

## **Analysis and Design of Solar Power Plants as Energy Source for Green Hydrogen Production at PLTU Banten 2 Labuan**

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### **ABSTRACT**

Climate change is a global challenge that demands collective efforts, including from Indonesia, which aims to reduce greenhouse gas emissions by 31.89% through domestic efforts and 43.20% with international support. As part of a state-owned company, PLN contributes to this effort by integrating hydrogen business development into its strategic program. PLTU Banten 2 Labuan has a hydrogen plant with the potential to produce excess hydrogen for economic use. This research simulates three hydrogen production schemes to optimize performance and cost efficiency. The analysis reveals significant differences in terms of CAPEX, OPEX, LCOH, NPV, PI, IRR, DPP, and carbon emissions. Scheme 4, despite having the lowest emissions and OPEX, has very high CAPEX, with the highest LCOH of 7.41 USD/kg and poor financial performance (negative NPV of -217,908.33 USD, IRR of 3.62%, and PI of 0.59). Scheme 2, with the lowest LCOH of 3.79 USD/kg, is attractive but results in high carbon emissions (318,864 kg CO<sub>2e</sub>). Scheme 5, with moderate CAPEX and LCOH of 4.03 USD/kg, performs best overall, showing positive financial indicators NPV of 163,593.97 USD, PI of 3.14, IRR of 32.62%, and a short DPP of 3.2 years. Scheme 5 is the most optimal and recommended for further implementation.

**Keywords:** Hydrogen, LCOH, Carbon Emission, PLTS, Electrolysis.

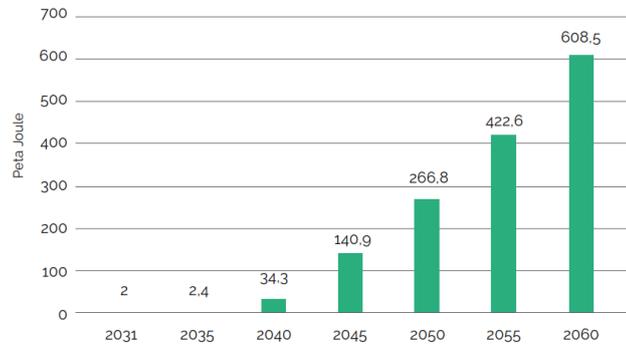
### **INTRODUCTION**

Climate change is the biggest challenge for countries around the world. The global agenda on climate change began with the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1989 which is an intergovernmental agency under the United Nations (UN) that serves as a knowledge centre on climate change [1]. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was established by the UN to develop an international policy framework related to climate change management. After that, two international agreements were agreed upon, namely the Kyoto Protocol in 1998 which came into force in 2005 and the Paris Agreement in 2015 which focuses on global efforts to limit global warming to below 2C compared to pre-industrial levels [2].

Indonesia is committed to supporting global policies on climate change with the issuance of the National Energy Policy (PP No. 79 of 2014) [3] and the ratification of the Paris Agreement (Law No. 16 of 2016) [4]. The policy is a step in Indonesia's energy transition towards new renewable energy, which is an effort to reduce greenhouse gas (GHG) emissions. Indonesia set a GHG reduction target through the Enhanced Nationally Determined Contribution (ENDC) document submitted to the UNFCCC on 23 September 2022, which is 31.89% by its own efforts and 43.20% with international support as a step to keep the global temperature rise no more than 1.5C by 2030 [5].

Hydrogen utilisation is one of the efforts to support the energy transition. Hydrogen has great potential to be a clean energy source, reducing dependence on fossil fuels and thus reducing GHG emissions [6]. According to projections by the Ministry of Energy and Mineral Resources, demand for low-carbon hydrogen is expected to grow from 2031 to 2060. In 2031, it is estimated that demand will reach around 0.2 PJ, increasing to 34.3 PJ in 2040, and finally peaking at 609 PJ in 2060. For

the transport sector, in 2031, the use of low-carbon hydrogen will start with an energy equivalent of 26,000 barrels of oil or 0.04 TWh, which is expected to increase to be the equivalent of 52.5 million barrels of oil or 89 TWh by 2060. Meanwhile, in the industrial sector, hydrogen use starts in 2041 with 2.8 TWh, and is expected to increase to 79 TWh by 2060 [2].



