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TECHNO-ECONOMIC STUDY OF PV INTEGRATION INTO A GAS ENGINE-BASED POWER SYSTEM CONSIDERING CURTAILMENT IMPACT: A CASE STUDY OF THE ALOR POWER SYSTEM

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ABSTRAK

Target penambahan kapasitas PLTS dalam Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2025–2034 ditetapkan sebesar 17,1 GW. Sistem Kelistrikan Alor memiliki potensi iradiasi surya yang tinggi, mencapai sekitar 6 kWh/m²/hari, namun hingga saat ini belum memiliki PLTS yang terintegrasi ke jaringan. Penelitian ini menganalisis kelayakan teknis dan ekonomi integrasi Pembangkit Listrik Tenaga Surya (PLTS) ke dalam sistem kelistrikan Alor dengan memanfaatkan kembali lahan eks pembangkit yang pembangunannya terhenti. Evaluasi dilakukan pada tiga skenario penetrasi PLTS, yaitu 15%, 20%, dan 30% terhadap kebutuhan energi harian menggunakan perangkat lunak HOMER Pro yang diintegrasikan dengan PLTMG Alor berkapasitas 10 MW. Berbeda dengan penelitian terdahulu yang umumnya berfokus pada optimasi kapasitas terpasang PLTS, penelitian ini mengevaluasi hubungan antara tingkat penetrasi PLTS, curtailment energi, konsumsi bahan bakar, dan Levelized Cost of Electricity (LCOE) sistem pada sistem kelistrikan terisolasi berbasis pembangkit mesin gas tanpa Battery Energy Storage System (BESS). Hasil simulasi menunjukkan bahwa peningkatan penetrasi PLTS mampu menurunkan konsumsi bahan bakar dan biaya operasi PLTMG, namun juga meningkatkan curtailment energi pada siang hari. Di antara skenario yang dievaluasi, penetrasi PLTS sebesar 20% menghasilkan LCOE terendah, yaitu Rp3.334/kWh, lebih rendah dibandingkan skenario 15%, 30%, maupun skenario dasar PLTMG saja sebesar Rp3.435/kWh. Hasil penelitian menunjukkan bahwa di antara skenario yang dievaluasi, konfigurasi sistem hibrida dengan penetrasi PLTS 20% dan PLTMG 10 MW memberikan kinerja tekno-ekonomi yang paling baik berdasarkan nilai LCOE, sehingga layak dipertimbangkan sebagai alternatif pengembangan Sistem Kelistrikan Alor dalam mendukung target penambahan kapasitas PLTS sebesar 17,1 GW sesuai RUPTL 2025–2034.

Kata kunci: PLTS, PV, hybrid, renewable energy, LCOE

ABSTRACT

The Solar PV capacity addition target in Indonesia's 2025–2034 Electricity Supply Business Plan (RUPTL) is 17.1 GW. The Alor Power System has high solar irradiation potential of approximately 6 kWh/m²/day but currently has no grid-connected photovoltaic (PV) plant. This study evaluates the techno-economic feasibility of integrating Solar PV into the existing 10 MW gas engine power plant (GEPP) by utilizing the former constrained power plant site in Alor. Three PV penetration scenarios (15%, 20%, and 30% of daily energy demand) were simulated using HOMER Pro. Unlike previous techno-economic studies that primarily optimize installed PV capacity, this study analyzes the relationship between PV penetration, renewable energy curtailment, fuel consumption, and system-level Levelized Cost of Electricity (LCOE) in an isolated gas-engine-based *power system without Battery Energy Storage Systems (BESS). The results show that increasing PV penetration reduces fuel consumption and operating costs but also increases daytime renewable energy curtailment. Among the evaluated scenarios, the 20% PV penetration configuration achieved the lowest system LCOE of IDR 3,334/kWh, outperforming the 15% and 30% scenarios as well as the GEPP-only base case (IDR 3,435/kWh). The findings demonstrate that balancing fuel savings and renewable energy curtailment is essential for determining economically favorable PV penetration in isolated gas-engine-based power systems. The proposed hybrid configuration is therefore considered technically and economically feasible for future PV integration in the Alor Power System.*

Keywords: *PLTS, PV, hybrid, renewable energy, LCOE*

1. INTRODUCTION

The Solar PV capacity addition target under Indonesia's Electricity Supply Business Plan (RUPTL) 2025–2034 is set at 17.1 GW [1] reflecting the national commitment to accelerate renewable energy deployment and reduce dependency on fossil fuels. East Nusa Tenggara Province has a solar energy potential of approximately 414 MW. In particular, the Kalabahi subsystem on Alor Island exhibits high solar irradiation potential of around 6 kWh/m²/day. However, to date, no grid-connected photovoltaic (PV) plant has been implemented within the system [2].

Currently, the Kalabahi power system has a peak load of 6.6 MW and remains predominantly supplied by diesel-based generation. In the RUPTL 2025–2034, the development of a 10 MW gas engine power plant (GEPP) was planned as part of the national diesel phase-out program [3]. Nevertheless, the project was terminated due to financial constraints faced by the EPC contractor. As a result, the Alor system continues to rely on leased diesel power plants, resulting in a relatively high Levelized Cost of Electricity (LCOE) of IDR 3,603/kWh.

