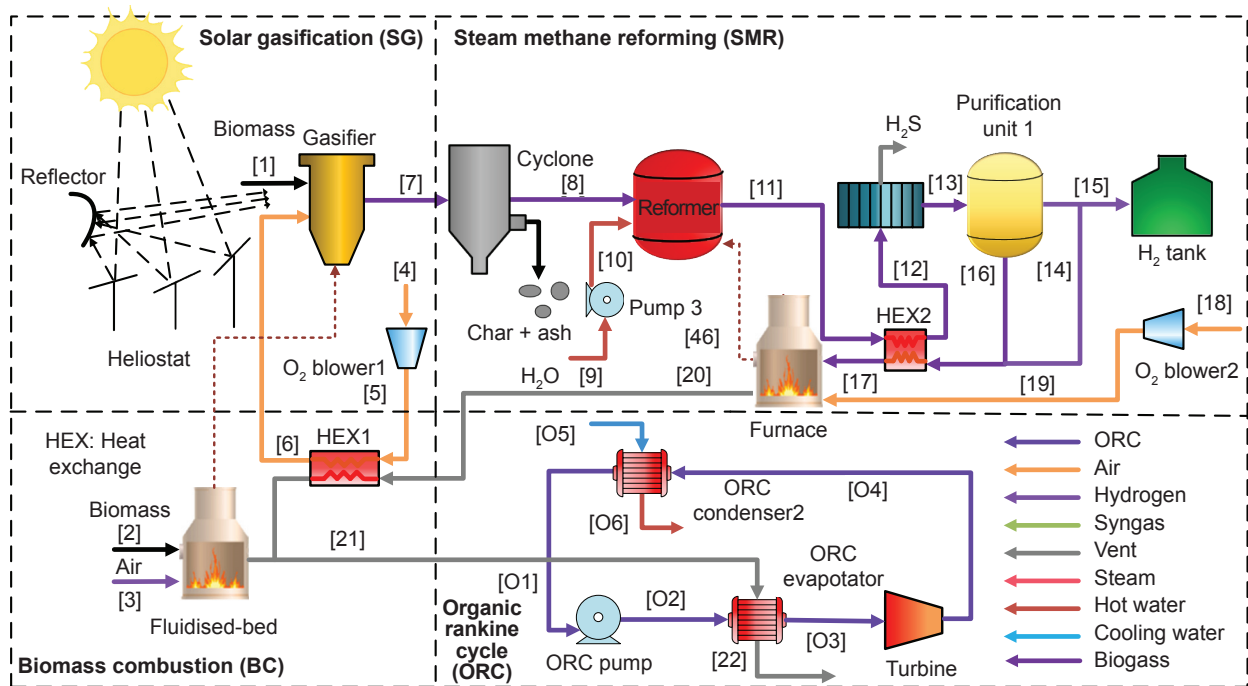


Figure 1. Integrated flowchart of the system.

carbon monoxide, methane and some unextracted hydrogen in a furnace. The ORC receives the leftover heat in order to generate power. After production, the hydrogen is stored for sale. The establishment of the entire model is based on the following assumptions: The reaction in the gasifier reduction zone achieves complete conversion with a 100% carbon conversion rate, where the biomass and the gasification agent are thoroughly mixed upon contact at a constant temperature (Zaman & Ghosh, 2021). The pyrolysis process of biomass is completed rapidly, and the volatile matter is evenly mixed with the gasification agent. Tar production is disregarded, as tar is considered an inert substance (Vikram et al., 2022). Nitrogen makes up 79% of the air and oxygen makes up 21%. The system operates in a steady state. The surrounding air is 25°C in temperature and 1 atm in pressure.

Analysis Methods

The specific proximate and elemental analysis parameters of the EFB (Ruya et al., 2020) are used in this study as listed in Table 1, and the lower heating value (LHV) is 19.06 MJ/kg (Huang et al., 2020). The mass input rate of EFB can be found in Table 2.

