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Techno-Economic Optimization of Excess Green Hydrogen Production at Tanjung Jati B Coal Fired Power Plant

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Abstract. With the increasing global demand for energy, the level of emissions and the impact of energy growth on ecosystems and climate change have become major global issues. In this context, green hydrogen offers a promising clean and sustainable energy solution.

This study analyses the feasibility of the hydrogen production system at the existing Hydrogen Plant of the Tanjung Jati B coal-fired power plant (TJB CFPP) to produce excess hydrogen gas categorized as green hydrogen. Integration of current electrolysis systems with solar energy sources will play a pivotal role in this study. This study employs a quantitative approach by collecting data from previous studies and operational reports from the TJB CFPP.

This study investigates six optimization scenarios for excess green hydrogen production, each combining electricity sources with electrolysis technologies. The integration of available electrolysis systems with an existing solar power plant has demonstrated the potential to produce excess green hydrogen at a competitive Levelized Cost of Hydrogen (LCOH). Notably, one scenario achieves an LCOH close to 4 USD/kg, significantly lower than the current average green hydrogen LCOH in Indonesia, which stands around 10 USD/kg.

Keywords: *Electrolysis, Excess Green Hydrogen, Coal Fired Power Plant.*

1 Introduction

Referring to the Paris Agreement of 2015, which aims to achieve net-zero carbon emissions by 2050 and limit the global temperature rise to below 2°C, concrete and significant efforts are required to achieve decarbonization across various sectors. According to recommendations from the International Renewable Energy Agency, achieving this decarbonization target will require a CO_2 emissions reduction of 37 gigatons annually. This can be achieved through increased electricity generation from renewable energy sources, improvements in energy conversion efficiency, the development of carbon capture technologies, and the production of green hydrogen and its derivatives [1].

From a renewable energy perspective, hydrogen plays a significant role as a future carbon-free energy carrier. Hydrogen is the most abundant element and has a high energy content per unit mass compared to conventional fuels as described at figure 1. At high pressure, hydrogen can store approximately 40 kWh per kilogram, whereas current Li-Ion batteries can only store 0.28 kWh per kilogram[2].

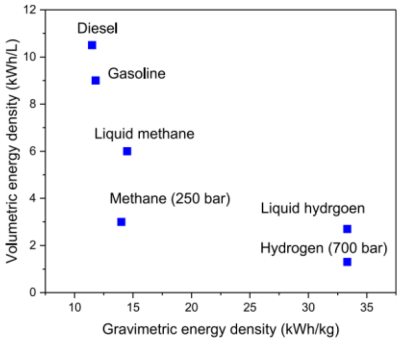

Figure 1 Volumetric vs gravimetric curve of various energy sources

Green hydrogen, produced by utilizing renewable energy sources, has significant potential as a clean fuel for various industries, including power generation, transportation, and manufacturing. In recent years, green hydrogen production processes have seen significant advancements in terms of efficiency, scalability, and cost-effectiveness. These developments are driven by innovations in electrolysis technology, biomass gasification, and solar-powered water splitting [3].

Among the various technologies for hydrogen production, the water electrolysis process, powered by renewable electricity, is one of the most promising technologies to produce sustainable hydrogen with minimal carbon footprint. Alkaline electrolyzer (AEL) is one of the most mature hydrogen production technologies, having been widely used in various industries since its initial development in 1927 [4]. Currently, AEL systems achieve an efficiency range of 70% to 80%, depending on operational conditions, input power sources, and system configurations [5]

The integration of electrolysis systems with renewable electricity sources presents a significant challenge for green hydrogen production. The primary issue with using renewable electricity sources is related to their intermittency and dependency on natural conditions.

TJB CFPP currently operates a hydrogen plant to produce hydrogen gas as a cooling medium for its generators. The amount of hydrogen gas produced at this hydrogen plant is adjusted to meet the internal cooling requirements. However, there is potential to utilize the excess hydrogen gas produced as a clean energy source for external applications.

