Techno-Economic Evaluation of Green Hydrogen Production from Off-Grid Solar PV Systems in Remote Areas of Indonesia

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Abstract. The increase of CO_2 emission is the main actor of climate change. Indonesia committed through NDC at COP26 to reduce GHG emissions by 31% and achieve NZE by 2060. Indonesia's State Electricity Company, PT PLN, has planned to develop 20.9 GW of renewable energy power plants by 2030 including PV Power Plant. The utilization of electricity supply from PV for massive production of green hydrogen potentially substitute the conventional fuel in the future. This study aims to obtain indicative green hydrogen gas tariff through off-grid Solar PV in remote area providing financial feasibility. The method is conducted by collecting manufacturers operation data, scoring analysis, project cost estimation, financial analysis and comparison to conventional fuel price. Results show the selected Manufacturer requires 67 kWh of electricity and 10 litres of water per kilogram of hydrogen. The PV system design will utilize 30 units of 480 Wp PV modules, 4 kWac inverter and one unit energy management system (EMS). Under 9 USD/kg hydrogen price, a positive Net Present Value (NPV) is obtained, IRR (11,03%) is above discounted rate, Payback Period (PBP) of 7.9 years and Benefit Cost Ratio (BCR) more than 1.

Keywords: Green hydrogen, Electrolyzer, Renewable energy, Off-grid pv system, Economic analysis.

1   INTRODUCTION

Over the past century, climate change has significantly turned out into main topic under evidence of snow cover reduction, the increase of air and sea temperatures, sea level rise, and glacier melt. Those are impacted by the inevitable increase of global warming which is correlated to the high accumulation of greenhouse gas (GHG) concentrations. To comply the Paris Agreement and limit global temperature rise to below 2°C [1], substantial GHG emission reductions are necessary. Carbon dioxide (CO2) emissions, primarily from transportation, industry, and power generation, are major GHG contributors. Indonesia aims to reduce GHG emissions by 31% through domestic efforts, potentially reaching 43% with international support, as stated in its Nationally

Determined Contribution (NDC) at COP26. The country also targets Net Zero Emissions (NZE) by 2060, with plans to begin using green hydrogen by 2031 [2].

Transitioning to zero carbon energy sources like hydrogen is essential for achieving these targets. Hydrogen can replace fossil fuels in applications such as fuel cells for transportation, energy storage, and powerto-X conversions. PT PLN, Indonesia's State Electricity Company, is crucial in this transition, planning to develop 20.9 GW of renewable energy (RE) power plants by 2030. The very large power production of renewable energy creates a significant opportunity to produce green hydrogen by utilizing the electricity supply from renewable energy such as photovoltaic power plant (PVPP). Under massive production, the green hydrogen could potentially substitute the conventional fuel oil for transportation and power plant industry sector in the future especially in remote areas.

Reducing fossil fuel utilization use and environmental risks are key issues [3]. Solar energy is a promising clean energy source as it is widely used in Indonesia for power plants, industry, and residential rooftops. However, solar energy output varies with weather and seasons, often resulting in excess power. The opportunity of excess power utilization to produce hydrogen will increase the optimization of solar power plant utilization [4]. The lower price of green hydrogen being produced compared to conventional fuel will take advantage in the NZE target encouragement.

On the other hand, researchers have proposed hybrid energy systems to produce hydrogen from solar power, such as off-grid PV systems with batteries through electrolysers [5], and hybrid solar power and fuel cell systems for residential areas electrification in deserts [6]. Other studies include off-grid wind/solar/hydrogen systems [7], standalone solar power and hydrogen fuel cell systems for research buildings [8], multi-objective optimization for hybrid systems and optimal designs for hybrid systems connected to unreliable grids [9]. The off-grid system is a common designed in remote area regarding the less integration of power system. The selection of remote area (Medang, Nusa Tenggara Barat, Indonesia) is based on the high solar irradiance of site location.

Research has also explored using excess power from renewables to produce hydrogen via electrolysis, with techno-economic analyses of various applications, power-to-gas applications [10], and feasibility studies for standalone/off-grid microgrids [11]. The cost of renewable hydrogen production in standalone photovoltaic plants has been analysed, considering electricity costs and electrolyser utilization rates [12]. This research advances previous studies by utilizing electricity from PV System in Indonesia to produce green hydrogen gas specifically in remote area as the initial study to encourage the growth of hydrogen utilization.