**Figure 1.** Hydrogen Demand Production 2031-2060 [2]

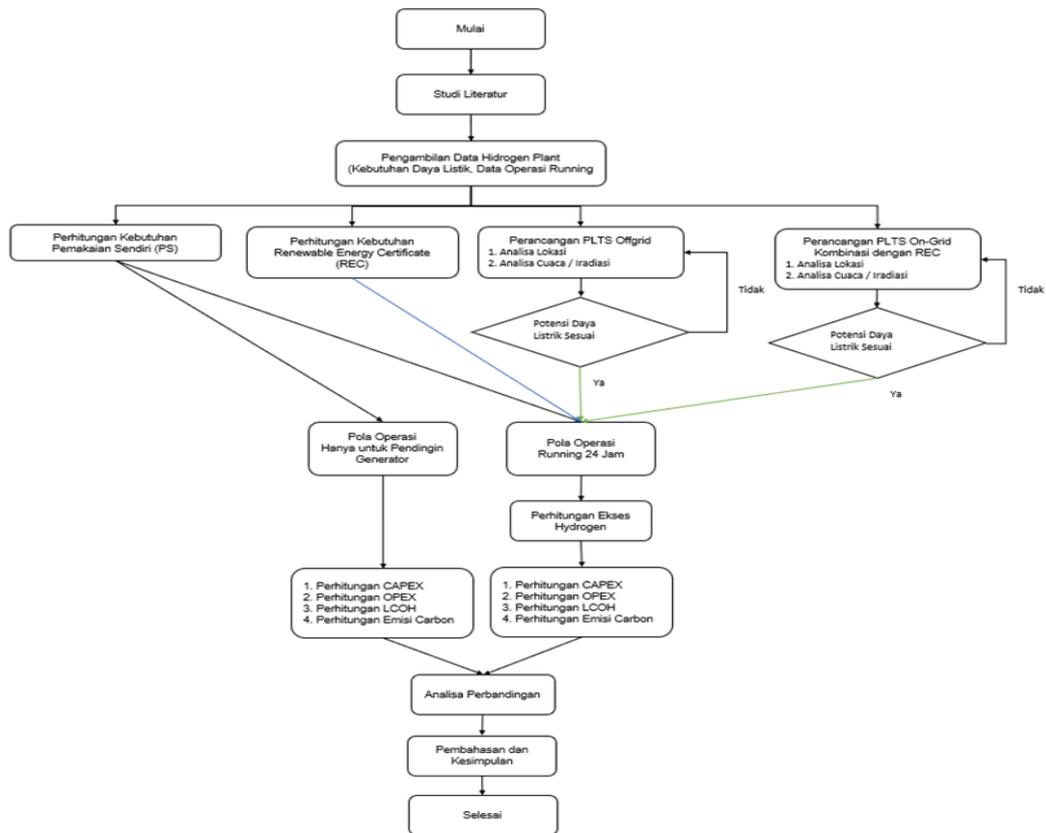
PLN (PT PLN (Persero)), a state-owned company that manages electricity in Indonesia, supports the government's efforts to reduce GHG emissions and achieve Net Zero Emission by 2060 [7]. In the draft RJP PLN 2024-2028, PLN includes the Development of Hydrogen Business as one of the Strategic Program. Currently PLN has Hydrogen Plants spread across various locations whose production has not been maximized. PLN's Hydrogen Plant has the main function of producing hydrogen gas which is used for generator cooling. This Hydrogen Plant if the production is maximized is estimated to have the potential for Excess hydrogen reaching 128 Tonnes / year [8]. PLTU Banten 2 Labuan is one of PLN's power plants that has a Hydrogen Plant. The Hydrogen Plant only operates if there is a need for hydrogen gas for generator cooling. Hydrogen in the generator will not decrease if there is no leakage. The need for hydrogen occurs when there is a leak in the generator or maintenance overhaul that requires disassembling the generator. Therefore, this hydrogen plant has the potential to be maximized so that excess hydrogen production can be used for co-firing power plants and hydrogen-based vehicles.

The importance of this research is that Labuan, Banten has a strategic position as it is close to Cilegon which is the centre of heavy industries such as steel and chemical. By developing green hydrogen infrastructure, Labuan has the potential to become a green hydrogen supply centre as the industry is starting to adopt clean technology as a sustainable solution to reduce carbon emissions. In addition, the main target of hydrogen is the transport sector, especially fuel cell-based vehicles. These vehicles have advantages over conventional battery-based vehicles including longer mileage and faster refueling.

## RESEARCH METHODS

### Materials

This research was conducted at Coal Fired Power Plant (PLTU) Banten 2 Labuan located at Latitude -6.391633, and longitude 105.828228, in Sukamaju Village, Labuan District, Pandeglang Regency, Banten Province, Indonesia, in January-April 2025. The method used is by taking primary data, namely existing hydrogen plant data such as electrical power requirements, production data and Hzusage which is carried out by taking data directly on the operator's logsheet, data on DCS and from the manual book.



**Figure 2.** Research Flow Chart

**Methods**

This research was conducted at Coal Fired Power Plant (PLTU) Banten 2 Labuan located at Latitude -6.391633, and longitude 105.828228, in Sukamaju Village, Labuan District, Pandeglang Regency, Banten Province, Indonesia, in January-April 2025. The method used is by taking primary data, namely existing hydrogen plant data such as electrical power requirements, production data and Hzusage which is carried out by taking data directly on the operator's logsheet, data on DCS and from the manual book. Then simulations were carried out with five schemes, namely:

1. Scheme 1: Self-use electricity source with operation pattern only for generator cooling.
2. Scheme 2: Self-use electricity source with continuous 24-hour running operation pattern
3. Scheme 3: Self-use electricity source with purchase of Renewable Energy Certificate (REC) with continuous 24-hour running operation pattern
4. Scheme 4: Source of electrical energy from offgrid solar power plant (PLTS) design with continuous 24-hour running operation pattern
5. Scheme 5: Source of electrical energy from on-grid PLTS design combined with self-use with purchase of Renewable Energy Certificate (REC), continuous 24-hour running operation pattern

The five schemes were then analzed and calculated the cost of Capital Expenditure (CAPEX), Operating Expenditure (OPEX), Levelized Cost of Hydrogen (LCOH) and Carbon Emissions. The source of electrical energy from self-use can be obtained from primary data, while the source of electrical energy from the design of PLTS is obtained from simulations using PVSyst 8.0.12 Student Version.



