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RESEARCH ARTICLE

Optimization of Economic Dispatch for PV-Diesel Hybrid System: A Comparative Analysis of Operation Strategies in Dulah Laut, Maluku

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Abstract

Eastern Indonesia, including regions like Maluku, has high potential for Renewable Energy Sources (RES), particularly solar energy, with irradiation levels ranging from 4.5 to 5.5 kWh/m²/day. However, limited access to the national electricity grid has led to many remote areas, such as Dulah Laut, Maluku, relying heavily on diesel generators. According to The Dedieselization program in Indonesia, which aims to transition from diesel-powered power plants to renewable energy sources, using a PV-diesel hybrid system is suitable for application in Indonesia's remote areas. This study evaluates four dispatch strategies—Conventional Method, Load Following (LF), Cycle Charging (CC), and Optimal BES Dispatch (OBD)—for a hybrid PV-Diesel-Battery system aimed at optimizing energy use in Dulah Laut, where the load profile exhibits peak load variations under a similar load factor due to predominantly residential consumption. Simulation and techno-economic analysis using Microsoft Excel indicate that the OBD strategy provides high-RES utilization and the lowest Levelized Cost of Electricity (LCOE) (Rp 5825/kWh), making it the most effective solution for energy system optimization in the Dulah Laut region.

Keywords: battery, diesel, economic dispatch, photovoltaic, hybrid system, operation strategy

1. INTRODUCTION

Access to affordable, reliable, sustainable, and modern energy is a key global objective, as reflected in Sustainable Development Goals No. 7. In Indonesia, although significant progress has been made in expanding national electrification, eastern regions such as Maluku still face challenges in energy access, especially in remote and outer islands where the national grid is unavailable or unstable [1]. Many of these areas continue to rely on diesel generator (DG) for electricity supply, resulting in high generation costs, fuel dependency, and environmental concerns.

To address these issues, the Indonesian State Electricity Company, or PT. PLN (Persero) has initiated the Dedieselization program, aiming to reduce thousands of diesel-based power plants in Indonesia's remote areas with cleaner and more sustainable energy systems with Renewable Energy Sources (RES). It is primarily applied by integrating solar photovoltaic (PV) systems with battery storage and hybrid configurations [2]. For example, Eastern Indonesia has high potential solar energy, with irradiation levels ranging from 4.5–5.5 kWh/m^2/day. Then, the hybrid system can combine PV-diesel and Battery Energy Storage (BES). Therefore, the use of RES is increasing and also reducing the conventional energy, such as diesel generation [3]. This transition not only supports national energy policy and climate commitments but also aligns with the Sustainable Development Goals. Research and development on these issues need to be conducted to support and succeed the program.

Figure 1. The location of PV-Diesel system in Dulah Laut, Maluku

Several studies have explored the technical and economic feasibility of hybrid PV-diesel systems, showing promising results in reducing fuel consumption, lowering electricity costs, and increasing the share of renewable energy, especially when combined with BES system and optimized dispatch strategies [4]. Various dispatch strategies have been proposed and evaluated in previous studies to optimize the operation of hybrid PV-Diesel systems. The Conventional method, often used as a baseline where diesel generators operate continuously or without dynamic coordination with renewable sources, has been applied in studies such as in [5], [6] and [7]. These studies rely on fixed generator schedules to meet demand regardless of solar availability. The Load Following (LF) strategy, where DG supplies only the residual load after renewable energy is prioritized, has shown high renewable utilization potential. Reference[8] reported 85.6% PV penetration using LF dispatch strategy. Reference [9] documented significant cost and emission savings under LF control. Both the conventional method and LF don't operate the DG to charge the battery.

Other strategies were also conducted to develop more efficient and optimal system. They operate DG to supply the load and charge the battery. The Cycle Charging (CC) strategy, which charges the battery whenever the DG is turned on, has been explored in multiple studies. Reference [10] found that CC may be more advantageous in low renewable penetration scenarios or where stable generator runtime is preferred. The Optimal Battery Dispatch (OBD) strategy, recently introduced in [11], enables flexible battery operation based on dynamic load and PV generation, improving overall system efficiency. The study concluded that OBD resulted in the lowest LCOE and high renewable fraction compared to other dispatch strategies. Those can be compared to a system to find the optimum economic dispatch with techno-economic assessment, especially for the hybrid renewable energy storage system [12].

