Integration of Green Hydrogen Plant with Geothermal Power Plants in Renewable Energy Microgrid of Lembata Island, East Nusa Tenggara

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Abstract

In support of Indonesia's national energy transition targets, PT PLN (Persero) has committed to accelerating the integration of renewable energy into isolated and microgrid systems. This study evaluates the techno-economic feasibility of utilizing excess power from the planned 10 MW Atadei Geothermal Power Plant (GPP) in Lembata Island's microgrid, which is significantly impacted by photovoltaic (PV) penetration and the resulting "duck curve" phenomenon. Based on merit-order economic dispatch, the GPP is expected to operate with an average capacity factor of 75% in the first eleven years of operation, leading to approximately 15% excess power during midday hours that cannot be absorbed by the system. To optimize this underutilized capacity, a green hydrogen plant using Proton Exchange Membrane (PEM) electrolyzers is proposed as a flexible demand-side solution. By absorbing excess electricity, the hydrogen facility enhances geothermal utilization and improves system stability. Economic analysis indicates that integrating hydrogen production yields a net present value (NPV) of USD 0.16 million and an internal rate of return (IRR) of 14.77%, with a minimum hydrogen price of USD 6.5/kg required to maintain project viability. These findings demonstrate the potential of green hydrogen as a strategic mechanism for supporting renewable energy integration and improving operational efficiency in isolated power systems.

Keywords: *Photovoltaic Penetration, Duck Curve Phenomenon, Geothermal Power Plant Excess Power, Hydrogen Production*

1. Introduction

Indonesia's national commitment to energy transition has prompted an accelerated shift toward renewable energy integration, especially in remote and isolated power systems. As part of this initiative, PT PLN (Persero), the state-owned electricity utility, supports the deployment of clean energy technologies particularly solar photovoltaic (PV) and geothermal power as a core strategy outlined in the national Electricity Supply Business Plan (RUPTL 2025–2034). This aligns witemissions andrts to reduce reliance on fossil fuels, lower greenhouse gas emissions, and promote sustainable electricity access across the archipelago. Indonesia's rich geothermal and solar energy potential makes it well-positioned to meet these objectives. PV technology alone is projected to contribute up to 70% of the country's energy mix by 2050 [1]. However, the growing share of variable renewable energy (VRE) such as PV introduces new operational challenges, particularly the "duck curve" phenomenon marked by a sharp drop in midday net load due to high solar output. Originally observed by the California Independent System Operator (CAISO)[2], this effect is now increasingly relevant to islanded systems like Lembata in East Nusa Tenggara.

The Lembata power system, currently served by a combination of diesel power plants (DPP), a small PV system (0.2 MW), and projected future installations, is undergoing transformation. According to RUPTL 2025-2034, planned additions include the 2 × 5 MW Atadei GPP, and 2 x 3 MW of new PV + BESS capacity. This configuration is expected to result in solar contributing 37% of total generation, increasing the risk of supply-demand imbalances due to non-dispatchable PV output. To address this operational inflexibility, the use of green hydrogen production as a flexible demand-side application is proposed. Utilizing Proton Exchange Membrane (PEM) electrolyzers, excess geothermal power can be redirected to hydrogen generation, thereby enhancing system flexibility. Electrolyzer efficiency, which varies with fluctuating power input, must be considered in modeling production potential under intermittent supply conditions [3]. Geothermal's high-capacity factor further supports stable and continuous hydrogen generation, making it economically attractive compared to other renewables [4]

2. Lembata Power System Plan

The electricity system in Lembata Island is an isolated islanded system that is not interconnected with surrounding islands.

2.1 Annual Growth in Electricity Demand

The electrical network on Lembata Island utilizes a 20 kV distribution system. The expansion of its power generation infrastructure is guided by PT PLN's Electricity Supply Business Plan (RUPTL 2025-2034), which serves as a 10-year strategic framework for national electricity development. In this plan, the annual growth in electricity demand for East Nusa Tenggara Province is projected to reach approximately 7.07%. [5].