In response to this condition, PT PLN (Persero) has proposed the development of a Solar PV plant by utilizing the existing land and infrastructure from the terminated project site. This initiative requires an alternative power system development strategy that not only optimizes the use of existing assets but also reduces electricity supply costs through a more efficient hybrid system configuration. Therefore, introduction of the technologies which can reduce the fuel consumption for power generation is important in those area [4], [5], [6].

Techno-economic analysis integrates technical performance evaluation with economic feasibility assessment, enabling a comprehensive evaluation of system configurations based on both engineering performance and cost-effectiveness. Previous techno-economic studies have predominantly focused on determining the optimum installed PV capacity or minimizing system cost in hybrid renewable energy systems [6], [7], [8]. However, limited attention has been given to evaluating how different PV penetration levels influence renewable energy curtailment and system-level Levelized Cost of Electricity (LCOE), particularly in isolated gas-engine-based power systems operating without Battery Energy Storage Systems (BESS). As PV penetration increases, excess renewable generation may not be fully utilized because of the operational constraints of conventional generators, resulting in renewable energy curtailment that directly affects the overall economic performance of the system [7], [8]. Therefore, understanding the relationship between PV penetration, renewable energy curtailment, and system-level LCOE remains an important research challenge for isolated hybrid power systems.

To address this research gap, this study investigates the techno-economic performance of a PV–gas engine hybrid system by explicitly analyzing the relationship between PV penetration, renewable energy curtailment, fuel consumption, and system-level LCOE under the operational constraints of an isolated gas-engine-based power system without Battery Energy Storage Systems (BESS). Unlike previous studies that primarily focus on optimizing installed PV capacity, this research evaluates the techno-economic implications of different PV penetration levels to determine how increasing PV penetration affects renewable energy curtailment and overall economic performance. Among the evaluated scenarios, the analysis identifies the scenario with the lowest system LCOE. This approach provides a more comprehensive system-level assessment of renewable energy integration than approaches based solely on installed PV capacity.

The study is conducted using the Alor Power System as a representative case study because it represents an isolated power system undergoing diesel phase-out while possessing high solar energy potential and existing infrastructure for future PV development. The findings are expected to provide practical guidance for PV integration planning in isolated gas-engine-based power systems and support renewable energy deployment in similar islanded power systems in Indonesia.

The scope of this research is limited to a techno-economic assessment of PV integration under representative penetration scenarios of 15%, 20%, and 30% relative to the planned 10 MW gas engine power plant. These penetration levels were selected to represent low, medium, and relatively high-renewable integration scenarios for comparative analysis while remaining consistent with the operational constraints of the gas engine power plant. The analysis was performed using HOMER Pro with solar resource data obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database, without incorporating Battery Energy Storage Systems (BESS) [9], [10], [11].

2. METHOD

This study employs a techno-economic analysis of a hybrid Solar PV–gas engine (PV–GEPP) system to evaluate the effect of PV penetration on the Levelized Cost of Electricity (LCOE) of the Alor Power System. The methodological framework consists of three main stages.

First, the required PV capacity is determined based on penetration levels of 15%, 20%, and 30% relative to the daily load demand of the Alor system. The selected PV penetration levels (15%, 20%, and 30%) were chosen as representative low-, medium-, and relatively high-renewable integration scenarios for comparative techno-economic assessment. The technical feasibility of each scenario was subsequently evaluated under the operational constraints of the gas engine power plant using HOMER Pro.

Second, annual energy production analysis is conducted for both the proposed hybrid PV–GEPP system and the GEPP-only configuration (base case) using HOMER Pro software [12], [13]. The simulation models system dispatch, fuel consumption, renewable energy contribution, and operational characteristics under each penetration scenario. The base case serves as a benchmark to assess the relative performance improvement of the hybrid configuration.

Third, a comprehensive economic evaluation is performed by incorporating relevant financial parameters and explicitly accounting for energy curtailment in the feasibility assessment. The economic analysis focuses on recalculating the system LCOE to reflect actual usable energy delivered to the grid[14].

HOMER Pro is utilized as the primary simulation tool in this research. It is widely applied for the design, optimization, and simulation of hybrid renewable energy systems [15], [16]. The software enables integration of multiple energy sources and provides detailed simulation outputs, including annual energy production, fuel consumption, operational costs, and curtailment values. These outputs form the basis for evaluating system feasibility and performance effectiveness [17], [18].

In this study, PV energy curtailment is directly obtained from HOMER Pro simulation results. Curtailment is defined as the portion of potential PV energy that cannot be utilized by the system due to load limitations, spinning reserve requirements, and ramp rate constraints of the gas engine power plant[19], [20]. HOMER Pro calculates curtailment as the difference between the theoretical PV energy generation based on available solar irradiation and the actual PV energy dispatched to the power system [21]. The calculated curtailment values are subsequently incorporated into the financial analysis to determine the economic feasibility of each hybrid system scenario.