In addition, the TJB CFPP facility has three PV power plant with capacities of 92, 32, and 100 kWp, which are used to supply electricity for administrative buildings within the TJB complex. Integrating the existing hydrogen plant with the PV power plants could enable the production of green hydrogen, which can serve as an alternative energy source.

Previous studies have extensively explored the potential of hydrogen production by integrating electrolysis systems with renewable energy sources[6], [7]. However, most approaches involve developing entirely new large hydrogen production facilities, which leads to significant capital investment requirements. This study aims to explore the utilization of the existing hydrogen plant at the TJB CFPP facility to produce green hydrogen as a clean energy source.

The study offers insights into the economic potential of utilizing excess hydrogen in existing hydrogen systems at coal-fired power plants, demonstrating cost advantages over constructing new, large-scale hydrogen facilities. The use of existing equipment is projected to lower capital expenditures for hydrogen generator development. Furthermore, the study will present a comparative analysis of the feasibility of green hydrogen production between optimizing existing equipment and developing new dedicated systems for producing green hydrogen.

2 Case Study: Existing System at TJB CFPP

The hydrogen plant at TJB CFPP currently employs Alkaline Electrolysis (AEL) technology, widely recognized for its robust design, long operational lifespan, and cost-effective components, making it a preferred choice for industrial-scale hydrogen production. While AEL offers economic advantages for large-volume hydrogen generation, its efficiency is generally lower compared to more advanced technologies such as Proton Exchange Membrane (PEM) and Anion Exchange Membrane (AEM) electrolyzers [8].

The table 1 shows the specifications of the electrolyzer equipment installed at the hydrogen plant in TJB CFPP.

Table 1 AEL specification on TJB site

Manufacturer	**Teledyne**
Type	HMXT-100
Production Capacity	134 nm^3/day or 12 kg/day
Feed Water Specification	ASTM D 1193-72 Type IV water

Feed Water Consumption	144 L / day
Energy Consumption	918.73 kWh/day

2.1 Production Rate and Hydrogen Gas Demand at TJB CFPP

At present, hydrogen gas usage at the TJB CFPP is primarily designated as a generator cooling medium. Therefore, meeting the existing hydrogen demand for generator cooling is crucial and must be prioritized to ensure continuous and reliable plant operations.

The average daily hydrogen consumption for generator cooling purposes is approximately 4 - 5 kg/day under normal operational conditions as illustrated in figure 2. In comparison, the maximum production capacity of the existing hydrogen plant at the unit is 12 kg/day. This indicates that the current system is operating at only a portion of its full production capacity, leaving unused hydrogen production potential that can be optimized for alternative clean energy applications.

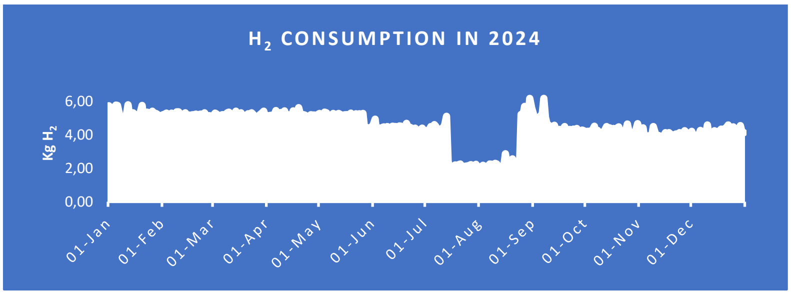

Figure 2 Hydrogen gas consumption in 2024 for TJB CFPP

Assuming the current electrolyzer system will only operates at 90% of its maximum production capacity, the daily production rate would be approximately 10,8 kg/day. This leaves an excess of 5 - 6 kg/day of hydrogen gas that could be further utilized as an alternative energy source.

2.2 Photovoltaic Power Plant at TJB

There are three photovoltaic (PV) power plants with varying capacities within the TJB facility (table 2). The availability of renewable energy will be a key factor in determining the ideal green hydrogen production system.