2.2 Renewable Energy Development Planning

According to the Electricity Supply Business Plan (RUPTL) 2025–2034, the renewable energy development plan for Lembata Island includes the construction of Atadei geothermal power plant (GPP) with a total capacity of 2 × 5 MW (COD 2030) , solar photovoltaic (PV) installations totaling 2 × 3 MW (COD 2026), and battery energy storage systems (BESS) sized at 20% of the capacity of each PV unit.

2.3 Netload Calculation

Based on the load projection, the assumed daily electricity demand data is represented by the set *D*, which is divided into several time slots denoted by the set *T*. The net load on day *d* during time slot *t* can be expressed using Equation (1), where $P_{load}\ (d,t)$ is the actual load demand and $P_{PV}\ (d,t)$ is the total PV power output on day *d* at time slot *t* [6].

$$P_{net}\ (d,t) = P_{load}\ (d,t) - P_{PV}\ (d,t), d \in D, t \in T \ldots \quad (1)$$

The successful implementation of photovoltaic (PV) systems relies heavily on the availability of solar energy at ground level, which is quantified by solar irradiance measured as the amount of solar energy received per unit area over a specific time period, typically in Wh/m². For this study, annual solar irradiance data for Lembata Island was sourced from the coordinates of the existing PV installation site in Oka Ile, Lembata Island (latitude -8.32, longitude 123.473). The data was obtained from NASA's Prediction of Worldwide Energy Resource (POWER) database, covering the full year from January 1 to December 31, 2023. Within this period, the highest irradiance was observed on October 16, while the lowest occurred on July 5, as illustrated in Figure 1. This NASA POWER dataset has also been utilized in prior analyses of PV integration in the Java-Bali power grid [7].

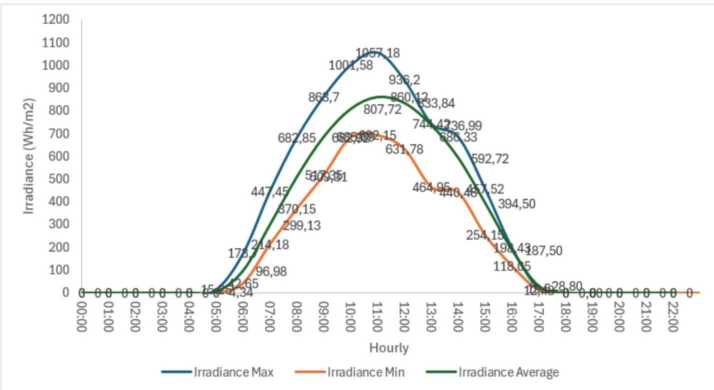

Figure 1. Highest, lowest, and average daily solar irradiance in Lembata Island.

3. Economic Dispatch Calculation

Utilizing the solar irradiance data for Lembata Island (Figure 1), a simulation of the duck curve phenomenon was performed for the local power system. Based on the average irradiance recorded throughout 2023, the combined photovoltaic (PV) capacity comprising the Oka Ile PV system along with PV Units 1 and 2 is estimated to reach a total of 5.27 MW within the Lembata grid.

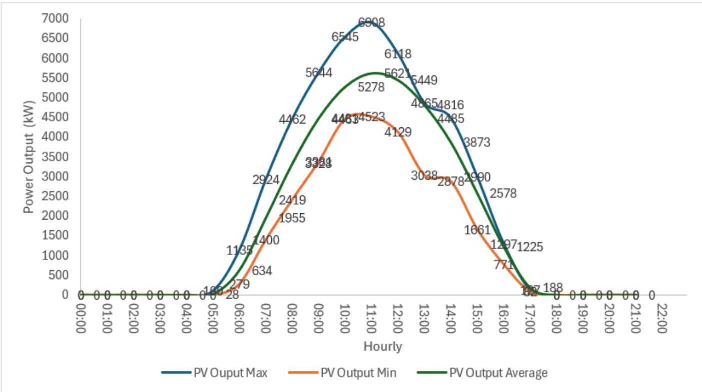

Figure 2. PV output from Oka Ile coordinate and 2 × 3 MW PV + BESS installations.

PV penetration and output as illustrated in Figure 2, the duck curve phenomenon resulting from daytime PV penetration in the Lembata system is depicted in Figure 3.