SG unit and BC. SG is the process of directly collecting and heating EFB using solar energy. The solar gasification system consists of two main components: The solar collection section and the biomass gasification section. The solar collection subsystem, including parabolic mirrors and a dish collector, concentrates solar radiation to generate high-temperature thermal energy. This energy, focused on the gasifier's opening, drives the gasification of EFB, converting biomass into

combustible gas. The high-temperature thermal energy provides the necessary conditions for the gasification reaction of EFB at elevated temperatures. The directly acquired solar energy and absorbed solar energy are calculated using the formulas as shown in Equation (1) and (2) (Bai et al., 2019):

$$Q_{solar} = DNI \times A_{helio\,stat} * \eta_{helio\,stat} \quad (1)$$

$$Q_{solar, absorb} = Q_{solar} \times \eta_{attenuation} \times \eta_{reflectance} \times \eta_{receiver} \quad (2)$$

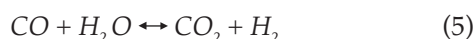
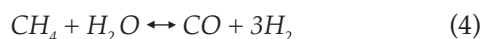
During the gasification process, the energy balance can be represented by the following equation as shown in Equation (3):

$$\sum_{i=p} (n_i(h_{T_{a,i}}^0 + C_{p,i}(T_G - T_a))) = \sum_{i=r} (n_i(h_{T_{a,i}}^0 + C_{p,i}(T_i - T_a))) + Q_{solar, absorb} + Q_{in} - Q_{out} \quad (3)$$

The total enthalpy of the products is on the left side, and the first term on the right side is the enthalpy of the reactants. The last three terms represent the changes in heat. For detailed specifics, please refer to reference (Wang et al., 2019). The gasification temperature range for EFB is 750°C–1,000°C (Im-orb et al., 2020), and this study utilises a temperature of 800°C.

Given the intermittent nature of solar energy, this study adopts the combustion of EFB as an alternative gasification method. Under certain assumptions, the combustion products include only carbon dioxide (CO₂), carbon monoxide (CO), hydrogen gas (H₂), water (H₂O), methane (CH₄), nitrogen gas (N₂), oxygen gas (O₂) and the emissions of harmful gases from the exhaust were not considered (Muhtadin et al., 2020).

The SMR Process. During the SMR process, the primary reactions are as follows Equation (4) and (5). The specific mass and energy balance equations are shown in Equation (6) to (8). For the SMR process, where the temperature range is 700°C–900°C, this study sets it at 800°C. Additionally, the CH₄ conversion rate is set to 90% (Kumar et al., 2024).



$$\frac{dc_i}{dt} = R_i \quad (6)$$

$$V_r C_p \frac{dT}{dt} = Q + Q_{ext} + \frac{dp}{dt} V_r \quad (7)$$

$$Q = -V_r \sum_j H_j r_j \quad (8)$$

where, c_i represents the molar flow rate of the species, V_r represents the volume of the reactor, C_p is the molar heat capacity of the species, H_j is the heat of the reaction and r_j is the reaction rate.

The ORC Process. To create the thermodynamic model of ORC, it is necessary to consider two governing equations: One for mass conservation and one for energy conservation. The mass balance, concentration balance and energy balance equations (Kholghi et al., 2019) can be expressed as follows [Equation (9) and (10)]. The symbol “ $\dot{m}$ ” represents the mass flow.

$$\sum_{in} (\dot{m}x)_{in} = \sum_{out} (\dot{m}x)_{out} \quad (9)$$

$$\sum \dot{Q} + \sum_{in} (\dot{m}h)_{in} = \sum_{out} (\dot{m}h)_{out} + \sum \dot{W} \quad (10)$$

Exergy. One important metric in this study that is impacted by thermodynamic irreversibility is exergy reduction (Talbi & Agnew, 2000). The total exergy consists of four components: Physical, chemical, kinetic and potential exergy. However, the latter two types of exergy can be neglected in the calculations, so only physical and chemical exergies need to be considered (Ahmadi et al., 2013). A system’s total heat release, computed as Equation (11), is the result of adding the system’s chemical and physical heat releases while ignoring the other heat release (Misra et al., 2006).

$$\dot{E} = m(\dot{e}_{ph} + \dot{e}_{ch}) \quad (11)$$

The mole flow is represented by the letter “ m ”. The quantities h and s stand for specific enthalpy and entropy, respectively. Chemical exergy can be calculated using standard chemical exergy (Farooqui et al., 2019). Potential and kinetic exergy are not taken into consideration while discussing the idea of chemical exergy (Oh et al., 2023). Equation designated as Equation (11) are used in the computation of exergy. Previous studies have shown that in the ORC system, the chemical exergy is very minimal and only the physical exergy has to be estimated (Cantone, 2019).