Since HOMER Pro performs hourly dispatch simulations, the operational flexibility of the GEPP is represented through minimum loading, spinning reserve, and ramping constraints rather than detailed transient response. Two gas engine units are maintained online at a minimum load factor of 30%, providing approximately 3–4 MW of hot spinning reserve to accommodate normal PV output variations. Nevertheless, short-term irradiance fluctuations caused by transient cloud cover are not explicitly simulated because they require high-resolution irradiance measurements and dynamic power system analysis beyond the scope of this study.

2.1 *HOMER Pro Simulation*

Solar irradiation data and daily load profile data are required as input parameters for modeling the hybrid PV–GEPP system, which is compared with the existing GEPP-only system (base case) [22], [23]. In the base case configuration, the entire electricity demand of the Alor system is fully supplied by the 10 MW Alor gas engine power plant (GEPP). Two system configurations are evaluated in the simulation:

2.1.1 Proposed System: Hybrid PV – GEPP

The proposed hybrid system utilizes Solar PV as the primary energy source during daytime operation, while the gas engine power plant functions as a spinning reserve margin and backup generator when PV output is insufficient to meet load demand or during intermittent solar conditions.

To determine the most optimal system design, the PV capacity is assessed based on penetration levels relative to the Alor Power System demand, namely 15%, 20%, and 30% of the total system load. These scenarios were selected to systematically investigate the effect of increasing PV penetration on renewable energy curtailment, fuel consumption, and system-level LCOE. The technical feasibility of each scenario was subsequently evaluated under the operational constraints of the gas engine power plant using HOMER Pro. The system configuration is illustrated in Figure 1.

This penetration-based approach is adopted to ensure that the analysis does not solely focus on nominal PV capacity but also considers its proportional contribution to the actual system demand. Consequently, the simulation results provide a more representative evaluation of the maximum PV penetration level that remains technically feasible and economically acceptable for the Alor Power System.

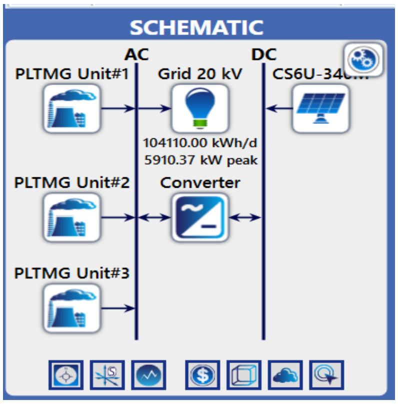

Figure 1. Schematic diagram of the proposed hybrid PV – GEPP system

2.1.2 *Base case: GEPP only*

The base case represents a power generation system fully dependent on the 10 MW Alor gas engine power plant. The plant consists of three gas engine units, each with a rated capacity of 2,445 kW. In this configuration, no renewable energy sources such as Solar PV or energy storage systems are integrated into the system. The base case configuration is illustrated in Figure 2.

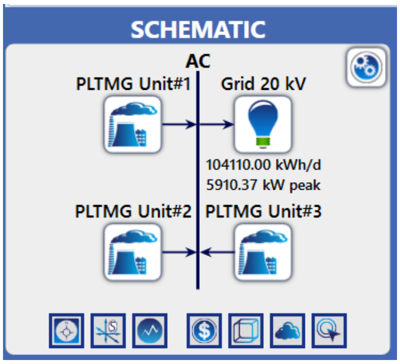

Figure 2. Schematic diagram of the GEPP-only base case system

2.2 *Daily Load Profile*

The Alor power system exhibits a nighttime peak load of 6,600 kW and a daytime peak load of 4,239 kW. The load composition is predominantly attributed to the residential sector. This characteristic is illustrated in Figure 3, where the relatively low electricity demand during daytime indicates limited industrial activity within the system. The load pattern reflects a typical residential-dominated isolated grid, with higher demand occurring during evening hours due to household consumption behavior [24].