Table 2 PV power plant specification

	Solar Cell Specification		
	PV Power Plant I	**PV Power Plant II**	**PV Power Plant III**
Manufacturer	REC	Ever Exceed	Sunergy

Capacity	92 kWp	32 kWp	75 kWp
Serial Number	REC345TP2572	ESM 400-M	Mars Series 72M-H8
Type of Cell	Polycrystalline	Monocrystalline Silicon	Monocrystalline
Pmax	345 Wp	400 Wp	550 Wp
Vmp	38.7 V	41.2 V	39.1 V
Imp	8.92 A	9.71 A	10.58 A
Efficiency	17.20%	19.63%	21.29%
Dimension	2005x1001x30 mm	2015x996x35 mm	2278x1134x35 mm
Total Modul	268 pcs	80 pcs	182 pcs

Figure 3 illustrates the amount of electricity generated by the three PV power plants located within TJB area. The graph presents the total monthly electricity production over the course of a year and the average daily electricity output from the three PV solar power plant units.

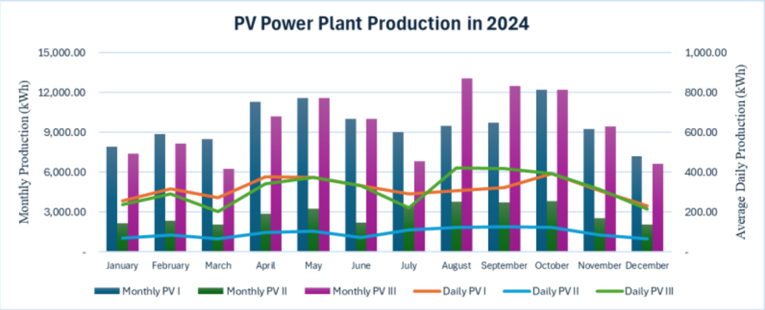

Figure 3 Actual electricity production of PV power plant at TJB site

Based on the actual production data from the three PV power plants in 2024 the average monthly electricity production was 21,942 kWh, with an average daily production of 722 kWh.

3 Scenario Design and Optimization Approach

The primary focus of this study is to explore ways to optimize the utilization of excess hydrogen gas produced by the existing hydrogen plant at TJB CFPP, once the primary requirement of using hydrogen as a generator cooling medium is fulfilled. Based on current operational conditions, the electrolyzer unit at the plant is operating at approximately 50% of its maximum capacity, which indicates a potential to generate excess hydrogen gas. This untapped potential serves as a compelling opportunity to conduct further studies on the feasibility of optimizing the excess hydrogen production for various sustainable energy applications.

This study will compare the Levelized Cost of Hydrogen (LCOH) for green hydrogen production using the existing hydrogen plant at TJB CFPP under six different scenarios described at table 3.

Table 3 Scenarios to Optimize Green Hydrogen Production

	Electrolyzer	**Power Source**
Scenario 1	AEL (existing equipment)	Unit auxiliary power + Renewable Energy Certificate (REC)
Scenario 2	AEL	Unit auxiliary power + REC + existing PV plant
Scenario 3	AEL	Full PV plant
Scenario 4	AEM (new equipment)	Unit auxiliary power + REC
Scenario 5	AEM	Unit auxiliary power + REC + existing PV plant
Scenario 6	AEM	Full PV plant

The current condition at TJB follows Scenario 1, in which the hydrogen plant utilizes AEL technology, and its electricity demand is supplied by the plant's auxiliary power.

3.1 Renewable Energy Potential at TJB CFPP

The continuous availability of renewable energy is a crucial factor in the green hydrogen production process. The daily electricity demand of the AEL system for full-scale hydrogen production exceeds the current capacity of the existing PV power plants. Therefore, additional PV power plants are required within the TJB area to ensure the electricity needs of the hydrogen plant system are adequately met.

This study also includes modeling to estimate the required capacity of a new solar power plant to meet daily electricity demand, using the PVsyst application. These tools can significantly simplify research on developing an ideal PV power plant to meet energy needs.