This paper focuses on Dulah Laut, a remote island in Maluku that is primarily served by diesel generation and inhabited by residential energy users. PV-diesel hybrid will be installed in the following location in Figure 1. The study will use the research strategy in Figure 2. Section II elaborates on dispatch strategies and cost calculation. It compares many strategies within a PV-Diesel-BES hybrid system. A techno-economic analysis is calculated using Microsoft Excel, considering real load profiles and peak variation patterns. Section III will present the simulation and the research results, including energy produced, operational pattern, and calculation results. Section IV is the discussion, which includes the analysis. The results are intended to identify the most efficient strategy in terms of RES utilization and costeffectiveness, contributing to ongoing efforts to accelerate the energy transition in eastern Indonesia. The last part, Section V, is the conclusion of the research.

2. Dispatch Power Strategy And Cost Calculation

The available charge power (P_c) and discharge power (P_d) of the Battery Energy Storage (BES) system depend on its State-of-Charge (SoC). The SoC at a specific time (Q_t) is the ratio between the current energy stored in the battery ($E_{t\,(bat)}$) and its maximum capacity ($E_{(bat)}$) expressed in (1).

$$Q_t = \frac{E_{t(bat)}}{E_{(bat)}} x100\% \tag{1}$$

The discharge capacity also considers the C-rate, defined as the rate at which the battery is charged or discharged in one hour relative to its capacity. Additionally, a minimum SoC is enforced to avoid deep discharge that can shorten battery life. The hybrid power system includes a diesel generator (DG), photovoltaic (PV) generator, and battery energy storage (BES). Each component is dispatched based on the remain-

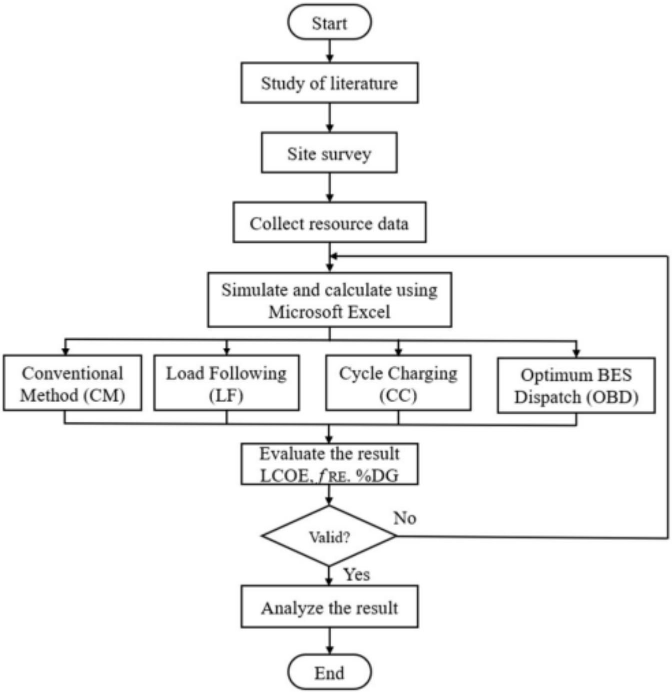


Figure 2. The research flowchart of comparative analysis

ing net load (P_{net}), which is computed after PV generation has been considered in (2) and (3).

$$P_{net} = P_{req} - P^{*}_{pv} \tag{2}$$

$$P^{*}_{pv} = Ef_{inv} \cdot P_{pv,dc} \tag{3}$$

Where P_{req} is the total load demand, P_{pv} is the effective PV output, and Efinv is the efficiency of inverter. If $P_{net} = 0$, the load is fully supplied by PV. If $P_{net} < 0$, the excess PV can charge the battery. If $P_{net} > 0$, the battery or generator must cover the deficit. The BES power setpoint P_{bat} is determined by the residual power P_{net} and SoC limits.

$$P_{bat} = \begin{cases} 0\ , if P_{net} = 0 \\ \\ -minP_{d}, if P_{net} > 0 \\ +minP_{c}, if P_{net} < 0 \end{cases} \tag{4}$$

Positive $P_{(bat)}$ indicates battery charging and receives charging power ($P_{c(bat)}$), while negative indicates discharging and supply using discharging power ($P_{d(bat)}$). The generator's dispatch setpoint ($P*_{gen}$) is calculated based on unmet load and required battery charging power in (5).

$$P^{*}_{gen} = min\left(P_{G,rate,}\left(P_{net} + \frac{P_c}{Ef_{inv}}\right)\right) \tag{5}$$