Figure 3. Satellite Image Google Maps PLTU Banten 2 Labuan

**Data Analysis**

The analysis was carried out by comparing CAPEX, OPEX, LCOH and carbon emissions generated from the five schemes of providing electricity for the Hydrogen Plant. Techno-economic analysis is carried out by looking at Net Present Value (NPV), Profitability Index (PI), Payback Period and Internal Rate of Return (IRR) to see the feasibility of investment in solar power plant procurement. Then it is concluded which scheme is the most optimal and feasible in terms of cost and carbon emissions. The simulation results will also be compared with literature studies relevant to this research.

**RESULT AND DISCUSSION**

**Irradiation Data at PLTU Banten 2 Labuan**

From the data obtained from the Global Solar Atlas in 2025, the irradiation in the PLTU Banten 2 Labuan area, Pandeglang, Banten, Indonesia is as follows:

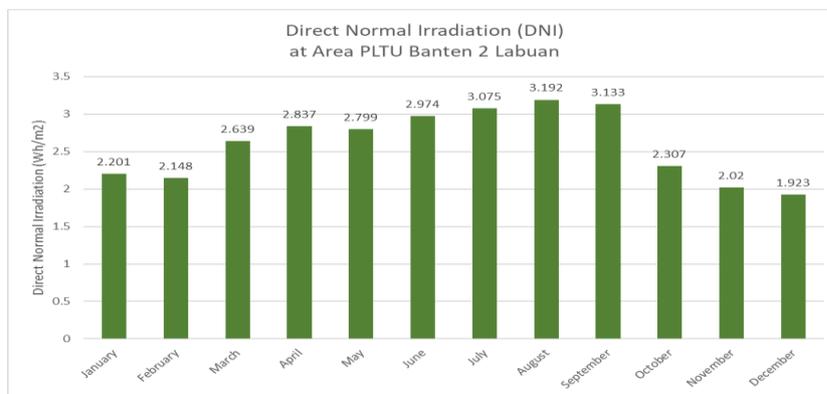


Figure 4. Direct Normal Irradiation at PLTU Banten 2 Labuan (Global Solar Atlas,2025)

Based on the data in the table above, it can be seen that irradiation throughout the year in the PLTU Banten 2 Labuan area is highest in August at 3.192 kWh/m<sup>2</sup>/day and lowest in December at 1.923 kWh/m<sup>2</sup>/day.

## Hydrogen Plant Energy Requirement Calculation

**Table 1.** Running Hour Hydrogen Plant 2023 Data

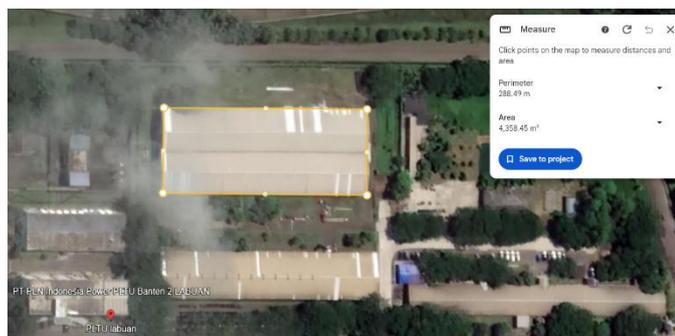
Month	Running Hour 2023	Running Hour 2024	Maximum Running Hour	Units
January	138.67	241.34	744.00	Hours
February	176.00	236.34	672.00	Hours
March	182.34	139.00	744.00	Hours
April	165.34	156.00	720.00	Hours
May	127.00	140.00	744.00	Hours
June	67.67	177.67	720.00	Hours
July	183.34	99.67	744.00	Hours
August	84.00	202.67	744.00	Hours
September	182.67	91.34	720.00	Hours
October	91.00	135.00	744.00	Hours
November	77.34	238.01	720.00	Hours
December	402.34	218.67	744.00	Hours
<b>Total Running Hour</b>	<b>1877.711803</b>	<b>2075.716563</b>	<b>8760</b>	<b>Hours</b>
<b>Annual Electricity Demand</b>	<b>75,108.47</b>	<b>83,028.66</b>	<b>350,400.00</b>	<b>kWh</b>

Based on operating data during 2023 and 2024 where the hydrogen plant only operates if there is a need for hydrogen production for generator cooling, the Total Running Hour during 2023 was 1877.71 Hours. The average electrical power required when the hydrogen plant operates was 40 kW according to table 2. So the energy consumed is 75,108.47 kWh during 2023 and 83,028.66 kWh during 2024.

If the hydrogen plant is maximized production so that it operates for 24 hours throughout the year then the energy requirement for one year based on the total running hours for 1 year is 8760 hours with the average electrical power when the hydrogen plant operates was 40kW then the total electrical energy required for 1 year is 350,400 kWh.

### PLTS Design for Hydrogen Plant

PLTU Banten 2 Labuan with a total land area of 750,000 m<sup>2</sup> has a potential area that can be utilized for PLTS Development in there are 17 locations with a total area of 325,000 m<sup>2</sup>. The roof of the shelter with an area of 4,358.45 m<sup>2</sup> with a daily energy potential of 11,317.86 kWh is one of the 17 locations chosen because of its large area and close to the location of the hydrogen plant.