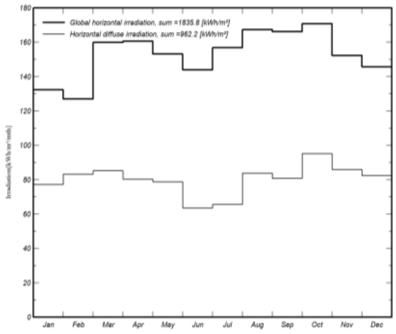

Figure 4 Monthly weather data from PVsyst for TJB site locations

Based on solar energy potential data obtained from PVsyst, the design of the additional PV power plant required to meet the electricity demand of the hydrogen plant can be modelled. A PV power plant with a minimum daily production capacity of approximately 480 kWh and a battery management system is needed. This model yields a PV power plant specification of 141 kWp, with the panel module details presented in Table 4

Table 4 PV Power Plant Module Specification

Solar Cell Specification	
Manufacturer	Sunerg Solar Energy
Serial Number	XMHCTP480BFDG+H
Type of Cell	Monocrystalline
Typical maximum power (P max)	363.4 Wp
Voltage at maximum power (Vmp)	35.13 V
Current at maximum power (Imp)	13.67 A
Efficiency	22.18%
Dimension	1926x1134x30 mm
Total Modul	294 pcs

The specifications based on table 4 solar panels are sufficient to meet the minimum electricity requirements of the existing hydrogen plant. Figure 5 presents the monthly energy output of the newly modeled PV power plant. The data shows that a daily energy deficit of 480 kWh can be fully covered, evidenced by a Solar Fraction consistently exceeding 0.95. Additionally, there remains an unutilized energy potential of approximately 36 MWh per year.

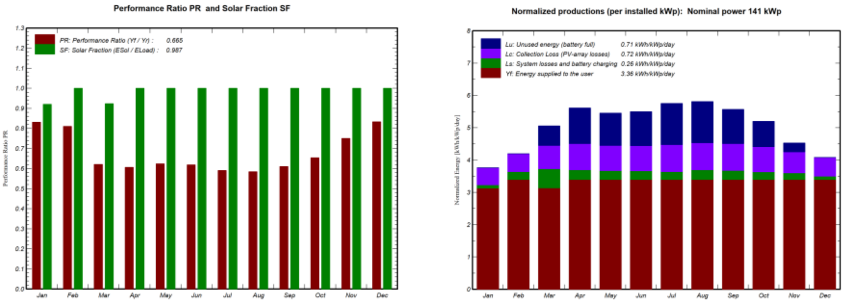

Figure 5 Performance ratio and solar fraction (left); and normalized productions (right) of new PV power plant

3.2 Anion Exchange Membrane (AEM) Electrolyzer

Anion Exchange Membrane (AEM) electrolysis technology is one of the latest innovations that combines the advantages of AEL, which is considered the most conventional, and Proton Exchange Membrane (PEM), which offers higher efficiency but involves high operational costs [9]. AEM provides better efficiency than AEL while maintaining lower investment and operational costs compared to PEM.

A feasibility analysis will be conducted for the development of a hydrogen production system based on AEM technology, with a production capacity equivalent to the existing hydrogen plant at TJB. The development of this AEM-based system will take into account electricity requirements, feedwater supply, and the investment costs needed to achieve the targeted daily hydrogen production.

Table 5 AEM electrolyzer specification

Manufacture	**Enapter**
Type	AEM EL 4.0
Production Capacity	1.078 kg/day (per stack)
Number of Stack	12 pcs
Total Production Capacity	12,94 kg/day
Feed Water Consumption	120,96 L/day
Energy Consumption	708,12 kWh/day

The transition from AEL to AEM electrolyzer technology will also require additional supporting equipment, such as a water tank, dryer, and new installation networks as described in table 6. The total cost of developing this system will be included in the overall investment cost.

Table 6 Equipment requirements for AEM electrolyzer system

Component	**Quantity**
Water tank	3 pcs
Elektrolizer EL 4.0	12 pcs
Dryer	3 pcs
Control System	1 lot
New Pipeline	1 lot

4 Methods

The approach to assess the feasibility of the green hydrogen production optimization will be based on a comparison of the LCOH and NPV values.