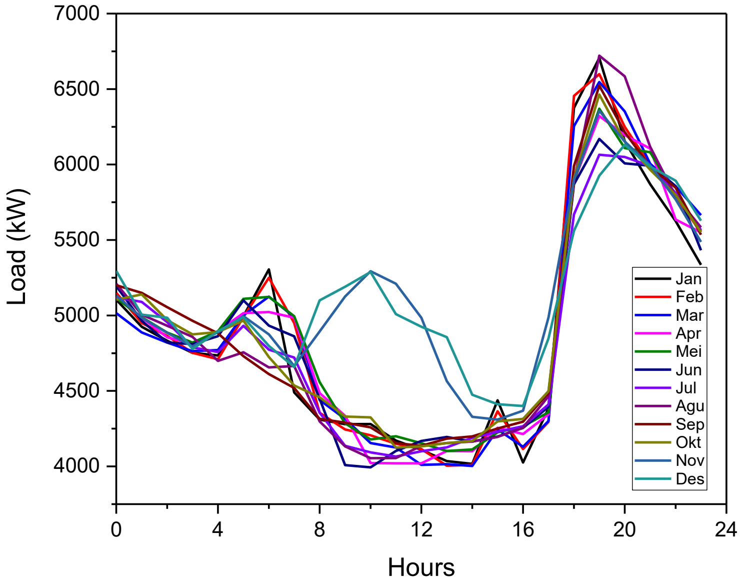

Figure 3. Average daily load profile of the Alor Power System 2025

2.3 *PV Capacity*

The installed PV capacity is determined through a systematic calculation process based on daily load data, solar irradiation data, and the targeted PV energy mix [25]. A dispatch strategy is applied to ensure that the power supplied by the PV modules does not exceed the available spinning reserve margin and ramp-up capability of the gas engine power plant (GEPP). The installed PV capacity is calculated under three energy mix scenarios: 15%, 20%, and 30% of the total daily electricity demand.

a) Daily Load Energy (kWh/day)
The daily load is calculated as the total electrical energy required by the Alor system over a 24-hour period:

$$\text{Total daily energy demand} = \sum_{t=1}^{24} hourly\ power\ load \quad (1)\ [25]$$

b) Average Daily Solar Irradiation (kWh/m²/day)
Solar irradiation data refer to the average daily Global Horizontal Irradiance (GHI) obtained from NASA satellite data. The average daily irradiation is expressed as:

$$\text{Average Daily Irradiation} = \sum GHI \quad (2)\ [25]$$

c) System Efficiency (%)
The overall PV system efficiency is calculated from the combined efficiency of the PV modules and inverter components:

$$\text{System Efficiency} = \eta\ PV\ modul\ x\ \eta\ inverter\ x\ \eta\ inverter\ battery \quad 3)\ [25]$$

Since this study does not incorporate Battery Energy Storage Systems (BESS), the battery inverter efficiency term is excluded where applicable.

d) Energy Mix Determination (kWh/day)
The PV energy contribution scenarios are defined as a percentage of total daily electricity demand:

For 15% penetration:
$$E_{mix\ 15\%} = 15\%\ \text{x Daily Load} \quad (4)\ [25]$$

For 20% penetration:
$$E_{mix\ 20\%} = 20\%\ \text{x Daily Load} \quad (5)\ [25]$$

For 30% penetration:
$$E_{mix\ 30\%} = 30\%\ \text{x Daily Load} \quad (6)\ [25]$$

e) Installed PV Capacity (kWp)

The required installed PV capacity is calculated by comparing the target PV energy contribution with the average daily solar irradiation and system efficiency:

$$\text{PV Capacity} = \frac{\sum PV\ energy\ mix}{GHI\ x\ Eff} \quad (7)\ [25]$$

This approach ensures that the installed PV capacity is aligned with both the targeted energy penetration level and the technical limitations of the Alor Power System.

2.4 *Hybrid System Operational Scheme (Proposed System)*

To enhance system reliability, PV penetration is further constrained by the ramp-up capability of the GEPP. Each gas engine unit has a ramp-up capability of 2,445 kW/min, allowing the system to respond to short-term reductions in PV output. During daytime operation (07:00–17:00), two gas engine units are operated continuously at a minimum capacity factor (CF) of 30%. The HOMER Pro settings for engine #1, engine #2, and engine #3 are illustrated in Figures 4 and 5.