**Figure 5.** Shelter Warehouse Location

The design of PLTS is carried out for scheme 4 and scheme 5. While schemes 1, 2 and 3 will go directly to the economic calculation because they did not use PLTS. The design of PLTS for hydrogen plant electrical energy needs is carried out with the help of PVSyst 8.0.12 Student Version.

### PLTS Design in Scheme 4

The solar panels that will be used in this simulation are as follows:

- PV module
- Manufacturer : Longi Solar
- Model : LR5-72HPH-560M G2
- Nom. Power : 242 kWp

Number of PV modules : 432 unit – 54 Strings x 8 In Series  
 Dimension : 2278 mm x 1134 mm (2.583 mm<sup>2</sup>)  
 Module area : 1116 m<sup>2</sup>

The batteries used in this simulation are as follows:

Battery : Huawei  
 Manufacturer : Huawei  
 Model : Luna2000-5-SO, with inverter 2.5 kW  
 Technology : Lithium-ion  
 Capacity : 4900 Ah  
 Number of Units : 49 In parallel x 5 in series

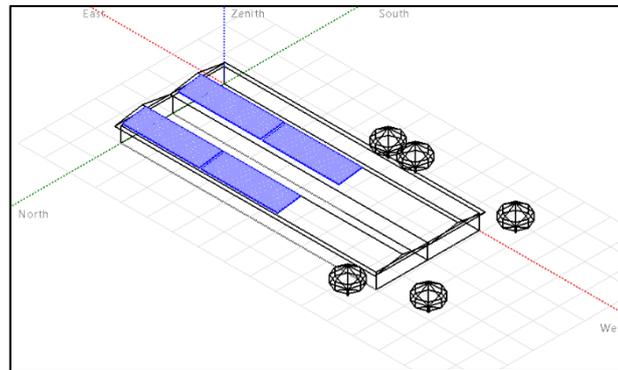


Figure 6. Schematic of Shelter Warehouse Area Utilized for Solar Power Plant

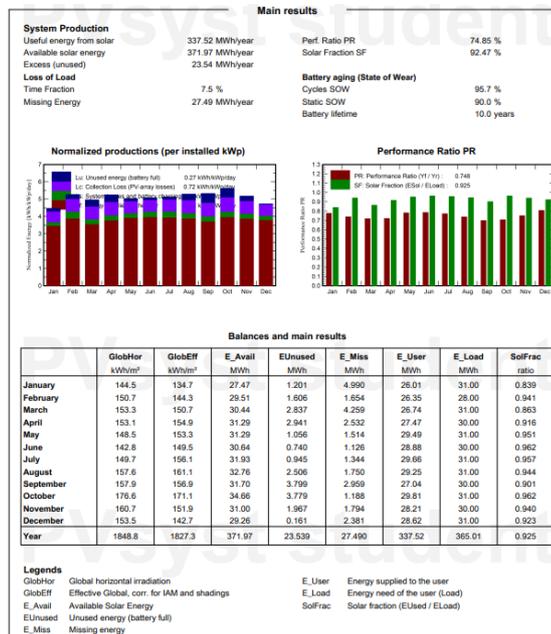
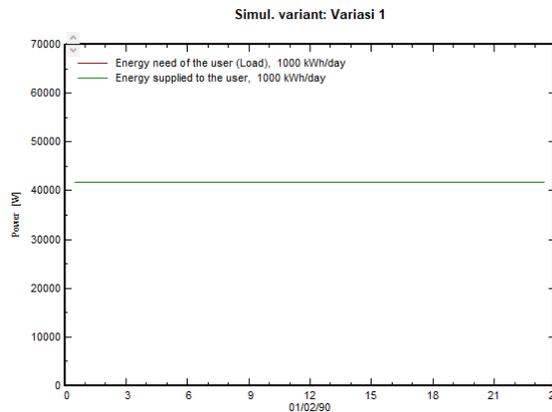
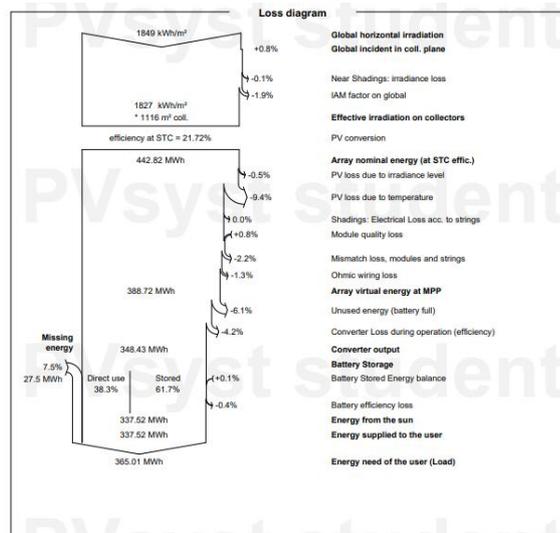


Figure 7. PVsyst Simulation Result



**Figure 8.** Hourly Electricity Power

Based on the simulation results above, it can be seen that the PLTS can full fill the energy needs of the Hydrogen Plant for 1 year of 350,400 kWh with a performance ratio of 0.744. The system is also able to provide 40 kW of constant power for 24 hours.