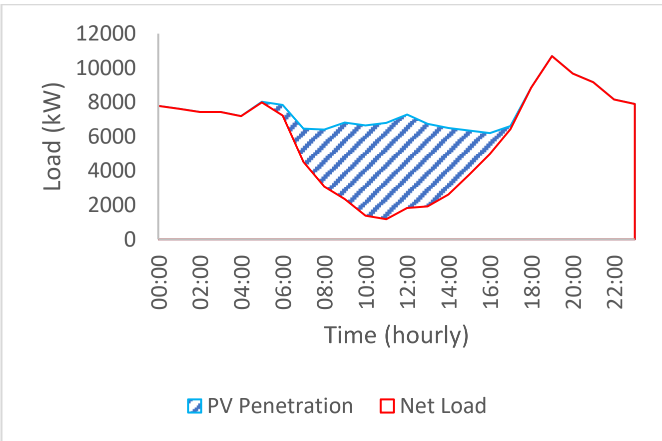

Figure 3. Duck curve phenomenon in the Lembata Island power system

PT PLN (Persero) employs the economic dispatch approach in planning power generation, aiming to operate generating units at the lowest possible cost while ensuring system reliability and meeting customer demand. This method accounts for various operational constraints within the generation and transmission infrastructure to guarantee that power supply always matches the load. In this process, generation costs primarily influenced by fuel prices and plant efficiency are evaluated to determine the most economical dispatch configuration [8]. PLN has issued average generation cost data (in Rp/kWh) for different types of power plants, which include expenditures related to fuel, maintenance, depreciation, personnel, and interest charges [9] The cost figures, derived from PLN's 2022 statistical report in Table 1, are utilized to establish a merit-based ranking of power plants in ascending order of operational cost. This ranking supports the application of the merit order dispatch method, a widely adopted approach in power system operations. Under this framework, generating units with the lowest operating costs are prioritized for dispatch, as they are considered the most economically efficient options for meeting system demand [10].

Table 1. Operational costs of PLN power plants (Rp/kWh) [9].

Unit	Capacity (kW)	Operational Cost (Rp/kWh)	Type
PLTP Atadei Unit 1	5000	119	Baseload
PLTP Atadei Unit 2	5000	119	
PLTS Oka Ile	200	1,035	Variabel
PLTS +BESS Unit 1	3000	1,035	Variabel + Smoothing
PLTS +BESS Unit 2	3000	1,035	
PLTD	5990	5,979	Peaker

In the economic dispatch of power plants using the merit order method, the following objective function is achieved:

$$\min \sum_{t=1}^{NT} \sum_{i=1}^{NG} C_i \quad (2)$$

Furthermore, the following constraints must be satisfied [11]:

$$C_i\left(P_i^t\right) = \alpha_i P_i^t + \beta_i u_i^t \quad (3)$$
$$\sum_{i=1}^{NG} P_i^t = P_D^t - P_S^t \quad (4)$$
$$u_i^t P_i^{min} \leq P_i^t \leq u_i^t P_i^{max} \quad (5)$$
$$-P_i^{down} \leq P_i^t - P_i^{t-1} \leq P_i^{up} \quad (6)$$

Where,

$C_i(P_i^t)$: *Generator operating cost i* $\left(\frac{Rp}{h}\right)$
α_i, β_i : *Generation unit cost function coefficients i* $\left(\frac{Rp}{kWh}\ dan\ \frac{Rp}{h}\right)$
P_i^t : *Power output of generator i at time t* (kW)
u_i^t : *Operational status of generator i at time t, where* 1 *indicates the unit is online and* 0 *otherwise*
NG, i : *Total number of generators, generator index*
NT, t : *Total number of scheduling periods, time index*
P_D^t : *Power demand at time t* (kW)
P_S^t : *Power output from the photovoltaic* (PV) *system at time t* (kW)
P_i^{min} : *Minimum power output of generator i* (kW)
P_i^{max} : *Maximum power output of generator i* (kW)
P_i^{down} : *Ramp − down limit of generator i* (kW/h)
P_i^{up} : *Ramp − up limit of generator i* (kW/h)

Equations (2) and (3) define the objective functions used for unit commitment and the minimization of operational costs. Equation (4) establishes the power balance condition, ensuring that total generation matches the system's electricity demand. Equation (5) sets the operational capacity boundaries for each generating unit, while Equation (6) addresses the ramp rate limitations for adjusting generator output. These formulations are applied to the dispatch planning of the isolated Lembata power system to determine the lowest possible total operating cost among all generators, as shown in Table 2. The simulation incorporates the average photovoltaic (PV) output during periods of solar generation, as depicted in Figure 2.