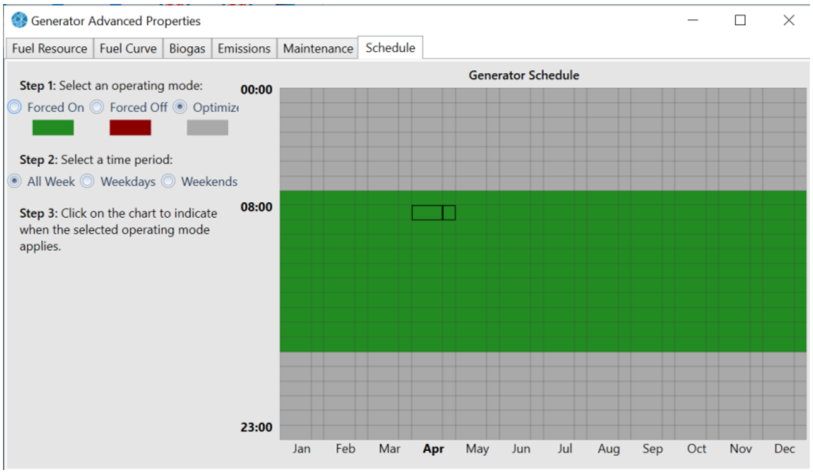

Figure 4. Operational pattern of GEPP engine units #1 and #2

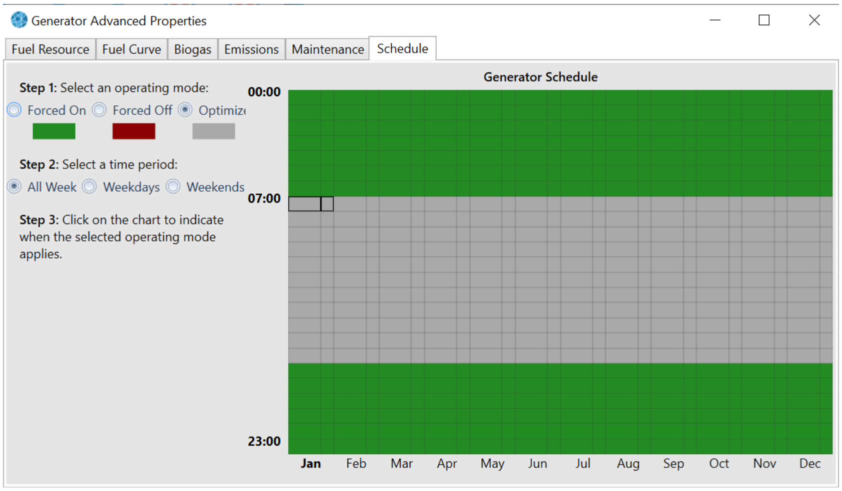

Figure 5. Operational pattern of GEPP engine unit #3

With two engine units operating continuously at a minimum load factor of 30% during daytime hours, the available hot spinning reserve ranges between approximately 3–4 MW. This operating strategy maintains sufficient operational flexibility for PV integration while avoiding extreme partial-load operation that may reduce gas engine efficiency. These operational constraints are implemented in HOMER Pro through the dispatch strategy by specifying the minimum number of operating generators and the minimum load fraction for each GEPP unit, as shown in Figures 4 and 5. Since HOMER Pro performs hourly simulations using NASA POWER solar resource data, short-term PV output fluctuations caused by transient cloud cover are not explicitly represented. Therefore, this study evaluates the long-term techno-economic performance of the proposed PV–GEPP system under practical operating constraints rather than transient dynamic behavior.

2.5 *Base Case Operational Scheme (GEPP Only)*

In the base case configuration, the Alor Power System is fully supplied by the 10 MW GEPP without integration of PV generation. The operational pattern is configured using the optimizer mode in HOMER Pro for all engine units, allowing the generators to operate according to load demand without considering PV penetration constraints. The HOMER Pro settings for engine units #1, #2, and #3 in the base case scenario are illustrated in Figure 6.

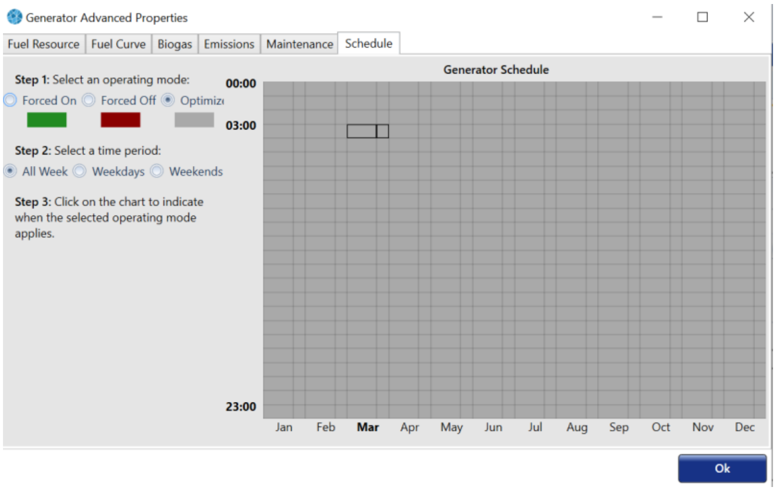

Figure 6. Operational pattern of GEPP engine units #1, #2, and #3

3. RESULTS AND DISCUSSION

3.1 *PV Capacity*

Based on the calculation using Equation (7), the required PV capacities for penetration levels of 15%, 20%, and 30% are 3,187 kWp, 4,247 kWp, and 6,377 kWp, respectively. Subsequently, PVsyst simulation was conducted to determine the module–inverter configuration and estimate the annual PV energy production, as summarized in Table 1.

Table 1. PV module and inverter configuration for each scenario

Spesification	3,187 kWp	4,247 kWp	6,377 kWp
Model	NUSA144H-450M	NUSA144H-450M	NUSA144H-450M
P max	450 Wp	450 Wp	450 Wp
Vmp	41,5 V	41,5 V	41,5 V
Imp	10,84 A	10,84 A	10,84 A
Module qty.	7.080	9.438	14.170
Module in Series	24	26	26
String qty.	295	363	545
Inverter			
Model	Sinacon PV1000	Sinacon PV1000	Sinacon PV1000
DC Voltage (Max MPP)	1.500 V	1.500 V	1.500 V
AC Voltage	400 V	400 V	400 V
Inverter qty.	3	4	6
Annual Production	6.488.216 kWh	8.646.205 kWh	12.978.468kWh

3.2 *Annual Energy Production Analysis*

The annual energy production is further simulated in HOMER Pro using the Alor site location map, assuming a PV module degradation rate of 0.5% per year. The hybrid PV–GEPP system performance is evaluated for installed PV capacities of 3,187 kWp, 4,247 kWp, and 6,377 kWp. The hybrid operational configuration is set such that two GEPP engine units (totaling 4,270 kW) operate during daytime, while three units operate during nighttime. Based on this configuration, the annual energy production results are obtained, as illustrated in Figure 7.