**Figure 9.** Lost Simulation result diagram

**PLTS Design in Scheme 5**

The solar panels that will be used in this simulation are as follows:

- PV module
- Manufacturer : Longi Solar
- Model : LR5-72HPH-560M G2
- Unit Nom. Power : 75.6 kWp
- Number of PV modules : 135 unit – 5 Strings x 27 In Series
- Dimension : 2278 mm x 1134 mm (2.583 mm<sup>2</sup>)
- Module area : 349 m<sup>2</sup>

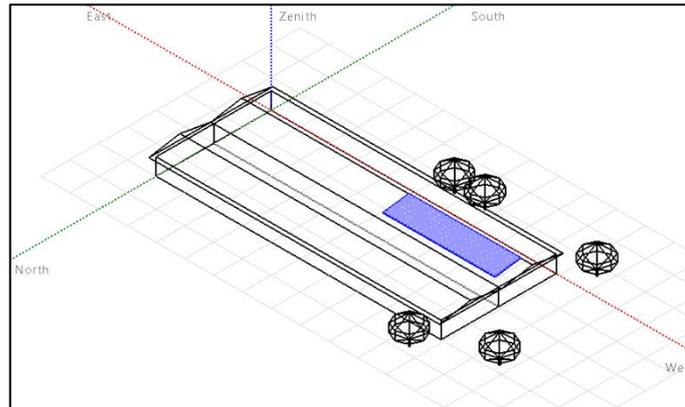


Figure 10. Schematic of Shelter Warehouse Area Utilized for Solar Power Plant

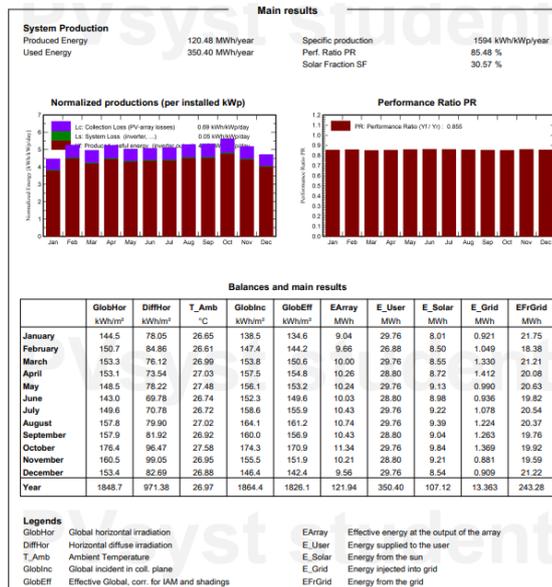


Figure 11. PVsyst Simulation Results

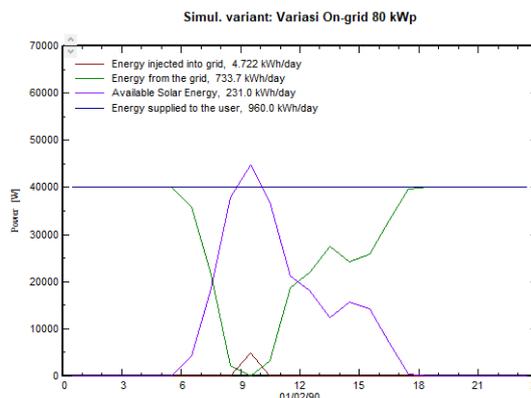
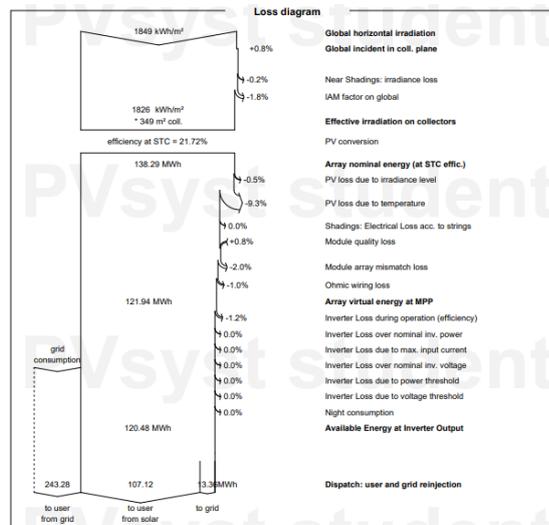


Figure 12. Visualization of power from PLTS, Grid, and H<sub>2</sub> Plant energy consumption in 24 hours

Based on the simulation results above, it can be seen that the PLTS can full fill the energy needs of the Hydrogen Plant for 1 year of 350,400 kWh with a performance ratio of 85.45%. The system is also able to provide 40 kW of constant power for 24 hours.

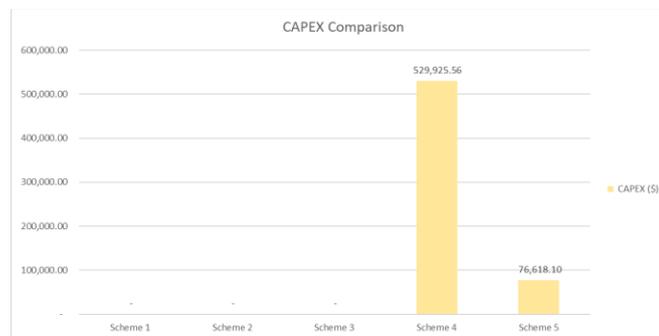


**Figure 13.** Lost Simulation result diagram

**Economic Calculation**

Technoeconomic analysis is an approach used to evaluate the feasibility of a project or technology by combining technical and economic aspects. The main objective is to assess whether the project can not only function technically, but also provide positive economic returns in the long run.