Table 2. Estimated Daily Minimum Operating Costs of Dispatchable Power Plants in the Lembata System Based on Economic Dispatch Simulation

Year	Power Plant Operational Daily Cost			Min.Operational Daily Cost
	PLTP Atadei 1	PLTP Atadei 2	PLTD	
2031	Rp10,698,474	Rp5,753,779	Rp15,048,564	Rp72,317,587
2032	Rp11,146,836	Rp6,515,144	Rp30,390,088	Rp88,868,838
2033	Rp11,605,410	Rp7,274,079	Rp50,735,842	Rp110,432,101
2034	Rp12,055,197	Rp7,815,003	Rp82,811,943	Rp143,498,913
2035	Rp12,456,776	Rp8,186,057	Rp142,952,391	Rp204,411,993
2036	Rp12,707,436	Rp8,725,330	Rp203,390,369	Rp265,639,905
2037	Rp12,823,920	Rp9,389,943	Rp271,340,107	Rp334,370,740
2038	Rp12,823,920	Rp10,226,228	Rp344,094,878	Rp407,961,796
2039	Rp12,823,920	Rp11,040,623	Rp426,067,238	Rp490,748,551
2040	Rp12,823,920	Rp11,799,399	Rp519,528,958	Rp584,969,046
2041	Rp12,823,920	Rp12,487,753	Rp625,839,194	Rp691,967,637
2042	Rp12,823,920	Rp12,776,048	Rp762,253,062	Rp828,669,800

During the dispatch process, the system operator establishes a minimum output threshold for each generating unit as outlined in Equation (5) to avoid reverse power flow conditions. If the combined generation is insufficient to meet system demand, additional capacity is allocated incrementally, beginning with the generator that has the lowest operational cost, in accordance with the merit order sequence illustrated in Figure 4, until demand is fully met. Conversely, if total generation surpasses the load requirement even when all generators are operating at their minimum levels, the operator will proceed to shut down the most expensive units in succession, again following the merit order principle.

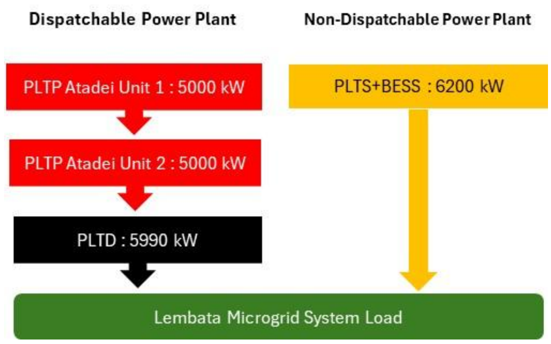

Figure 4. Merit order dispatch of power generation units in the Lembata microgrid system

4. Excess Power of Atadei geothermal Power Plant

Based on the results of economic dispatch simulations using the merit order method and projected load growth in the Lembata power system, the annual capacity factor (CF) of the geothermal power plant (GPP) was calculated and subsequently used to estimate the amount of excess power. The GPP is expected to reach full utilization with a CF of 90% starting in the twelfth year of operation. However, during the first to the eleventh year, the system is unable to fully absorb the plant's maximum output. The CF during this period ranges from 59% in the initial year and gradually increases to 89%, with an average CF over the eleven years of approximately 75%. As a result, the plant must operate flexibly, adapting its output in response to varying levels of photovoltaic (PV) penetration. To address this, the GPP is typically dispatched at full capacity during evening peak load hours. The unutilized portion of its installed capacity during midday when PV output is high constitutes the excess power from the GPP, as summarized in Table 3.