Several components are included within the system, such as fuel, product and exergy destruction. For the calculation of exergy efficiency (η) and exergy destruction ($\dot{E}_{D,i}$) for each component, Equation (12) is employed.

$$\dot{E}_{D,i} = \sum \dot{E}_{in,i} - \sum \dot{E}_{out,i} \quad (12)$$

The efficiency formulae for the system are listed below in Equation (13). The exergy calculation formula for biomass EFB is shown in Equation (14) (Huang et al., 2020). The system all design parameters are in Table 2.

$$\eta = \frac{LHV_{H_2} \times \dot{m}_{H_2} + W_{e,orc}}{\dot{E}_{bio}} \quad (13)$$

$$E_{x_{Bio}} = \dot{m}_{Bio} LHV_{Bio} (2.0144 + 0.0342 \frac{w_H}{w_C} - 1.2536 \frac{w_O}{w_C}) \quad (14)$$

Environment. In this article, the reduction of greenhouse gas (GHG) emissions serves as the primary environmental evaluation index. The bio-hydrogen process involved in phosphoric acid fuel cell (PAFC) operation primarily emits CO and CO₂, with CO being converted into equivalent CO₂ for calculation purposes (U.S. Environmental Protection Agency, 2024). The penalty cost associated with CO₂ emissions is USD24/t (You et al., 2020). This penalty cost is considered an environmental expense and will be incorporated into the overall system cost (Wu et al., 2023).

Economic Valuation. A technique used in the economic analysis of the hybrid system involves the categorisation of the costs presented in Table 3. The economics of the system over its lifespan were assessed using net present values (NPV). The NPV included in this study are total project cost, total overnight cost, total as-spent cost, bare erected cost,

engineering, procurement and construction cost (Abbasi et al., 2023). Table 4 provides a summary of the parameters used to evaluate the economic analysis.

RESULTS AND DISCUSSION

Exergy Performance

The material and energy balance data show that, during the SG operation, the process's total input exergy is 2,556.81 kW (Figure 2). This comprises 1,070.71 kW from BC and solar exergy, and 1,470.10 kW from EFB. At 500.38 kW, or 36.54% of the total exergy loss, the gasification process shows the largest exergy loss. With an exergy loss of 420.23 kW, the cyclone comes next, making up 30.69% of the overall loss. At 177.9 kW, or 12.75% of the total exergy loss, the furnace exhibits the third-highest exergy loss. The ORC uses furnace waste heat while burning biomass, which raises the ORC's exergy loss from 82 to 305 kW. Within the ORC, the gasification, cyclone and ORC have the most exergy losses (31.42%, 26.39% and 19.15%, respectively).

TABLE 2. MAIN OPERATING PARAMETERS AND SYSTEM CONDITIONS

Parameter	Value	Unit
Ambient temperature	25	°C
DNI	600	w/m ²
Solar collection efficiency	44.00	%
Reflectance efficiency	90.00	%
Attenuation efficiency	90.70	%
Combustion efficiency	57.00	%
Heat exchanger efficiency	80.00	%
Pump efficiency	95.00	%
Land area	4,727	m ²
Fluidised bed surfance	10	m ²
EFB gasification	548	kg/hr
EFB combustion	925	kg/hr
Pressure	1	Atm
Gasification temperature	800	°C
Steam to feed ratio	6	
CH ₄ conversion	74.00	%
Oxygen to feed ratio	0.25	
SMR operating temperature	800	°C
Chilled water inlet and outlet	7/15	°C
DHW water inlet and outlet	25/60	°C
Voltage	0.67	V
Current density	125	mA/cm ²
Proximate analysis (V:FC:A:M)	69:18.5:7:5.5	
Elemental analysis (C:H:O:N:S)	42.33:5.28:50.85:1.46:0.08	
LHV	19.06	MJ/kg

Note: DNI - direct normal irradiation; DHW - domestic hot water; LHV - lower heating value; EFB - empty fruit bunches; CH₄ - methane; SMR - steam methane reforming.