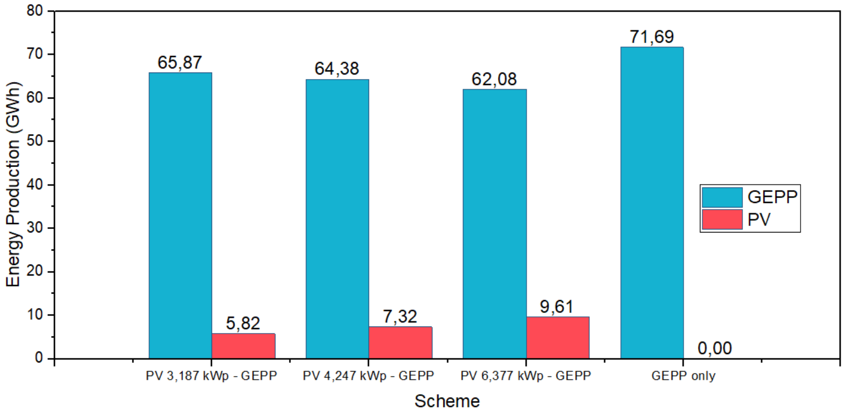

Figure 7. Annual energy production after curtailment

Simulation results indicate that annual energy production from the 10 MW GEPP decreases as PV penetration increases in the system. The average annual PV energy production for 3,187 kWp, 4,247 kWp, and 6,377 kWp configurations is 5.82 GWh/year, 7.32 GWh/year, and 9.61 GWh/year, respectively. This result is consistent with Dembélé et al. (2025), who reported that increasing installed PV capacity directly increases total electricity generation [26].

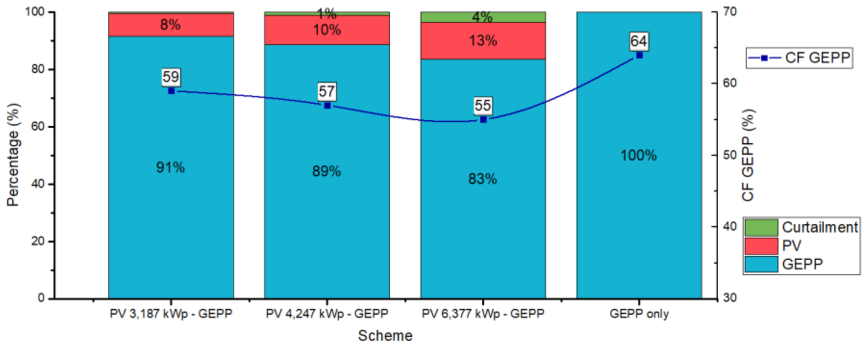

Figure 8. Percentage of energy production in the proposed scheme and base case after curtailment

Figure 8 shows the percentage of energy production for various PV–GEPP hybrid schemes compared to the GEPP-only base case after curtailment is applied. Increasing PV capacity enhances the PV energy contribution but reduces the GEPP energy share and its capacity factor (CF) from 59% to 56%, while increasing PV curtailment. This finding aligns with Bunodiere and Lee (2020), who stated that variable renewable energy (VRE) curtailment tends to increase as penetration levels rise [27]. In the GEPP-only scenario, all energy is supplied by the gas engine plant without curtailment, resulting in the highest CF of

64%. These findings indicate that higher PV penetration increases curtailment levels, necessitating appropriate curtailment management and optimized GEPP operational strategies.

3.3 *Fuel Consumption Analysis*

Fuel consumption of the GEPP is calculated based on the engine heat rate and power output. The Alor GEPP is planned to operate using compressed natural gas (CNG) starting in 2026.

$$\sum \text{Fuel Consumption}_{\ (t1\ -\ t20)} = \frac{GPHR}{LHV}\ x\ Energy\ Production_{(t1\ -\ t20)} \tag{8}$$

$$\sum \text{Fuel Cost}_{\ (t1\ -\ t20)} = \text{Fuel Consumption}_{\ (t1\ -\ t20)}\ \text{x Fuel Price} \tag{9}$$

The discounted average lifetime fuel cost results are illustrated in Figure 9.