Table 3. Excess Power of Atadei Geothermal Power Plant

Year	Atadei Geothermal Power Plant Excess Power Hourly (kW)											
	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	11:00 AM
2031	1,210	1,380	1,564	1,563	1,823	1,012	1,786	4,495	5,923	6,661	7,629	7,822
2032	659	841	1,039	1,038	1,316	446	1,232	4,038	5,471	6,179	7,159	7,342
2033	70	265	476	475	774	-	638	3,550	4,986	5,663	6,656	6,828
2034	-	-	-	-	192	-	3	3,026	4,468	5,111	6,118	6,277
2035	-	-	-	-	-	-	-	2,466	3,912	4,519	5,541	5,688
2036	-	-	-	-	-	-	-	1,866	3,318	3,886	4,924	5,057
2037	-	-	-	-	-	-	-	1,224	2,681	3,208	4,263	4,381
2038	-	-	-	-	-	-	-	537	2,000	2,483	3,555	3,657
2039	-	-	-	-	-	-	-	-	1,270	1,706	2,798	2,883
2040	-	-	-	-	-	-	-	-	489	874	1,986	2,054
2041	-	-	-	-	-	-	-	-	-	-	1,118	1,166
2042	-	-	-	-	-	-	-	-	-	-	188	215

Year	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM	6:00 PM	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM	12:00 AM	CF
2031	7,169	7,077	6,384	5,240	4,023	2,583	144	-	-	-	853	1,102	1,209	31%
2032	6,655	6,601	5,925	4,792	3,585	2,116	-	-	-	-	277	544	659	27%
2033	6,104	6,091	5,434	4,313	3,116	1,616	-	-	-	-	-	- 54	69	23%
2034	5,514	5,545	4,909	3,799	2,614	1,081	-	-	-	-	-	-	-	19%
2035	4,883	4,961	4,346	3,250	2,076	509	-	-	-	-	-	-	-	17%
2036	4,207	4,335	3,743	2,661	1,500	-	-	-	-	-	-	-	-	14%
2037	3,484	3,665	3,098	2,031	884	-	-	-	-	-	-	-	-	12%
2038	2,709	2,948	2,408	1,357	224	-	-	-	-	-	-	-	-	9%
2039	1,879	2,180	1,668	635	-	-	-	-	-	-	-	-	-	6%
2040	991	1,358	877	-	-	-	-	-	-	-	-	-	-	3%
2041	40	478	29	-	-	-	-	-	-	-	-	-	-	1%
2042	-	-	-	-	-	-	-	-	-	-	-	-	-	0%

5. Integration Of Green Hydrogen Plant

Excess electricity is an inevitable challenge in renewable energy-based power systems, particularly within isolated or off-grid networks. However, this surplus energy should be either minimized or redirected towards secondary applications to enhance overall system efficiency. One approach to mitigate excess electricity involves the introduction of additional loads or secondary applications such as hydrogen production [12]. Among these options, green hydrogen production with PEM technology has emerged as a promising strategy for excess load absorption. Power balance of green hydrogen plant is described in equation [3]

$$P_{Load} = P_{El(t)} + P_{StandBy(t)} \quad (7)$$

To maintain the electrolyzer's operation within its designated power range, a binary variable $\beta_{On(t)}$ is employed, which takes the value of 1 when the system is actively operating. In instances where hydrogen production is not occurring, the electrolyzer is assumed to enter a standby mode rather than a complete shutdown. During this standby condition, power consumption is estimated at 1% of the installed capacity P_{Cap}.. Furthermore, the system is constrained by dynamic ramping limitations, with ramp-up and ramp-down rates assumed at 10% and 50% per second, respectively.

$$P_{El(t)} \geq \beta_{On(t)} \cdot P_{ElMin} \quad (8)$$
$$P_{El(t)} \leq \beta_{On(t)} \cdot P_{ElMax} \quad (9)$$

Where,

$$P_{ElMin} = 0.1\, P_{Cap} \text{ and } P_{ElMax} = P_{Cap} \quad (10)$$
$$\beta_{SU(t)} \leq \beta_{On(t)} - \beta_{On(t-1)} - \beta_{SB(t-1)} \quad (11)$$
$$\beta_{off(t)} + \beta_{SB(t)} \leq 1 \quad (12)$$
$$\beta_{SB(t)} + \beta_{On(t)} + \beta_{Off(t)} = 1 \quad (13)$$

Equation (11) tracks the transition of the electrolyzer from the off state to the on state. When such a transition occurs, the binary variable $\beta_{SU(t)}$, included in the objective function (Eq. (7)), is set to 1, thereby activating the elevated start-up energy consumption within the optimization model. Equation (12) ensures mutual exclusivity between the off and standby states, preventing direct transitions between them. Additionally, Equation (13) imposes a constraint that the electrolyzer can occupy only one operational state off, standby, or on at any given time step *t*.