TABLE 3. ORIGINAL EQUIPMENT COST AND COST CONVERSION

Component	Equation	Unit of parameter	Reference
Land cost	$88 \times \text{Area}$	A (m ²)	Seo et al. (2022)
Heliostat	$75 \times \text{Area}$	A (m ²)	Seo et al. (2022)
Gasifier	$1,600 \times (\dot{m}_{\text{Biomass}})^{0.67}$	kg/s	Habibollahzade et al. (2019)
Tower height	USD3M/86.5m	m	Bai et al. (2019)
Fluidised bed	USD4.51M/1,748m ²	Surface (m ²)	Stenberg et al. (2020)
Absorber	$52.84 \times \dot{W}_{\text{Absorber}}$	$\dot{W}_{\text{Absorber}}$ (kW)	Cormos (2014)
H ₂ tank	$4.28 \times m_{\text{H}_2}$	m_{H_2} (Kg)	Le et al. (2017)
Reformer	$76.29 \times \dot{W}_{\text{Reformer}}$	$\dot{W}_{\text{Reformer}}$ (kW)	Cormos (2014)
Furance	$1,479 \times (\dot{Q}_{\text{Furance}})^{0.75}$	$\dot{Q}_{\text{Furance}}$ (kW)	Wu et al. (2023)
Purification	$1,785 \times \dot{Q}_{\text{Puri}}$	$\dot{Q}_{\text{Puri}}$ (kW)	Wu et al. (2023)
Blower	$91,562 \times (\dot{W}_{\text{Blower}}/445)^{0.67}$	$\dot{W}_{\text{Blower}}$ (kW)	Sammes et al. (2004)
Pump	$16,800 \times (\dot{W}_{\text{Pump}}/200)^{0.67}$	$\dot{W}_{\text{Pump}}$ (kW)	Whitaker (1998)
Heat exchange	$235 \times (\dot{Q}_{\text{HEX}})^{0.75}$	$\dot{Q}_{\text{HEX}}$ (kW)	M. Xu et al. (2023)
ORC condenser	$597 \times (\dot{Q}_{\text{Con}})^{0.68}$	$\dot{Q}_{\text{Con}}$ (kW)	Desai and Bandyopadhyay (2015)
Turbine	$3,143.7 + 217.423 \times (\dot{V}_{\text{Tur}})^{0.68}$	$\dot{V}_{\text{Tur}}$ (1/sec)	Astolfi (2015)
ORC pump	$200 \times (\dot{W}_{\text{Pump}})^{0.65}$	$\dot{W}_{\text{Pump}}$	Zhang et al. (2019)
ORC evaporator	$209.14 \times (A_{\text{Eva}})^{0.85}$	A_{Eva}	Zhang et al. (2019)

Note: H₂ - hydrogen; ORC - organic rankine cycle.

TABLE 4. ESSENTIAL ECONOMIC FACTORS AND PRESUMPTIONS

Component	Equation	Unit
Interest (discount) rate (i)	4.35	%
Owner's cost	5.00	%
Construction	2	yr
Insurance cost	1.00	%
Contingency	0.02	%
OPEX		
O ₂ prices	0.02	USD/kg
Hydrogen prices	2.5	USD/kg
CO ₂ prices	0.024	USD/kg
EFB prices	0.00	USD/Nm ³
Depreciation cost of equipment	1.00	%
Cost of installation	5.00	%
Economic		
Average inflation rate	2.00	%
System lifetime	20	yr
SG (annual plant operating hours)	3,000	hr/yr
EFB (combustion Annual plant operating hours)	5,000	hr/yr
Payback time	8	yr

Note: O₂ - oxygen; CO₂ - carbon dioxide; EFB - empty fruit bunch; SG - solar gasification.