4.1 Levelized Cost of Hydrogen (LCOH)

LCOH is an economic assessment parameter used to determine and evaluate the cost of hydrogen production over the project’s lifetime. The LCOH value varies across different production methods and process types, and is highly dependent on both the investment costs and the operational expenses associated with the process

$$LCOH = \frac{\sum_{t=1}^{n} \frac{It+Ot+Ft}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Ht}{(1+r)^t}} \tag{1}$$

4.2 Economic Study

To assess the economic feasibility of the project, an approach was taken by evaluating the Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PbP) for each planned scenario. The financial analysis provides insight into which scenario offers the most viable option for implementation based on its feasibility.

$$NPV = \sum_{t=0}^{n} \frac{Ct}{(1+r)^t} \tag{2}$$

5 Results and Discussion

This section outlines the simulation results for new PV power plant development, detailing investment estimates and the corresponding LCOH values across all proposed scenarios.

5.1 PV Power Plant Enlargement

With the development of a new PV power plant, the energy demand required to fully support the hydrogen plant can be met. This development also includes the addition of a battery management system to ensure energy availability during non-operational hours of the PV plant, from late afternoon until morning.

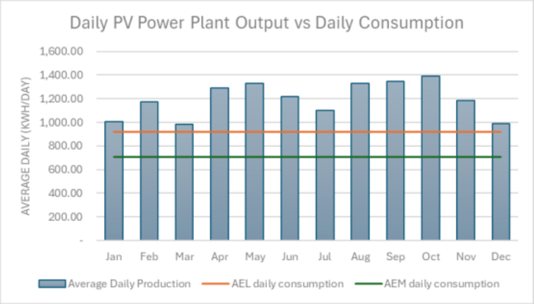

Figure 6 Average Daily Production Combined PV Power Plant

Referring to the equipment specifications of the new PV power plant as presented in table 4, and based on the assumed development cost of the battery management system for PV at USD 400 per kWh [10], the total investment cost can be estimated.

5.2 Investment Cost

Based on six proposed scenarios for optimizing the green hydrogen production process at TJB, the investment cost requirements for each option were calculated. The investment costs include the installation of new PV power plants, an integrated battery management system, and the upgrading of electrolyzer equipment. To assess the economic feasibility in this study, several assumptions are applied, including an exchange rate of IDR 16,000/USD, a 7% annual discount rate, and a project equipment lifetime of at least 15 years. Investment costs for the existing PV system at TJB CFPP refer to the original construction price, while estimates for AEM system development and the new PV plant rely on data from various references.

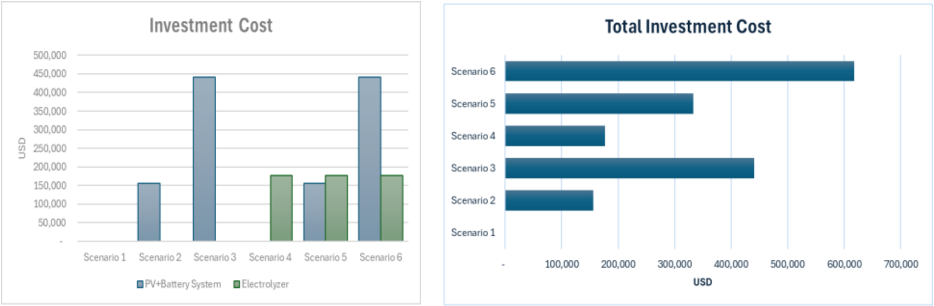

Figure 7 Investment cost calculations of each scenario

Scenario 1 represents the existing condition of the hydrogen plant equipment at TJB CFPP and therefore does not require any investment for modifications. In contrast, Scenario 6, which involves upgrading the equipment to AEM technology and utilizing electricity sourced entirely from PV power plants, incurs the highest investment cost, reaching up to USD 617,000.