2   METHODOLOGY

This study utilizes the document analysis and observation to collect data. The step of gathering existing operation data from several manufacturers is crucial for analysis. The manufacturer will be selected by scoring analyst based on operation data provided. The selected manufacturer operation data will be further analysed to obtain the green hydrogen cost. Several electrolyzers from different manufacturers will be thoroughly assessed to determine their suitability for small-scale, remote applications.

Solar irradiation data source is obtained from Solargis Prospect to evaluate the potential power provided by the planned PV system. To determine the capacity of the PV power plant, a simulation using PVsyst software will be performed. The simulation will consider various parameters, including panel orientation, inclination angle, local environmental conditions, and system efficiency, ensuring a comprehensive and accurate assessment of the plant's potential output. The electrolysis technology selected should accommodate the PV system load fluctuations [13], achieving higher hydrogen conversion efficiency. PVsyst software is used to assess PV energy potential, while Dow software calculates feedwater requirements for optimal electrolyser efficiency. The research also analyses hydrogen production costs including electrolyzer with the auxiliary equipment. Operational cost will not include PV electricity prices since the PV power plant is included in this new built facility package integrated with hydrogen plant. The production and operational cost will be the basis to calculate the price of green hydrogen through financial model to obtain competitive price of green hydrogen considering financial feasibility. There will be comparative analysis between green hydrogen and the existing conventional fuel price.

Table 1. Data Scoring Analysis

Parameter	Weighting Factor	A	B	C
Fluctuative Electricity Supply	20%	3	5	1
Efficiency	20%	3	5	3
Adaptability to Poorer Water Quality	20%	3	3	3
Narrower Land Area Required	10%	3	3	3
Modularity	30%	1	5	3
Total	100%	5.0	8.6	5.2

Note: 1 = Lowest, 3 = Medium, 5 = Highest

The weighting factor is assumed to be equal of each other except the modularity parameter at 30%. The modularity enrols as the most dominant aspect to support the plant utilization in remote area. The data scoring is based on the comparison towards manufacturers datasheet and expert engineering judgment.

The parameter to be most considered for manufacturer selection specifically in remote area is modularity regarding the mobilization access and relocation along the utilization of the hydrogen plant from one remote area to another remote area. The other aspects are the adaptability to the poorer water quality, fluctuated electricity supply and efficiency. Water treatment will be utilized to ensure the water quality supply to electrolyzer, hence it is clearly inevitable to consider a water quality change in remote area due to the environmental condition. Fluctuated electricity supply is affected by the PVPP power production trend relying on the sunshine intensity. Higher efficiency of electrolyzer will be an advantage to gain good performance of hydrogen production. The last one is the narrower land area requirement for green hydrogen to reduce the

investment cost. However, the land area provided in remote area is abundant since most of the lands remains undeveloped yet.

There are 3 (three) options of manufacturers to be scored. The data will have compared each other, and each aspect utilizes weighting factor. Unsignificant difference of operation data among manufacturers will gain equal score. The financial model analysis will utilize 10% of discounted rate for 20 years of project lifetime. The NPV formula is as follow.

$$NPV = \sum_{n=1}^{N} \frac{(Revenue - O\&M\ cost)_n}{(1 + i)^n} - Production\ cost$$

Where:
i = discounted rate
N = 20 years

The Internal Rate of Return (IRR) formula is as follow.

$$\sum_{n=1}^{N} \frac{(Revenue - O\&M\ cost)_n}{(1 + IRR)^n} - Production\ cost = 0$$

The revenue will be adjusted to obtain the variation of IRR. Moreover, the production cost is calculated based on Manufacture quotation data. On this study, the power produced by PV power plant will not be intended to comply energy demand required in a specific location. However, this study figures out the optimal power being produced considering the site data to obtain hydrogen product in Medang area (Nusa Tenggara Barat, Indonesia).

3 RESULTS AND DISCUSSION

3.1 Hydrogen Production

From the Table 1 data scoring result, the manufacturer B has obtained the highest score. Therefore, operation data of Manufacture B (further called as "Selected Manufacturer") will be the basis for further analysis. The selected manufacturer has capacity of 12 kW, with hydrogen production 2 Nm^3 per hour, and an energy consumption of 67 kWh per kg. For water, the electrolyzer theoretically requires 9 litres per kilogram of hydrogen, but in practice, it uses about 10 litres to account for inefficiencies in the system. The delivery pressure ranging from 15 bar to 30 bar. The specification of selected electrolyzer can be seen in Table 2.