Economic Performance

Figure 3 presents a detailed study of the NPV parameters for the system, using an EFB cost of USD0.00/t (Reeb et al., 2014), an electricity price of USD0.15/kWh (GlobalPetrolPrices.com, 2023), and a hydrogen price of USD2.50/kg (Ríos et al., 2024). Given that EFB is the primary energy input

and hydrogen makes up the bulk of the energy output relative to electricity, the analysis focuses on how changes in the prices of EFB and hydrogen affect the net present value. With a hydrogen selling price of around USD2.10/kg and an EFB purchasing price of USD0.00/t, the system can pay for itself in eight years under current market circumstances. The payback period is still within

eight years despite market fluctuations, where the price of EFB climbs to USD15.00/t and the price of hydrogen sold increases to about USD2.60/kg, as shown by the junction locations of the vertical lines in Figure 3's subplots.

Figure 4 presents a sensitivity analysis of the NPV in the eighth year with respect to the prices of EFB, hydrogen and electricity. In this figure, deep blue represents lower or even negative NPV values,

indicating that the project may not be profitable under these price combinations. In contrast, red indicates higher NPV values, suggesting greater profitability under favourable conditions. It can be observed that in the eighth year, there are numerous scenarios where $NPV > 0$, showing that various combinations of EFB and product prices result in profitability. This demonstrates a degree of economic resilience within the project.

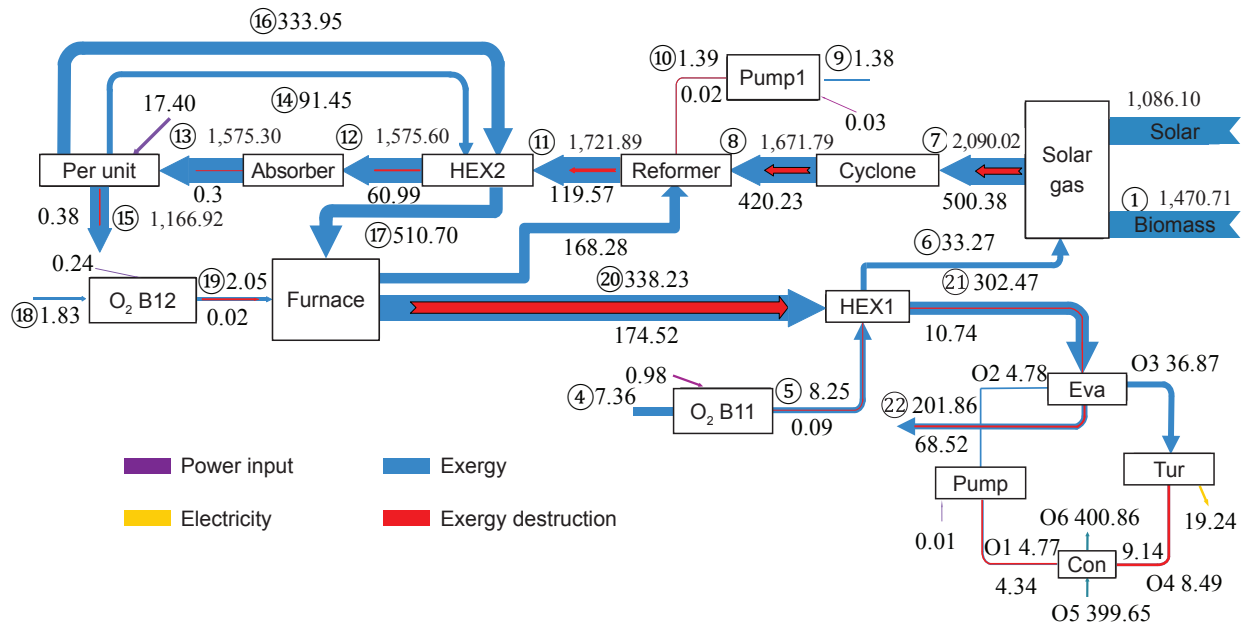


Figure 2. Sankey diagram of exergy flow.