5.3 LCOH Calculation

To determine the Levelized Cost of Hydrogen (LCOH) for the six scenarios discussed in the proposed system section, calculations will be performed on three key parameters. These parameters are electricity cost, operational cost (including feedwater cost and equipment operation and maintenance cost), and investment cost. Feedwater and electricity costs in this study are based on the assumed basic production costs of demineralized water and electricity generated by the TJB power plant.

Table 7 Each LCOH component scenario

Scenario	Investment Cost (USD/kg)	Electricity Cost (USD/kg)	Operational Cost (USD/kg)	LCOH (USD/kg)
Scenario 1	USD 0.00	USD 4.08	USD 0.20	USD 4.27
Scenario 2	USD 2.64	USD 0.98	USD 0.21	USD 3.83
Scenario 3	USD 7.46	USD 0.00	USD 0.20	USD 7.65
Scenario 4	USD 2.77	USD 2.91	USD 0.18	USD 5.87
Scenario 5	USD 5.22	USD 0.00	USD 0.18	USD 5.40
Scenario 6	USD 9.69	USD 0.00	USD 0.18	USD 9.87

Figure 8 LCOH component (left); summary of LCOH calculation for six scenarios (right)

Based on the graph in figure 8, it can be concluded that the green hydrogen production process under Scenario 2 yields the lowest LCOH value.

5.4 Financial Justification

An analysis was conducted on the potential profit from utilizing excess hydrogen gas produced by the hydrogen plant at TJB CFPP, using the assumed hydrogen production price in Indonesia. Referring to recent studies on LCOH values across various electrolysis scenarios in ASEAN countries [11], hydrogen production in Indonesia using AEL technology in 2023 still yields an LCOH of approximately USD 13/kg.

Table 8 Profit projection calculation

Scenario	LCOH (USD)	Excess Gas (kg)	Production Cost (USD)	Revenue (USD)	Profit/year (USD)
Scenario 1	4.27	2,300	9,826	29,894	20,067
Scenario 2	3.83	2,300	8,803	29,894	21,090
Scenario 3	7.65	2,300	17,597	29,894	12,297
Scenario 4	5.87	2,609	15,306	33,916	18,610
Scenario 5	5.40	2,609	14,086	33,916	19,830
Scenario 6	9.87	2,609	25,742	33,916	8,175

Table 9 below presents a further analysis to assess the financial feasibility of the project for each scenario. By applying a discount rate of 7% and assuming an equipment lifespan of 15 years, the NPV, IRR, and Payback Period (PbP) for all six scenarios can be calculated.

Table 9 Economic study parameters for each scenario

Scenario	Investment Cost (USD)	Profit / Year (USD)	IRR	PbP (year)	NPV (USD)
Scenario 1	-	20,067	-	-	182,771
Scenario 2	156,000	21,327	11%	7	36,090
Scenario 3	440,899	12,297	-9%	36	-328,900
Scenario 4	176,925	18,610	6%	9	-7,428
Scenario 5	332,925	19,830	-1%	17	-152,315
Scenario 6	617,824	8,175	-16%	76	-543,371

Apart from the current existing condition (Scenario 1), the hydrogen production system developments that yield a positive IRR are Scenario 2 and Scenario 4. Scenario 2 appears to be the most promising in terms of both IRR and Payback Period. However, when viewed from the NPV perspective, the currently implemented Scenario 1 demonstrates a superior value compared to the other scenarios.

A study conducted in Chile [12] concluded that the development of small-scale green hydrogen production systems using electrolysis resulted in negative NPV and IRR values, indicating that the implementation of such systems is not economically viable. Therefore, utilizing excess hydrogen gas from CFPP serves as an alternative solution for small-scale hydrogen production. A longer lifetime of hydrogen production equipment, along with improvements in electrolyzer efficiency and the use of renewable energy sources, will have a significant impact in reducing the LCOH value [13].

Increased LCOH in other scenarios is mainly driven by additional capital needs for new PV plant development or transitioning to AEM electrolysis. In Scenarios 4 to 6, where the electrolyzer is upgraded to AEM technology, the system can produce a greater volume of excess hydrogen compared to the current AEL setup. However, due to the substantial investment required for the upgrade, the resulting LCOH is higher than Scenario 2.