Table 2. Selected Manufacturer Specifications

Electrolyzer Type	PEM
Capacity	12 kW
Production Rate	2 Nm3/h
Power Consumption	6 kWh/Nm^3
Power Consumption	67 kWh/kg
Delivery Pressure	15-30 bar
Water Consumption	10 l/kg

To supply water as per electrolyzer specification, water treatment plant (WTP) will be installed. The water will be taken from deep well. The system will consist of deep well

water pump, reverse osmosis (RO) and supply water pump. The total power consumption for WTP system approximately is 700 kW.

3.2   Solar Power Energy Simulation

The location chosen has high solar radiation and minimal shading, ensuring maximum energy capture from sunlight. To provide the electricity needs for hydrogen production and WTP system, the simulation of PVsyst suggests that a 13.5 kWp solar power system is optimal for this project, considering factors like panel orientation, inclination, and local conditions.

The process initiates with PV modules converting solar energy into direct current (DC) electricity, which is subsequently managed by an Energy Management System (EMS). The EMS optimizes and regulates the electricity throughout the system. The DC electricity is then supplied to an electrolyzer, where water (H_2O) is subjected to electrolysis, resulting in the production of hydrogen (H_2) and oxygen (O_2). The hydrogen can either be stored for future use or utilized in real-time for applications such as energy generation or industrial processes.

Additionally, the system includes an inverter, which converts a portion of the DC electricity into alternating current (AC) for use in components that require AC electricity. A water treatment plant system is incorporated into the system to provide purified water to the electrolyzer, ensuring the efficiency and integrity of the electrolysis process. The system configuration can be seen in Figure 1.
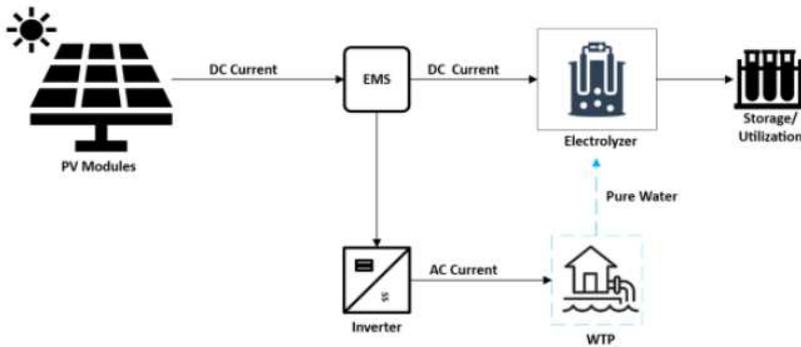

Fig. 1. PV System Configuration Diagram

Based on the average energy production data obtained from the PVsyst simulation, the system is expected to generate approximately 26,778 kWh per year, with a monthly average of 2,232 kWh and a daily average of 74 kWh. The PV system design can be seen in the Table 3 below.

Table 3. PV System Design

Capacity	13.5 kWp
PV Modules	480 Wp
No. of Modules	30 Units
Inverter	4 kWac
Energy Production	26,778 kWh/year
Energy Production	2,232 kWh/month
Energy Production	74 kWh/day
Auxiliary Consumption	5 kWh/day

The electrical energy provided from PV System is 74 kWh per day. The energy required by the electrolyzer to produce 1 (one) kg hydrogen is 67 kWh and there is additional power from WTP system 5 kWh. Given this energy requirement, the amount of hydrogen that can be produced daily by the PV System is calculated as follows. The hydrogen production from this PV system will be estimated 1.04 kg per day.

3.3 Financial Analysis

The total project cost of small-scale green hydrogen plant in remote area is estimated at USD 21,118 (under exchange rate of IDR 16,000/USD) including material costs, transportation, and installation. Major components include solar panels, inverters, wiring, control systems (EMS), water treatment systems and the electrolyzer.

Table 4. Bill of Quantity Hydrogen System

No	Bill of Quantity	Quantity
1	PV Modules	30 Units
2	Solar Inverter	1 Unit
3	Cabling System	1 Set
4	Control System (EMS)	1 Unit
5	Water Treatment System	1 Set
6	Electrolyzer	1 Unit
7	Civil Works	Lumpsum

The project has a 20-year operational lifetime, indicating a long-term focus on hydrogen production. Annual O&M costs are set at 422 USD, while a 10% discount rate is applied. The O&M cost is a preliminarily set at 2% of CAPEX according to reference [16]. Hydrogen production is estimated at 342 kilograms per year. These assumptions establish a solid framework for evaluating the project's overall feasibility and long-term viability.