Where $P*_{gen}$ is the rated power of the diesel generator. This ensures that the generator does not exceed its maximum capacity. At each dispatch step, the unmet load (P_u) is calculated based on which source is dispatched first.

$$P_u = \begin{cases} P_{net} - P_{bat} & \textit{if BES is dispatched first} \\ P_{net} - P^{*}_{gen} & \textit{if DG is dispatched first} \\ P_{net} - P_{bat} + P^{*}_{gen} & \textit{if both BES and DG are dispatch first} \end{cases} \tag{6}$$

To evaluate the performance of each dispatch strategy, we use cost parameters, such as Renewable Energy Fraction (f_{RE}), Net Present Cost (*NPC*), and Levelized Cost of Energy (*LCOE*).

$$f_{RE} = \left(I - \frac{E_{nonRE}}{E_{served}}\right) x100\% \tag{7}$$

$$NPC = \frac{C_{ann,total}}{CRF_{(i,n)}} \tag{8}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{9}$$

Where C_t is the capital cost, O_t is the fixed O&M cost, V_t is variable operating cost and E_t is energy delivered. These are calculated in from year t until total operation year n. Real discount rate i is also considered to find cost calculation result. It is influenced by nominal discount rate i' and inflation rate f. The Capital Recorvery Factor (*CRF*) can be calculated using this formula.

$$CRF_{(i,N)} = \frac{i(1+1)^N}{i(1+i)^N - 1} \tag{10}$$

$$i = \frac{i - f}{i' + f} \tag{11}$$

Since the energy produced from each generation can be different from each dispatch strategy. The literatures show relevant strategies that are generally used in PV-diesel hybrid systems. These are used to compare which strategy can be optimally applied.

2.1 Conventional Method (CM)

This method uses time management and scheduling priority for the operating system. It divides PV and diesel percentage according to P_{load} in 24 hours. Since the PV is an intermittent source and adaptive to the condition, the diesel generator can firstly manage with time schedule. While the other schedule uses PV energy with BES. The recommendation portion in [13] is 50– 70% for PV. Consequently, the portion for the diesel generator is 30–50% of the load profile. The diesel generator will be scheduled to operate during the load peak and adaptively operate when $P_{net} > 0$ to supply the load without changing the battery. Identifying the load profile is mandatory for arranging time schedules for diesel operation and calculating the prediction of each PV and diesel portion to supply the system.

2.2 Load Following (LF)

This strategy prioritizes renewable energy sources, mainly PV, to meet the load demand. The DG only operates when the PV and BES cannot fulfill the load or $P_{net} > 0$ condition. Importantly, the generator is not used to charge the battery, and battery charging only occurs using excess PV energy [11] . Discharging of the BES is allowed when it is more economical than operating the DG, provided that *SoC* exceeds the minimum level. This strategy is generally efficient when daytime PV production exceeds the load, but it may result in suboptimal battery utilization and lower DG efficiency, especially if the DG must run at low load simultaneously with battery discharge. Compared to the CM, this strategy doesn't use time-scheduled operating for DG. Therefore, PV, DG, and BES can operate adaptively.

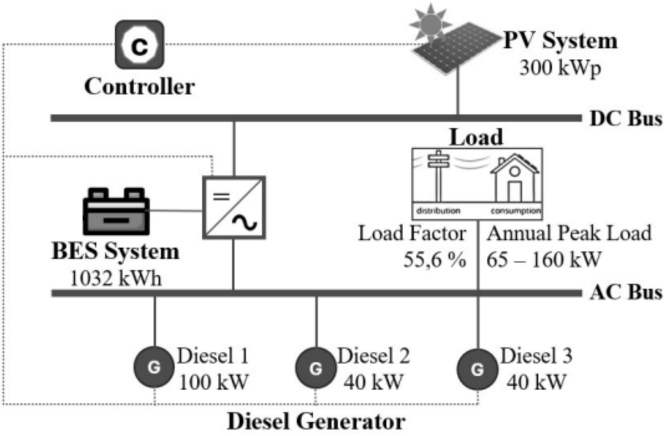


Figure 3. Configuration of the hybrid power generation system in Dulah Laut

2.3 Cycle Charging (CC)

In the Cycle Charging (CC) strategy, the DG operates not only to supply the P_u but also to simultaneously charge the battery. Once the DG starts, it will continue running until the BES reaches a predetermined SoC setpoint [11]. The BES is only discharged when it was previously discharging or reaches the maximum SoC. This strategy ensures high DG load and efficient operation, but can lead to overcharging, leaving no room to store excess PV generation. As a result, CC may cause energy curtailment and underutilization of renewable energy, particularly during sunny periods.