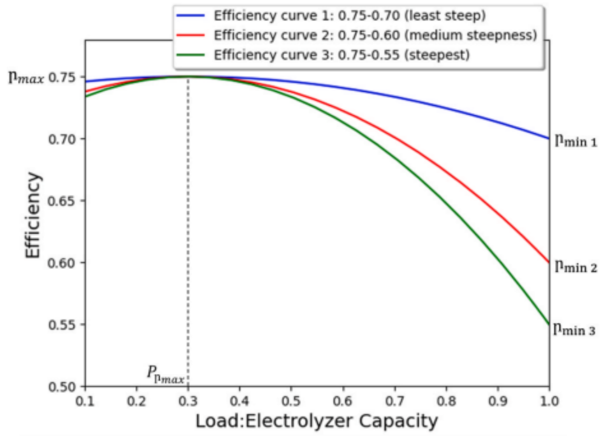

Figure 5. Efficiency curve used in modelling [3]

The efficiency curves used in modeling variable hydrogen production, as illustrated in Figure 5, can be parameterized using a piecewise or polynomial approximation that captures the nonlinear relationship between input power and electrolyzer efficiency. This approach enables accurate representation of partial-load performance characteristics, which are essential for simulating dynamic operating conditions under variable renewable energy input.

$$\eta = \frac{-\Delta\eta}{0.49}((\left(\frac{P_{El}}{P_{Cap}}\right) - P_{\eta max})^2 + \eta_{max} \quad (14)$$

Where,

$$\Delta\eta = \eta_{max} - \eta_{min} \quad (15)$$

The hydrogen production rate (kg/ h) depends on the efficiency, power input (MW) and lower heating value of hydrogen (LHV_{H_2} = 0.033 MWh/kg) and is given as Eq. (17)

$$m = \frac{((\eta_{max} P_{El}) + \left(\frac{\Delta\eta}{0.49}\right)\left(\left(\frac{-P_{El}^3}{P_{Cap}^2}\right) + \left(2 P_{El}^2 \frac{P_{\eta max}}{P_{Cap}}\right) - (P_{El} P_{\eta max}^2)\right))}{LHV_{H_2}} \quad (17)$$

The amount of hydrogen produced $M_{(t)}$ in kg at any time *t* can be calculated using Eq. (18), where ΔT represents the timestep resolution.

$$M_{(t)} = m\,\Delta T \quad (18)$$

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5.1 CAPEX Green Hydrogen Plant

This study utilizes the Proton Electolyzer Membrane (PEM) HyLYZER 200 water electrolyzer as the core technology for green hydrogen production, with a unit capacity of 2 MW (Table 4). The proposed system includes a total installed capacity of 6 MW, comprising operational schemes: 6 MW modular system (3 × 2 MW) designed to operate flexibly under a demand response strategy to mitigate photovoltaic penetration in system. The projected operational time of the green hydrogen plant is 8 years. The total capital investment required for the total 6 MW green hydrogen facility is estimated at approximately USD 10.2 million (Table 5).

Table 4. Technical Specifications of HyLYZER-200

Technology	PEM
Hydrogen Production	200 Nm3 / h (431 kh/day)
H2 Delivery Pressure	30 barg (435 psig)
H2 Quality Max. Impurities	99.998%
Operating Range	5 - 10%
DC Power Consumptions at Stack	40 to 48 kWh/kg
System Spesific Consumption	≤ 55 kWh/kg
Potable Water Consumption	1.2 to 1.5 L/Nm3 to produce 0.8 L/Nm3 demin water
Product Setup	Outdoor (40 ft + 20 ft ISO container)
Installation Environment	Outdoors -20 °C to 40 °C

Table 5. CAPEX Hydrogen Production Plant [13]

No.	Activity	Volume	Unit	Unit Price (USD)	Sub Total (USD)
1	PEM	6000	kW	1500	9,000,000
2	Kompresor & H2 Tank	2000	kg	600	1,200,000
					10,200,000