The green hydrogen tariff as the result of calculation is 9 USD/kg. The tariff will obtain Net Present Value (NPV) of USD 1,499 at a discount rate of 10%. Positive value of NPV indicates the profitability of the project. Internal Rate of Return (IRR) is 11.03%, which is above the discount rate. The project has a payback period of 7.9 years shorter than the project lifetime as designed in 20 years. The benefit-cost ratio (BCR) is 1.18 indicates that the project's total revenue will exceed its combined investment and operational expenses. The BCR is a financial measure used to compare a project's benefits to its costs [14] by dividing the total present value of benefits by the total present value of costs. The total present value of benefits encompasses all discounted

cash inflows expected from the project over its operational period, while the total present value of costs includes the initial capital outlay and any subsequent expenses incurred, adjusted to their present value.

3.4   Sensitivity Analysis

The sensitivity analysis of this study has not involved the seasonal variation of solar energy production in the chosen location leading to the implications towards hydrogen production. The sensitivity analysis provides valuable insights into how changes in hydrogen pricing impact the financial viability of the project [15]. By examining three key financial metrics such as Internal Rate of Return (IRR), Return on Investment (ROI), and Benefit-Cost Ratio (BCR) under different hydrogen price scenarios (3 USD/kg, 6 USD/kg, and 9 USD/kg), we will understand the project's resilience in varying market conditions. Each price point reveals the potential profitability and risk associated with the investment, offering a clearer picture of how hydrogen prices drive financial performance.
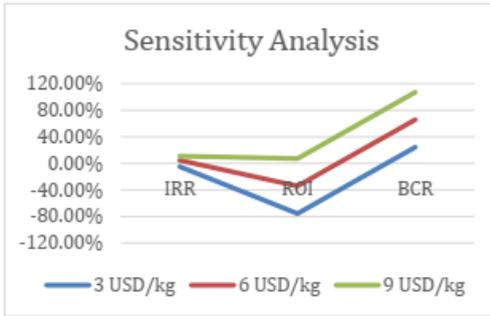

Figure 2. Sensitivity Analysis

For the IRR, a lower hydrogen price of 3 USD/kg leads to a negative outcome, as the line dips significantly below 0%. This suggests that at this price level, the project is not financially viable, with costs outweighing returns. As the hydrogen price increases to 6 USD/kg and 9 USD/kg, the IRR improves, eventually crossing into positive territory at 9 USD/kg, indicating that the project becomes profitable at this higher price. The ROI follows a similar trend. At 3 USD/kg, the ROI is negative, suggesting losses for investors. However, as the price increases, the ROI steadily improves, becoming positive at 6 USD/kg and continuing to rise sharply at 9 USD/kg. This indicates that as hydrogen prices rise, the project's returns become increasingly attractive to investors. For the BCR, which compares the project's benefits to its costs, the 3 USD/kg price results in a ratio well below 1, indicating that the project is not financially feasible at this price. At 6 USD/kg, the BCR approaches 1, suggesting a near break-even point. When the price reaches 9 USD/kg, the BCR surpasses 1 highlighting that at this price, the project's benefits outweigh its costs making it financially viable. The hydrogen produced in this study categorized as green hydrogen which is generally more expensive than the grey hydrogen. The price of green hydrogen at 9 USD/kg has been being competitive according to hydrogen price market availability in 2024 [17]. The

reference has shown that the green hydrogen price through PEM electrolysis in Canada in 2024 has reached more than 8 USD/kg.

4   CONCLUSION

This study is purposed to produce green hydrogen through PV power plant in Medang (Nusa Tenggara Barat). Several conclusions are obtained as follows:

1. Energy production data obtained from the PVsyst simulation is expected to generate approximately 26,778 kWh per year, with a monthly average of 2,232 kWh and a daily average of 74 kWh.
2. The designed PV System is designed to produce approximately 1.04 kg of hydrogen per day.
3. The green hydrogen tariff as the result of calculation is 9 USD/kg to provide financial feasibility of the green hydrogen plant in remote area of Indonesia.
4. The financial analysis has obtained positive value of Net Present Value (NPV) projection for USD 1,499. The Internal Rate of Return (IRR) is 11.03% higher than discount rate at 10%. The project has a payback period of 7.9 years shorter than the project lifetime as designed in 20 years. The benefit cost ratio (BCR) is 1.07 meaning that the cumulative revenue will be higher than the investment and operational cost.
5. Green hydrogen price at 9 USD/kg has been being competitive according to hydrogen price market availability in 2024.
6. Green hydrogen through PV power plant in remote area is a worth solution to utilize the high solar irradiance in Medang, Nusa Tenggara Barat, Indonesia.

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