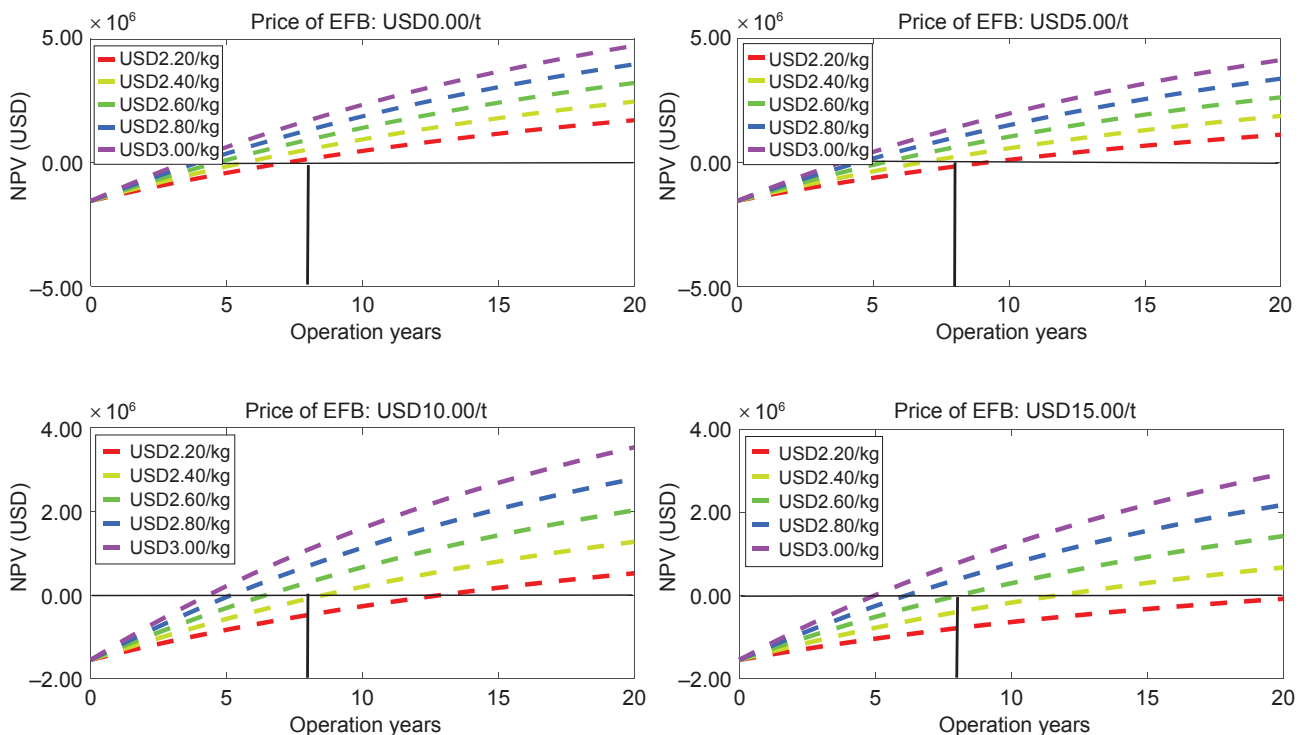


Figure 3. Net present values (NPV) analysis.

Environment Analysis

Table 5 shows that the hydrogen production efficiency of EFB is higher than that of general biomass and fossil fuels (Al-Qahtani et al., 2021), reaching 23.83 H₂ g/kg feed. However, its CO₂ emissions are lower than those of general biomass gasification, which are 32.84 kg CO₂/kg H₂, but higher than those of fossil fuels, at 25.65 kg CO₂/kg H₂, as well as hydrogen production via wind and solar-powered electrolysis (Parkinson et al., 2019). The reason is that EFB is not only gasified to produce hydrogen but also burned for heating when there is no sunlight. However, the CO₂ emitted from biomass is considered not to increase the atmospheric CO₂ concentration (Kemper, 2015), making it environmental-friendly.