5.2 Economic Analysis

An economic feasibility analysis was performed based on the merit-order economic dispatch simulation, the average GPP's CF is approximately 75% (see Table 3). When the 15% excess power from the GPP is utilized by a green hydrogen system comprising 6 MW hydrogen production for demand response applications—the project IRR 14.77%, and the NPV USD 0.16 million.
The minimum hydrogen selling price required to achieve the target economic indicators is estimated at USD 6.5 per kilogram. The annual hydrogen production is calculated using Equation 17, while the annual capacity factors of the green hydrogen plant, following the optimized operational strategy, are presented in Table 6.

Table 6. Annual Hydrogen Production and Capacity Factor of the Green Hydrogen Plant

Year	Hydrogen Production (kg)	GHP CF
2031	584,244	48%
2032	526,448	44%
2033	469,796	39%
2034	386,941	32%
2035	337,029	28%
2036	284,918	24%
2037	231,820	19%
2038	174,540	15%
2039	120,662	10%
2040	68,698	6%
2041	22,423	2%
2042	2,578	0%

The annual capacity factors (CF) of the green hydrogen plant (GHP) over the eleven-year operational period are presented in Table 6. The 3 × 2 MW GHP system, operating under a demand response strategy, achieves a CF of 48.4% in the first year, which progressively declines to 1.9% by the eleventh year. This downward trend primarily results from the decreasing availability of excess power from the geothermal power plant (GPP), as the system gradually achieves load-growth equilibrium and fully absorbs the GPP's output in later years.

6. Conclusion

This study presents a power dispatch strategy for the Lembata Island microgrid under high photovoltaic (PV) penetration, using the economic dispatch merit order method to minimize total operational costs. The Atadei Geothermal Power Plant (GPP) is dispatched as a baseload unit, resulting in an average capacity factor of 75% during the initial years of operation. However, due to reduced net load during midday hours, a portion of the geothermal output remains unutilized, leading to excess power. To address this issue, the integration of a green hydrogen plant is proposed as a flexible demand-side solution. By absorbing surplus geothermal electricity, the hydrogen plant enables the GPP to operate closer to its full capacity, improving its utilization and supporting stable baseload performance. The hydrogen system, equipped with fast ramping capabilities 10% per second ramp-up and 50% per second ramp-down demonstrates strong potential to function as a dynamic load and demand response asset within the microgrid. Economic analysis indicates that this integration yields an internal rate of return (IRR) of 14.77% and a net present value (NPV) of USD 0.16 million, with a minimum hydrogen selling price of USD 6.5 per kilogram required for financial viability. These findings underscore the viability of green hydrogen as a strategic solution for managing excess power and enhancing operational flexibility in isolated renewable energy systems.

7. Discussion

The integration of a green hydrogen plant as a flexible additional load in the Lembata Island microgrid addresses one of the most pressing challenges in high photovoltaic (PV) penetration systems excess power during midday due to the duck curve phenomenon. By coupling the geothermal power plant (GPP) with a Proton Exchange Membrane (PEM) electrolyzer system, this study demonstrates that a previously underutilized resource can be harnessed for hydrogen production, increasing the effective capacity factor of the GPP and enhancing overall system efficiency. Compared to other studies, the results of this research show both alignment and distinction in economic feasibility. For instance, Li et al. (2022) investigated a hybrid off-grid renewable energy system for hydrogen production in Western China and reported a levelized cost of hydrogen (LCOH) of approximately USD 5.3/kg under optimized scenarios [13]. In contrast, the present study identifies a break-even hydrogen selling price of USD 6.5/kg due to lower capacity utilization over time as system demand grows and excess power diminishes. This highlights the economic sensitivity of green hydrogen projects to resource availability and operational flexibility. Moreover, Rad et al. (2023) emphasized the importance of integrating flexible demand-side solutions to mitigate excess electricity in isolated renewable systems [12]. Their review underscores hydrogen production as a highly effective approach in managing overgeneration while supporting grid stability. The findings of the present study reinforce this perspective by demonstrating the dual role of hydrogen plants: improving geothermal plant utilization and acting as a dynamic demand-response unit with fast ramping capabilities. A further point of comparison lies in the use of ramping flexibility. While most literature assumes steady electrolyzer operation for cost efficiency, this study integrates dynamic operation with PEM characteristics (10% /s ramp-up and 50% /s ramp-down), based on the operational modeling proposed by Virah-Sawmy et al. (2024) [3]. Their work cautions against overestimating hydrogen yield by ignoring electrolyzer efficiency curves, a pitfall that is explicitly avoided in this study by incorporating variable efficiency modeling. In summary, this study not only validates the techno-economic feasibility of green hydrogen integration in microgrid systems but also expands upon existing literature by:

1. Applying operational flexibility as a primary constraint in modeling electrolyzer performance,
2. Using excess geothermal power as the sole renewable input in contrast to hybrid PV-wind-geothermal systems,
3. Demonstrating how economic dispatch (merit order) planning directly informs hydrogen sizing and CF optimization.

These contributions provide a realistic and adaptable framework for integrating hydrogen production into isolated renewable grids, particularly in contexts where geothermal resources are abundant but underutilized due to grid limitations.

References

[1] IRENA, *World Energy Transitions Outlook 2024: 1.5°C pathway*. 2024. [Online]. Available: www.irena.org

[2] T. A. Edmunds, P. Sotorrio, J. M. Bielicki, and T. Buscheck, “Geothermal Power for Integration of Intermittent Generation,” 2014. [Online]. Available: https://www.researchgate.net/publication/267749628

[3] D. Virah-Sawmy, F. J. Beck, and B. Sturmberg, “Ignore variability, overestimate hydrogen production – Quantifying the effects of electrolyzer efficiency curves on hydrogen production from renewable energy sources,” *Int J Hydrogen Energy*, vol. 72, pp. 49–59, Jun. 2024, doi: 10.1016/j.ijhydene.2024.05.360.

[4] A. Dean, G. Ussher, F. Fininda, and F. Loudoe, “Economic Comparisons and Scenarios for Producing Geothermal Hydrogen,” 2022.

[5] PLN, "RUPTL PT PLN (Persero) 2025-2034," 2025.
[6] F. Wang *et al.*, "A distributed PV system capacity estimation approach based on support vector machine with customer net load curve features," *Energies (Basel)*, vol. 11, no. 7, 2018, doi: 10.3390/en11071750.
[7] H. B. Tambunan *et al.*, "The challenges and opportunities of renewable energy source (RES) penetration in Indonesia: Case study of Java-Bali power system," *Energies (Basel)*, vol. 13, no. 22, Nov. 2020, doi: 10.3390/en13225903.
[8] M. Bachtiar Nappu, A. Arief, and R. C. Bansal, "Transmission management for congested power system: A review of concepts, technical challenges and development of a new methodology," 2014, *Elsevier Ltd*. doi: 10.1016/j.rser.2014.05.089.
[9] PLN, "Statistik PLN - 2022," 2023.
[10] Y. M. Safarudin, R. Stephani, N. Fatowil Aulia, A. H. Su'udy, N. Apriandi, and B. Hermawan, "Perhitungan Economic Dispatch Tiga Buah Pembangkit Tanpa Losses Dengan Metode Merit Order," 2020.
[11] C. F. Nugraha and L. Subekti, "Optimisasi Penjadwalan Pembangkit pada Microgrid dengan Mempertimbangkan Respons Beban," *Jurnal Listrik Instrumentasi dan Elektronika Terapan (JuLIET)*, vol. 3, no. 1, Jun. 2022, doi: 10.22146/juliet.v3i1.74669.
[12] M. A. Vaziri Rad, A. Kasaeian, X. Niu, K. Zhang, and O. Mahian, "Excess electricity problem in off-grid hybrid renewable energy systems: A comprehensive review from challenges to prevalent solutions," Aug. 01, 2023, *Elsevier Ltd*. doi: 10.1016/j.renene.2023.05.073.
[13] J. Li, P. Liu, and Z. Li, "Optimal design and techno-economic analysis of a hybrid renewable energy system for off-grid power supply and hydrogen production: A case study of West China," *Chemical Engineering Research and Design*, vol. 177, pp. 604–614, Jan. 2022, doi: 10.1016/j.cherd.2021.11.014.