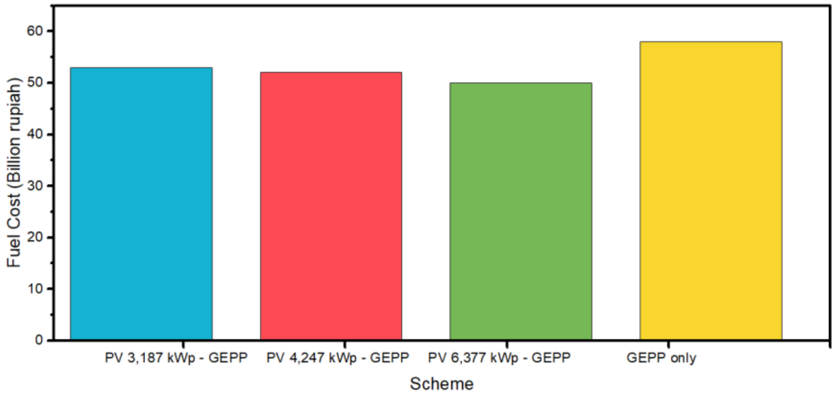

Figure 9. Discounted average fuel cost of proposed system and base case

Simulation results show that the discounted average annual fuel cost for the proposed hybrid system is IDR 53 billion (3,187 kWp), IDR 52 billion (4,247 kWp), and IDR 50 billion (6,377 kWp), compared to IDR 58 billion for the GEPP-only base case. This corresponds to fuel cost savings of 8.62%, 10.34%, and 13.79%, respectively. As shown in Figure 9, while fuel cost consistently decreases with the addition of PV capacity, the reduction rate diminishes at higher penetration levels. Beyond a certain optimum capacity, this diminishing return is driven by a significant increase in PV curtailment, which ultimately leads to an upward trend in the LCOE as the unutilized energy reduces the overall economic efficiency of the system, aligning with the pattern discussed in Figure 8.

3.4 *Project Cost*

The PV capital cost was derived from the EPC cost of a similar 4 MWp utility-scale PV project developed by PT PLN (Persero). The investment costs for the evaluated PV capacities were estimated by proportional scaling based on the installed PV capacity while maintaining consistent unit capital cost assumptions across all scenarios, as summarized in Table 2.

Table 2. Project Cost Assumption

Item	Value	Reference
PV Project Cost	20.740.806 Rp/kWp	PLN Internal Project Feasibility Study (KKP)
GEPP Project Cost	35.957.715 Rp/kW	PLN Internal Project Feasibility Study (KKP)

Figure 10 presents the total capital cost comparison between the hybrid PV–GEPP configurations and the GEPP-only base case. The GEPP-only system requires approximately IDR 360 billion as the baseline investment. With PV integration, the total capital cost increases proportionally with installed capacity. The 3,187 kWp, 4,247 kWp, and 6,377 kWp scenarios require approximately IDR 425 billion, IDR 450 billion, and IDR 490 billion, respectively. The increase is mainly attributed to additional PV modules, inverters, and balance-of-system components, while the GEPP investment remains constant.

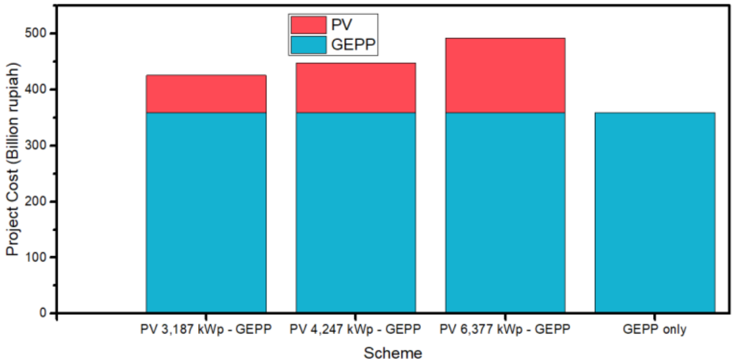

Figure 10. Project cost breakdown

Although the hybrid configurations require higher upfront investment, this additional capital cost is compensated by long-term fuel savings, as reflected in the lifecycle economic performance discussed in the subsequent section.

3.5 *Levelized Cost of Electricity (LCOE) Analysis*

LCOE is calculated by dividing the total project cost over its lifetime by the total net electricity produced (after deducting curtailed energy):

$$LCOE = \frac{NPV\ of\ Total\ Cost}{NPV\ of\ (E_{produced} - E_{curtailed})} \tag{10}$$

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - Io \tag{11}$$

$$IRR = \text{the discount rate } (r) \text{ at which NPV equals zero.} \tag{12}$$

The financial assumptions used in the LCOE, NPV, and IRR calculations are summarized in Table 3.

Table 3. Financial Assumption

No.	Parameter	Value	Reference
1.	Project Lifetime	20 years	KKP PLTMG Alor
2.	Discount rate	9,7 %	RKAP PLN 2025
3.	Inflation	2%	RKAP PLN 2025
4.	O&M Cost GEPP	1.535.711 Rp/kW/year	KKP PLTMG Alor
5.	O&M Cost PV	154.500 Rp/kWp/year	KKP PLTS Alor
6.	USD exchange rate	Rp.15.000	RKAP PLN 2025
7.	CNG cost	15.781 Rp/kg	PLN EPI
8.	LHV Gas	50 MJ/kg	PLN EPI
9.	SFC	0,156 kg/kWh	Engine Alor Data Sheet

3.6 *Economic Performance Results*

In the first year of operation, the hybrid system exhibits a higher cumulative discounted cash flow than the GEPP-only case due to the additional PV capital investment. However, throughout the project lifetime, the hybrid system achieves lower cumulative discounted cash flow than the base case due to fuel cost savings[28].