2.4 The Optimal BES Dispatch (OBD)

This strategy was proposed to overcome the limitations of LF and CC. In this method, the BES is discharged whenever its available power exceeds the net load ($P_D > P_{net}$), allowing it to actively support the system rather than waiting for SoC or previous discharge conditions [11]. Meanwhile, every time the DG is turned on to supply the load, it also charges the battery, enhancing DG efficiency by ensuring it operates in its optimal load range. The strategy avoids BES idling, minimizing wasted PV energy.

3. Simulation And Results

The simulation uses a hybrid power generation system that is shown in Figure 3 that uses AC coupling system strategy [14]. The system data was obtained by observing from [15]. The proposed system will be installed in Dulah Laut, Maluku, and completely simulated using Microsoft Excel with four different dispatch strategies. The profile of average solar irradiance in Dulah Laut is provided from [15] and shown in Figure 4. The detailed irradiance will be adapted from [15] and adjusted according to the weather in Maluku. The system has a load profile that is shown in Figure 5, and the load factor is 55.6%. For the simulation, it will calculate until 20 years (2026–2045) based on the assumption in Table 1. Since the prediction from [15] stated that the system has an increasing peak load of 5 kW/year from 65 kW in the first year, the simulation will consider the variation of peak load until 160 kW in the 20^{th} year. Another term is considering the similar load factor due to predominantly residential consumption. All energy and other parameters will be monitored using the controller. In this simulation, it assumes that the operator can control, manage, and monitor the system using a dispatch strategy.

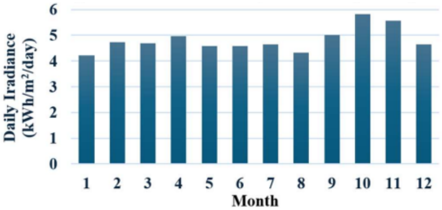


Figure 4. The daily average solar irradiance profile in Dulah Laut

The calculation also uses the equipment specifications. The system has three DGs with a single unit of 100 kW capacity (Diesel 1) and two units of 40 kW capacity (Diesel 2 and Diesel 3). They had specific fuel consumption (SFC) base and were defined as 0.255 l/kWh for Diesel 1, 0.271 l/kWh for Diesel 2, and 0.316 l/kWh for Diesel 3. The DGs may operate at 80% capacity. These technical constraints can impact on CM strategy for time scheduling DG operation. Therefore, it has a schedule for 6 hours around peak load time. Since the peak load occurs during the evening, it can be operated during the time after PV produces energy. While DG priority is figured out in Figure 5 after considering the capacity of the DG and the adaptation to the load profile variations. Diesel 1 becomes the primary priority because of its higher capacity and efficiency compared with the other DG units.

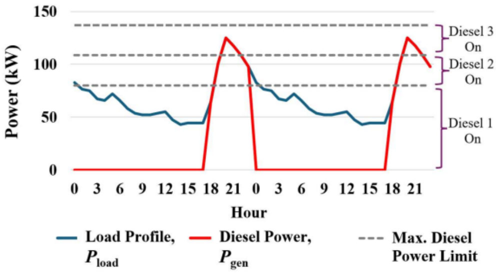


Figure 5. The load profile in Dulah Laut and the CM schedule for DG operation

The PV system has a capacity of 300 kWp and is connected to the DC bus. It serves as the primary renewable energy source, delivering electricity during daylight hours. The BES has an energy capacity of 1032 kWh. It consists of 8 units of a 129 kWh battery. It has 100 kW of a maximum charging and discharging power. It plays a crucial role in storing surplus PV energy and supplying power during periods of high demand or low solar availability. The battery has 5% degradation per year. The BES is interfaced with the AC bus through a bidirectional inverter. This configuration enables flexible energy management, where renewable penetration can be maximized while maintaining supply security through dispatchable DG and BES support.