TABLE 5. COMPARED WITH OTHER TECHNO-ECONOMIC STUDIES

Technologies	H ₂ yield (H ₂ g/kg feed)	CO ₂ emission (kg CO ₂ /kg H ₂)
Fossil-based SMR	297.00	9.26
Coal gasification	118.00	22.00
Biomass gasification	27.00	32.84
Electrolysis wind	-	1.34
Electrolysis solar	-	4.47
This study	23.83	25.65

Note: H₂ - hydrogen gas; CO₂ - carbon dioxide; SMR - steam methane reforming

Influences of DNI in Work Conditions

The DNI ranges from 500 to 50 W/m², based on real measurements in Seri Iskandar and other cities (Mohammad et al., 2020). Figure 5 illustrates the system's energy inputs and outputs. From January to July, the system's hydrogen and electricity output meet the expected results. However, excess solar thermal energy occurs when the DNI surpasses the design parameter of 600 W/m² due to capacity limitations. From August to December,

due to the rainy season, the DNI is below the design standard, resulting in reduced output. The variation in DNI throughout the year is attributed to seasonal changes in Malaysia: January to July (dry season) contribute nearly 63% of the total DNI, while August-December (rainy season) contribute 37%.

Compare Comparison and System Efficiency

Figure 6 compares the hydrogen production costs of various technologies. The average hydrogen cost from this study is significantly lower than that of other technologies, reaching the levels of coal (USD0.86–USD1.89/kg) and geothermal (USD1.08–USD4.38/kg), indicating that the system is more cost-effective. Specifically, the hydrogen cost in this study is around USD1.21–USD1.42/kg, which on average is lower than all other listed technologies, including solar, biomass, wind, grid, geothermal, nuclear, natural gas and coal (Farhana et al., 2024). This demonstrates the substantial economic advantage of the system evaluated in this research.

The overall energy and exergy efficiencies of the developed system are compared with other solar and biomass-based energy systems found in the literature. As shown in Table 6, the present system achieves higher energy and exergy efficiencies compared to biomass-based systems that produce electricity as the useful output energy and exergy efficiencies of 60.37% and 46.33%, respectively, by utilising waste heat for additional energy production.

Other studies have developed multigeneration systems that utilise both solar and biomass energy resources, but they did not consider EFB biomass for producing these commodities, nor did they evaluate the systems from the perspectives of exergy efficiency and economic analysis simultaneously. Therefore, the present study provides important results associated with the use of EFB biomass in combination with solar energy.

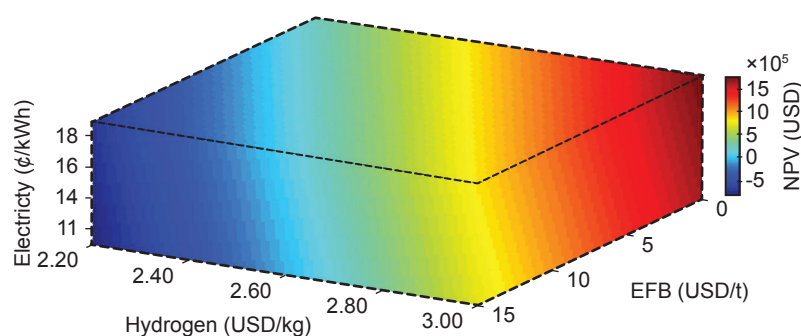


Figure 4. Sensitivity analysis of net present value (NPV) on empty fruit bunch (EFB) price and productions in the eighth year.