Over a 20-year project lifetime, the 4,247 kWp PV–GEPP configuration yields the lowest Net Present Cost (NPC) among all simulated scenarios. At year 20, the NPC values for 3,187 kWp, 4,247 kWp, and 6,377 kWp configurations are IDR 1.652 trillion, IDR 1.650 trillion, and IDR 1.661 trillion, respectively, compared to IDR 1.70 trillion for the base case.

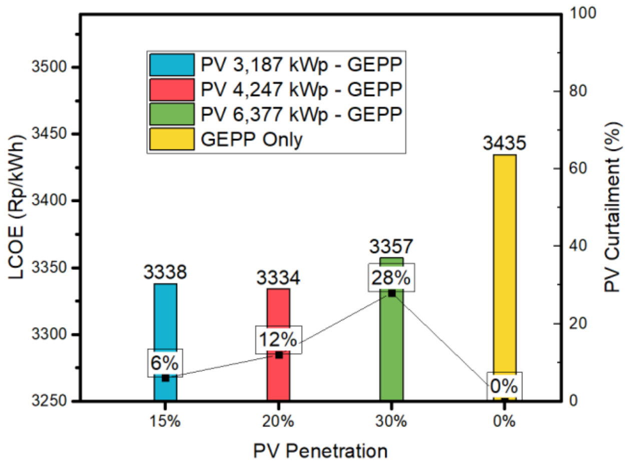

Figure 11. Levelized Cost of Energy (LCOE)

Figure 11 illustrates the variation of LCOE and PV curtailment across different PV penetration scenarios. At 15% penetration, LCOE is IDR 3,338/kWh with 6% curtailment. At 20% penetration, LCOE decreases slightly to IDR 3,334/kWh, while curtailment increases to 12%. At 30% penetration, LCOE rises to IDR 3,357/kWh with a significant increase in curtailment to 28%. These results indicate that PV penetration improves system LCOE up to a certain level. However, excessive penetration leads to higher curtailment, reducing the effective utilization of PV energy and consequently diminishing economic feasibility.

3.7 *Financial Comparison of Proposed and Base Case Systems*

The financial comparison between the hybrid PV–GEPP configurations and the GEPP-only base case, including NPV, IRR, and LCOE, is summarized in Table 4.

Table 4. Financial Analysis

Description	Scenario			
	Hybrid System PV - GEPP			Base Case
	Penetration 15%	Penetration 20%	Penetration 30%	-
	GEPP 10 MW	GEPP 10 MW	GEPP 10 MW	GEPP 10 MW
NPV	131 billion	133 billion	121 billion	83 billion
IRR	11,88%	11,83%	11,58%	11,49%
LCOE (Rp/kWh)	3.338	3.334	3.357	3.435

The financial analysis shows that increasing PV capacity from 3,187 kWp to 4,247 kWp increases the Net Present Value (NPV) from IDR 131 billion to IDR 133 billion, with an Internal Rate of Return (IRR) of 11.83%. At this level, curtailment remains moderate, allowing additional PV energy to generate positive economic value. However, increasing capacity to 6,377 kWp reduces NPV to IDR 121 billion due to significantly higher curtailment. This indicates that part of the PV energy is not effectively monetized, thereby reducing overall economic feasibility despite the larger installed capacity.

4. CONCLUSION

The simulation results indicate that the hybrid PV–GEPP system (proposed system) with PV penetration levels of 15%, 20%, and 30% produces an Alor system LCOE of IDR 3,338/kWh, IDR 3,334/kWh, and IDR 3,357/kWh, respectively. In comparison, the GEPP-only scenario (base case) results in a higher LCOE of IDR 3,435/kWh.

Among the evaluated scenarios, the hybrid system with 20% PV penetration yields the lowest system LCOE. Increasing PV penetration beyond 20% increases the system LCOE due to significant daytime PV curtailment. Excessive PV generation cannot be fully absorbed by the system because of operational constraints, resulting in reduced effective energy utilization.

The 20% PV penetration scenario achieves a lower LCOE than the 15% scenario because the additional renewable energy contribution outweighs the relatively limited curtailment. In contrast, the 30% penetration scenario experiences substantially higher curtailment, which offsets the benefits of further fuel savings. These findings highlight the importance of evaluating renewable energy curtailment together with fuel consumption and system-level LCOE when assessing PV penetration in isolated gas-engine-based power systems without BESS.

This study is limited to a long-term techno-economic assessment based on hourly simulations in HOMER Pro and does not consider transient system dynamics or Battery Energy Storage Systems (BESS). As battery technologies become more cost-competitive, future studies should evaluate whether the integration of BESS can economically reduce PV curtailment and further improve overall system performance.

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