Under the current setup (Scenario 1), the LCOH is still higher than in Scenario 2, even though no new investment is required. This outcome is mainly driven by the relatively high cost of electricity used internally by the power plant, which is less economical compared to electricity supplied by PV power plant.

5.5 Sensitivity Analysis

To identify the factors that have the greatest impact on the achievement of NPV, a sensitivity analysis was conducted based on the conditions of Scenario 2. Two parameters were used as comparative variables influencing the NPV value: the capital cost of the project and the selling price of hydrogen gas.

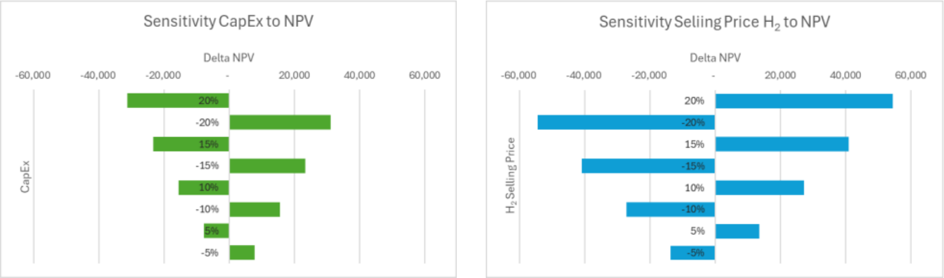

Figure 9 Tornado diagram of parameter CapEx (left); and selling price hydrogen (right) to NPV result

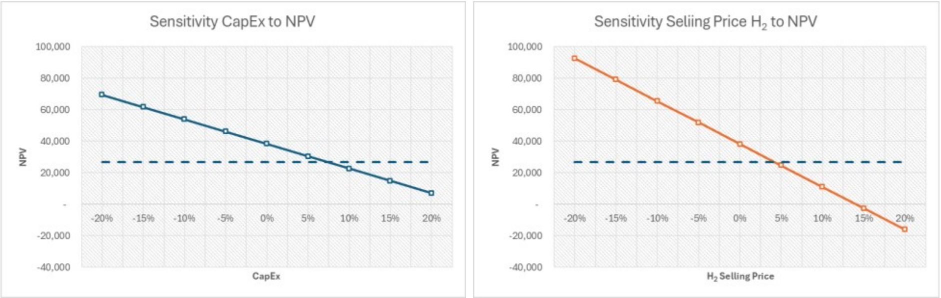

Figure 10 Sensitivity parameter CapEx (left); and selling price hydrogen (right) to NPV result

Based on the tornado diagram and line chart presented in Figures 9 and 10, it can be observed that changes in CapEx and the hydrogen selling price significantly affect NPV. Considering the slope of the line chart and the structure of the tornado diagram, it can be concluded that variations in the hydrogen selling price have a more substantial impact on the NPV of the scenario. This indicates that securing buyers for excess hydrogen gas at the most favourable price will be a critical factor in determining the feasibility of the hydrogen production system development project at TJB CFPP.

6 Conclusions

The findings of this study indicate that the LCOH for excess hydrogen production at a coal-fired power plant is relatively competitive when compared to other hydrogen production pathways. However, due to the plant's original design not being intended for large-scale hydrogen generation, several scenarios still yield green hydrogen production costs above USD 7 per kilogram. This contrasts with earlier studies, which suggest that green hydrogen production costs can potentially be lowered to approximately USD 6 per kilogram [14].

Scenario 2, which employs AEL technology powered by PV, emerges as the most promising option for system development, both in terms of achieving a low LCOH and financial viability. In Scenario 2, the LCOH can achieved at 3,83 USD/kg. This is made possible by leveraging several existing components and hydrogen generation systems already available at the TJB CFPP unit. The LCOH value in Scenario 2 significantly lower than the projected hydrogen production costs for similar schemes, ranged at USD 13 per kilogram in Indonesia[11].