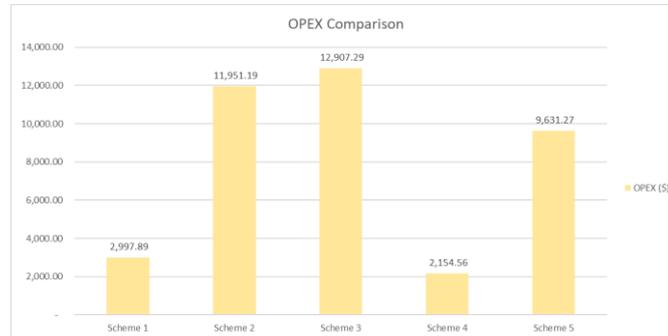
In general, technoeconomic analyses focus on the initial investment costs (CAPEX), operating costs (OPEX), and expected returns from the project. This analysis aims to determine whether the costs incurred can generate sufficient benefits, as well as to determine whether the project is financially viable.



**Figure 14.** CAPEX Comparison of each Scheme

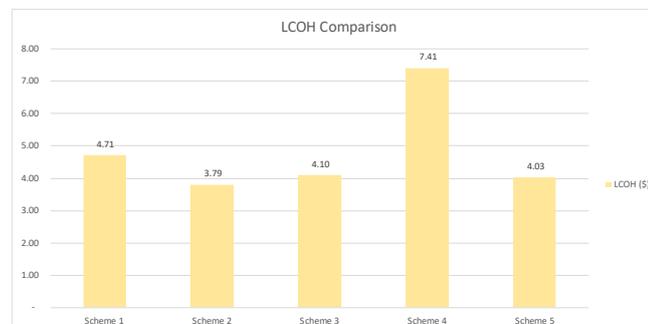
The graph above shows the Capital Expenditure (CAPEX) comparison for the five schemes in this project. From the graph, it can be seen that Scheme 4 has the highest CAPEX value of \$529,925.56, which indicates that this scheme requires a very large initial investment compared to the other schemes. This is because in the provision of electrical energy from offgrid PLTS, all electrical energy required for the operation of the Hydrogen plant in 24 hours must be collected at the time of the PLTS output during the day. Therefore, the number of solar power plants and batteries required is quite large, resulting in a much higher investment. On the other hand, Scheme 5 comes second with a CAPEX value of \$76,618.10, which is much lower than Scheme 4. This difference is due to the fact that Scheme 4 does not require batteries, hence the investment required is lower. Meanwhile, Scheme 1, Scheme 2, and Scheme 3 have no CAPEX value because the source of electrical energy comes from PS. In addition, the REC cost in scheme 3 is also included in the OPEX cost so that no investment cost is required. Overall, the graph indicates that further evaluation of the feasibility of each scheme needs to be done, especially by considering other factors such as operational costs

(OPEX), levelized cost of hydrogen (LCOH), and carbon emissions to obtain a more comprehensive picture in making investment decisions.



**Figure 15.** OPEX comparison of each Scheme

The graph above shows the Operational Expenditure (OPEX) comparison for each schemes. Scheme 3 shows the highest OPEX value of \$12,907.29, followed by Scheme 2 at \$11,951.19, and Scheme 5 at \$9,631.27. These figures indicated that all three schemes have high operating costs. This is because all the electrical energy used comes from PS electricity costs in scheme 2 and in scheme 3 there are additional REC costs. Meanwhile, Scheme 1 has a lower OPEX value of \$2,997.89 due to its non-continuous 24-hour operation pattern, operating only when hydrogen production is required. The lowest OPEX cost is Scheme 4 with only \$2,154.56 as all the electrical energy required comes from the solar power plant which requires little maintenance cost. Interestingly, although in the previous graph Scheme 4 has the highest CAPEX, its OPEX is the lowest, indicating that this scheme could be more economical in the long run if its efficiency is high. In contrast, Schemes 3 and 2 have high OPEX, which could potentially burden annual operating costs if not offset by significant output. Therefore, this graph provides important insights for decision-making, where the balance between CAPEX and OPEX needs to be carefully considered to determine the most economically viable scheme.



**Figure 16.** Comparison of LCOH in each Scheme

The graph above shows a comparison of the Levelized Cost of Hydrogen (LCOH) for five different schemes. LCOH is an important indicator for assessing the economics of hydrogen production over the life of the project. From the graph, it can be seen that Scheme 4 has the highest LCOH of \$7.41/kg, indicating that although this scheme has the lowest OPEX, the very high CAPEX value is likely to drive up the total average cost of hydrogen production. In contrast, Scheme 2 recorded the lowest LCOH of \$3.79/kg, indicating that the combination of CAPEX and OPEX in this scheme is quite efficient, despite its high operating costs. However, it is also necessary to review the environmental or carbon emission value.