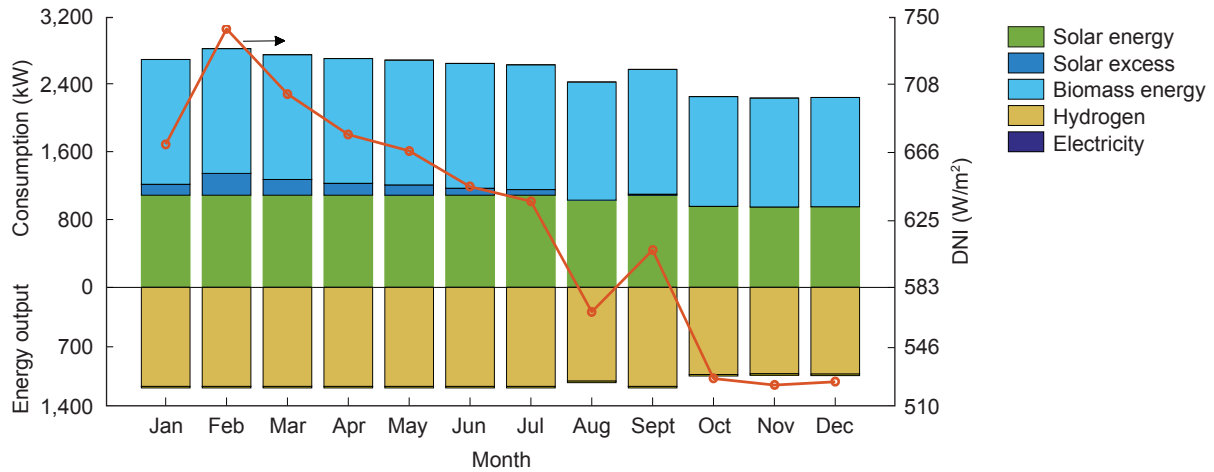


Figure 5. Input and output variations with direct normal irradiation (DNI) in months.

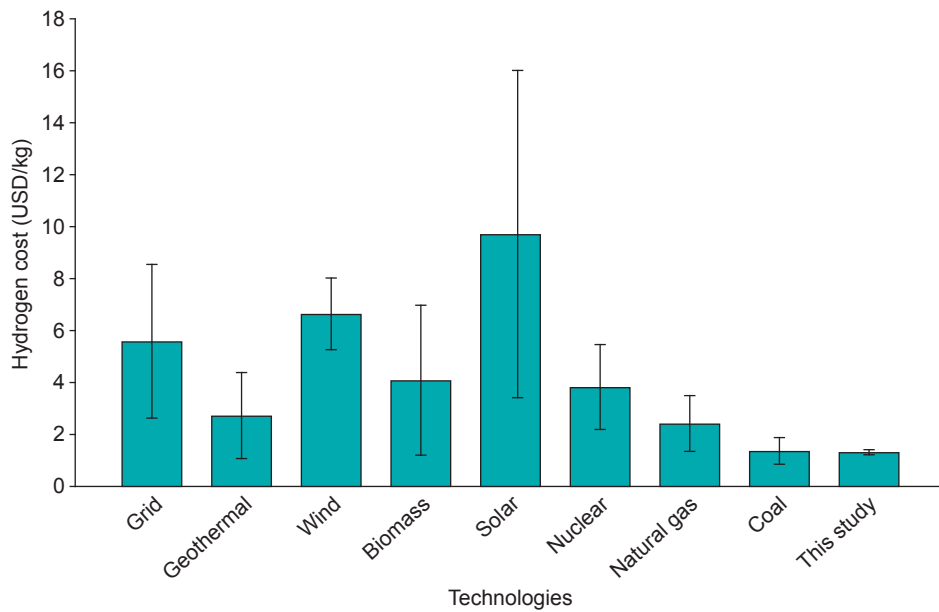


Figure 6. Comparison chart of the hydrogen cost of production from various sources.

TABLE 6. COMPARISON OF THE STUDY WITH OTHER SYSTEMS

Input	Output	Energy efficiency	Exergy efficiency	Reference
Oil palm shell	Hydrogen	19	22	Cohce et al. (2011)
Oil palm shell and EFB	Hydrogen	47.5–49.0	9.0–30.0	Ruya et al. (2020)
Solar and beech, charcoal, sewage sludge and fluff	Hydrogen	14.14–27.29	10.43–27.29	Kalinci et al. (2013)
Solar and coal	Electricity, hydrogen	49.84	4.97	Xue et al. (2023)
This study	Hydrogen electricity	60.37	46.33	This study

CONCLUSION

This study developed an innovative energy system that uses EFB biomass to produce hydrogen and electricity. The overall energy efficiency of the system is evaluated at 60.37%, with an exergy efficiency of 46.33%. A comparison of CO₂ equivalent emissions with other biomass-based hydrogen production systems shows that this system emits 25.65 kg CO₂/kg H₂, which is

lower than typical biomass systems. Additionally, economic analysis reveals that the system can achieve a payback period of eight years and demonstrates economic resilience. The study further highlights the system's environmental sustainability and economic viability, particularly given its relatively low hydrogen production cost, ranging from USD1.21 to USD1.42/kg, which brings the cost of biomass-based hydrogen production on par with that of coal gasification.

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