Further studies evaluating the cost of excess hydrogen across power plants with existing hydrogen infrastructure may uncover significant hidden value through the utilization of this underused resource.

7 Nomenclature

It = Investment cost
Ot = Operational expense
Ft = Fuel or electricity cost
Ht = Hydrogen gas production
r = Discount rate over lifetime
n = Lifetime of System
Ct = Cash flow

References

[1] IRENA Renewable Cost Database, *Renewable Power Generation Costs in 2020*. 2020.
[2] A. Kakavand, S. Sayadi, G. Tsatsaronis, and A. Behbahaninia, "Techno-economic assessment of green hydrogen and ammonia production from wind and solar energy in Iran," *Int J Hydrogen Energy*, vol. 48, no. 38, pp. 14170–14191, 2023, doi: 10.1016/j.ijhydene.2022.12.285.
[3] S. R. Naqvi, B. kazmi, S. A. Ammar Taqvi, W. H. Chen, and D. Juchelková, "Techno economic analysis for advanced methods of green

hydrogen production," *Curr Opin Green Sustain Chem*, vol. 48, no. Figure 1, p. 100939, 2024, doi: 10.1016/j.cogsc.2024.100939.

[4] J. Brauns and T. Turek, "Alkaline water electrolysis powered by renewable energy: A review," *Processes*, vol. 8, no. 2, 2020

[5] S. Godfrey, A. K. Hamzat, J. Whidborne, B. Kuang, and K. W. Jenkins, "International Journal of Hydrogen Energy Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production," *Int J Hydrogen Energy*, no. xxxx, 2024, doi: 10.1016/j.ijhydene.2024.06.342.

[6] A. Chahtou and B. Taoussi, "Techno-economic of solar-powered desalination for green hydrogen production: Insights from Algeria with global implications," *Int J Hydrogen Energy*, vol. 121, no. January, pp. 210–227, 2025, doi: 10.1016/j.ijhydene.2025.03.306.

[7] A. Alhajeri, H. Ghazal, V. Olabi, and H. Jouhara, "Technical assessment of green hydrogen production in Kuwait," *Int J Hydrogen Energy*, no. October 2024, 2025, doi: 10.1016/j.ijhydene.2025.01.273.

[8] B. Amini Horri and H. Ozcan, "Green hydrogen production by water electrolysis: Current status and challenges," *Curr Opin Green Sustain Chem*, vol. 47, p. 100932, 2024, doi: 10.1016/j.cogsc.2024.100932.

[9] L. J. Titheridge and A. T. Marshall, "Techno-economic modelling of AEM electrolysis systems to identify ideal current density and aspects requiring further research," *Int J Hydrogen Energy*, vol. 49, pp. 518–532, 2024, doi: 10.1016/j.ijhydene.2023.08.181.

[10] W. Cole and A. W. Frazier, "Cost Projections for Utility-Scale Battery Storage: 2023 Update," *National Renewable Energy Laboratory*, no. June, p. 20, 2023.

[11] R. D. Rusli, "Chapter 5 Hydrogen Economics for Southeast Asian Industries," 2024.

[12] A. Sánchez-Squella, M. Muñoz, M. Toledo, and F. Yanine, "Techno-economic assessment of a green hydrogen production plant for a mining operation in Chile," *Int J Hydrogen Energy*, vol. 112, no. February, pp. 531–543, 2025, doi: 10.1016/j.ijhydene.2025.02.164.

[13] E. D. Gulay, C. Ozgur Colpan, and M. A. Ezan, "Techno-economic assessment of green hydrogen production in Izmir: Evaluating electrolyzer technologies, modularization strategies, and renewable energy integration," *Energy Convers Manag*, vol. 333, no. April, p. 119797, 2025, doi: 10.1016/j.enconman.2025.119797.

[14] M. K. Abbas *et al.*, "Techno-economic analysis for clean hydrogen production using solar energy under varied climate conditions," *Int J Hydrogen Energy*, vol. 48, no. 8, pp. 2929–2948, 2023, doi: 10.1016/j.ijhydene.2022.10.073.