Meanwhile, Scheme 5, which has a medium CAPEX and high OPEX, shows an LCOH of \$4.03/kg, which is quite competitive. Scheme 1 and Scheme 3 recorded LCOH of \$4.71/kg and \$4.10/kg respectively, which put them in the middle category from an economic perspective. Thus, this graph shows that the cost efficiency of hydrogen production does not only depend on low OPEX, but also

has to consider the size of CAPEX. Overall, Scheme 2 can be considered as the most economical option in terms of hydrogen production costs, although it needs to be reviewed in terms of its technical aspects and operational sustainability.

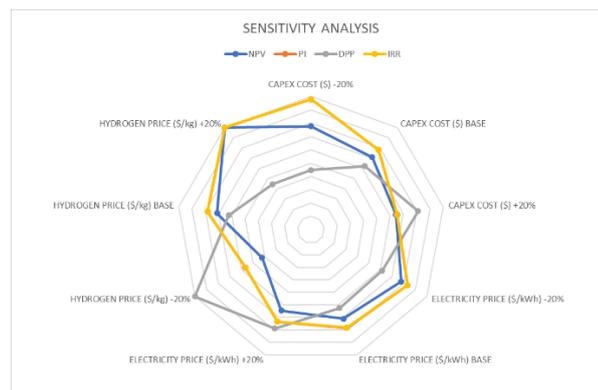
The LCOH obtained in Schemes 1 and 2 is higher than the literature of 0.7 to 2.3 USD/kg for grey hydrogen and 1.3 to 2.5 USD/kg for black and brown hydrogen [9]. This is due to high electricity prices. For Schemes 3, 4 and 5 have LCOH into the LCOH range in the research conducted by Incer-Valvedre which is 1.9 to 8.2 USD/kg [9]. But of the three schemes, scheme 5 has the lowest LCOH value for the green hydrogen category.

**Table 2.** Comparison of NPV, PI, DPP and IRR for Scheme 4 and Scheme 5

Description	Scheme 4	Scheme 5
NPV	-217,908.33	163,593.97
PI	0.59	3.14
DPP	-	3.2
IRR	3.62%	32.62%

Based on the financial evaluation table between Scheme 4 and Scheme 5, there was a significant difference in terms of the economic viability of the project. Scheme 4 has a Net Present Value (NPV) of -217,908.33, indicating that the project is not profitable as the value of all cash inflows is less than the initial investment. In contrast, Scheme 5 shows a positive NPV of 163,593.97, indicating that the project is economically viable. In terms of Profitability Index (PI), Scheme 4 only generates 0.59, meaning that each dollar of investment only generates \$0.59 and makes the project inefficient. In contrast, Scheme 5 has a PI of 3.14, meaning every dollar invested can generate a return of \$3.14, making it a very attractive option.

Furthermore, in terms of Discounted Payback Period (DPP), Scheme 4 could not recover the investment within the period analysed, while Scheme 5 was able to recover the capital in 3.2 years—a relatively quick rate for energy projects. Finally, in terms of Internal Rate of Return (IRR), Scheme 4 shows only 3.62%, which is far below the discount rate of 9.28% and therefore not feasible. In contrast, Scheme 5 has an IRR of 32.62%, signalling a very high and promising return on investment. Based on all these indicators, it can be concluded that Scheme 5 is the most viable and financially favourable option compared to Scheme 4.



**Figure 17.** Scheme 5 Sensitivity Analysis

The radar graph above shows the financial sensitivity analysis of several key parameters that affect the project economics, namely: CAPEX cost, electricity price, and hydrogen price, with the output being four economic indicators: NPV, PI, DPP, and IRR.

From this graph, it can be seen that changes in hydrogen prices have the most influence on all economic parameters. When the hydrogen price increases by +20%, all four indicators—especially NPV and IRR—show significant improvements, reflecting the increased profitability of the project.

Conversely, when the hydrogen price drops by -20%, the NPV and PI indicators experience a sharp decline, even entering the very low zone, which indicated the potential infeasibility of the project.

The effect of electricity price is also significant but more moderate than that of hydrogen price. A 20% decrease in electricity price improves the NPV and IRR, while an increase worsens the financial performance of the project.

Meanwhile, changes in CAPEX (both 20%) showed relatively less impact on DPP and IRR than changes in energy and product prices. This suggests that the project is more sensitive to operational cost and revenue (product price) factors than the initial investment cost.

Overall, this graph made it clear that the selling price of hydrogen is the most significant factor to the feasibility of the project. Therefore, a strategy of securing market prices or long-term sale and purchase contracts is essential to maintain profit stability in this hydrogen project.

### **Carbon Emissions Analysis**

To determine the carbon emissions generated from the three schemes, carbon emissions were calculated using the following formula:

$$\text{CO}_2\text{e emissions (kg)} = \text{Energy consumption (kWh)} \times \text{Emission factor (kg CO}_2\text{e/kWh)}$$

With an emission factor of 0.91 kg CO<sub>2</sub>e/kWh for coal power plants.

#### **Emissions Calculation in Scheme 1**

The energy consumption in 1 year in scheme 1 is 75,108.47 kWh. Therefore, the carbon emission generated from scheme 1 is:

$$\text{CO}_2\text{e emissions (kg)} = 75,108.47 \text{ kWh} \times 0.91 \text{ kg CO}_2\text{e/kWh} = 68,348.71 \text{ kg CO}_2\text{e}$$

#### **Emissions Calculation in Scheme 2**

The energy consumption in 1 year in scheme 2 is 75,108.47 kWh. Therefore, the carbon emission generated from scheme 2 is:

$$\text{CO}_2\text{e emissions (kg)} = 350,400 \text{ kWh} \times 0.91 \text{ kg CO}_2\text{e/kWh} = 318,864 \text{ kg}$$

#### **Emissions Calculation in Scheme 3**

In scheme 3, the source of electrical energy comes from PS but by purchasing RECs, it can be claimed that the electrical energy used is renewable energy so that it did not produce carbon emissions. Energy consumption in 1 year in scheme 3 is 350,400 kWh. Then the carbon emissions that can be avoided from scheme 3 are:

$$\text{CO}_2\text{e emissions (kg)} = 350,400 \text{ kWh} \times 0.91 \text{ kg CO}_2\text{e/kWh} = 318,864 \text{ kg}$$

#### **Emissions Calculation in Scheme 4**

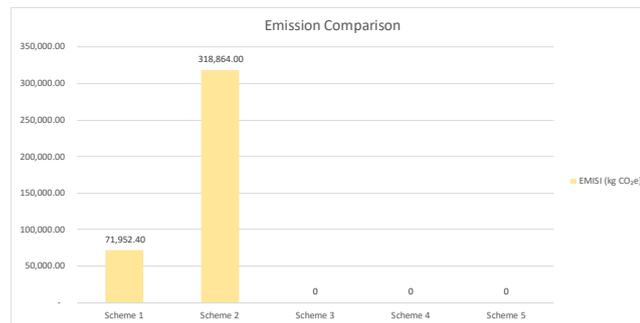
In scheme 4, the source of electrical energy comes from renewable energy, namely the PLTS, so it did not produce carbon emissions. The energy consumption in 1 year in scheme 4 is 350,400 kWh. Then the carbon emissions that can be avoided from scheme 4 are:

$$\text{CO}_2\text{e emissions (kg)} = 350,400 \text{ kWh} \times 0.91 \text{ kg CO}_2\text{e/kWh} = 318,864 \text{ kg}$$

#### **Emissions Calculation in Scheme 5**

In scheme 5, the source of electrical energy comes from renewable energy, namely the PLTS combined with the use of PS and RECs so as not to produce carbon emissions. Energy consumption in 1 year in scheme 5 is 350,400 kWh. Then the carbon emissions that can be avoided from scheme 5 are:

$$\text{CO}_2\text{e emissions (kg)} = 350,400 \text{ kWh} \times 0.91 \text{ kg CO}_2\text{e/kWh} = 318,864 \text{ kg}$$



**Figure 18.** Comparison of Emissions in each Scheme

The graph above shows a comparison of carbon dioxide equivalent (CO<sub>2</sub>e) emissions in each production scheme. It can be seen that Scheme 2 produces the highest emissions of 318,864 kg CO<sub>2</sub>e, followed by Scheme 1 with emissions of 71,952.40 kg CO<sub>2</sub>e. Meanwhile, Scheme 3, Scheme 4, and Scheme 5 produce no emissions (0 kg CO<sub>2</sub>e), this is because the three schemes use renewable energy sources Scheme 3 uses RECs, Scheme 4 uses energy sources from PLTS and Scheme 5 uses a combination of PLTS and the use of RECs.

The high emissions in Scheme 2 indicate a heavy reliance on fossil-based energy sources from environmentally unfriendly coal-fired power plants, despite this scheme having the most economical cost of hydrogen production (LCOH).

Thus, while Scheme 2 is cost-advantaged, it is not ideal from an environmental perspective. Scheme 5 remains the most balanced option as it is not only economically viable, but also generates no carbon emissions, making it highly relevant in the context of clean energy transition and decarbonisation targets.

## CONCLUSION

Based on the series of graphs and tables that have been analyzed, there are notable differences between hydrogen production schemes in terms of investment costs (CAPEX), operating costs (OPEX), economics (LCOH, NPV, PI, IRR, DPP), sensitivity to economic parameters, and environmental impacts in the form of carbon emissions. Scheme 4 has the lowest emissions and least OPEX, but its CAPEX is very high with the highest LCOH. Financially, the scheme is not feasible due to negative NPV, low IRR (3.62%), and PI below 1. In other words, although environmentally friendly, the scheme is difficult to implement practically due to the large initial investment burden and weak returns. Scheme 2 recorded the lowest LCOH (\$3.79/kg), making it very attractive in terms of production costs. However, its emissions were very high (318,864 kg CO<sub>2</sub>e), which goes against the principle of clean energy transition. In addition, OPEX is high and does not have a strong enough financial advantage when compared to its environmental impact. Scheme 5 shows the best overall and balanced performance. With moderate CAPEX, low LCOH (\$4.03/kg), and zero emissions, this scheme also excelled financially: Positive NPV (\$163,593.97), high PI (3.14), excellent IRR (32.62%), and relatively short DPP (3.2 years). Sensitivity analyses also showed good financial performance resilience under various price and cost change scenarios. Based on the combination of all aspects analysed in terms of economics, environment and risk sensitivity, Scheme 5 is the most optimal option. It is not only technically and financially feasible, but also supports the decarbonisation target as it produces no emissions. With a balance of cost, return on investment, and sustainability, Scheme 5 is highly recommended for implementation.

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