Table 1. Economic Assumption

Parameter	Value
Discount Rate	9.24 %
Inflation Rate	3 %
Capital Cost	Rp 4.200.000.000
Project lifetime	20 years
PV lifetime	20 years
BES lifetime	10 years
HSD price	Rp 9518/liter

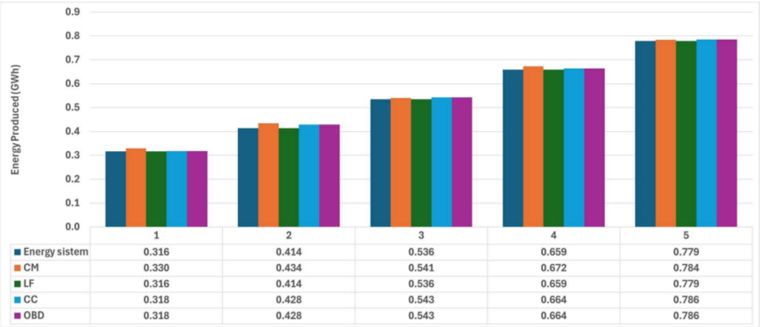
The results of the simulation are shown to validate the best strategy for the economic dispatch in the system. Each strategy will produce calculated energy that will be supplied to the load. Figure 6 presents the total energy production of the hybrid system over a 20-year lifetime under four different operational strategies. All strategies exhibit a steady increase in energy production, indicating the system's adaptability and resilience over time. By the 20^{th} year, all strategies converge at around 0.75 GWh annually, with minor variations. The OBD and LF strategies consistently yield slightly higher energy output, suggesting better management of energy dispatch and storage. Table 2 presents a summary of key performance indicators, including LCOE, renewable fraction (fRE), and DG. The LF strategy yields the LCOE as Rp 5900/kWh, while the CC strategy records the highest (Rp 6350/kWh). Regarding renewable integration, LF and OBD achieve higher renewable fractions (59.59% and

57.24%, respectively), suggesting that these strategies better utilize PV energy while reducing reliance on diesel.

The operational hours of the three diesel generators under each strategy are also included in Table 2. The LF strategy requires the longest diesel operation, especially for Diesel 1, which operates over 80,000 hours throughout the project lifespan. Conversely, the OBD strategy reduces generator usage significantly, suggesting better BES utilization and lower fuel consumption. While, CM strategy has a long operational period due to time scheduling operations and adaptive operations following PV and SoC Battery variation. The operation patterns are shown in detail in Figure 7 and Figure 8 for further analysis in the discussion section. The samples of the pattern are taken from different times. So that the SoC shown starts from the different condition due to the continuity of BES usage.

Table 2. Summary Result

Parameter	CM	LF	CC	OBD
LCOE (Rp/kWh)	6043	5900	6350	5825
f_{RE} (%)	52.27	59.59	43.15	57.24
DG (%)	47.73	40.41	56.85	42.76
Total DG operational time				
Diesel 1 (h)	70489	80881	62357	45224
Diesel 2 (h)	30061	18021	29407	23324
Diesel 3 (h)	14201	4949	14245	14245



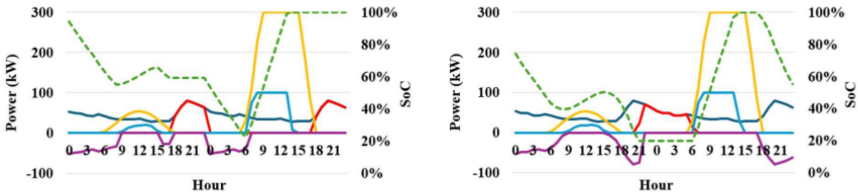
	1	2	3	4	5
■ Energy sistem	0.316	0.414	0.536	0.659	0.779
■ CM	0.330	0.434	0.541	0.672	0.784
■ LF	0.316	0.414	0.536	0.659	0.779
■ CC	0.318	0.428	0.543	0.664	0.786
■ OBD	0.318	0.428	0.543	0.664	0.786

Figure 6. The calculation result of the energy produced in each dispatch strategy

4. Discussion

After calculating based on the simulation results and the system configuration illustrated in Figure 2, the hybrid PV–Diesel–Battery Energy Storage (BES) system, with a 300 kWp PV capacity, three diesel generators (100 kW, 40 kW, and 40 kW), and a BES of 1032 kWh, exhibits distinctive operational performance across various dispatch strategies.

The CM represents the baseline scenario, where DG follows a predefined operation schedule independent of real-time load or battery state. This approach results in rigid operation patterns, often leading to inefficiencies. As shown in the simulation, CM yields the highest total energy generation (11.4 GWh over 20 years), but this comes at the cost of excessive diesel runtime and high fuel consumption. Consequently, the *LCOE* is elevated, and the f_{RE} remains low due to the minimal integration of PV and BES. Furthermore, the fixed schedule leads to a lack of supplyevents during the highest peak demand periods when the SoC is low and the diesel output is insufficient.



(a) Conventional Method

(b) Load Following (LF)

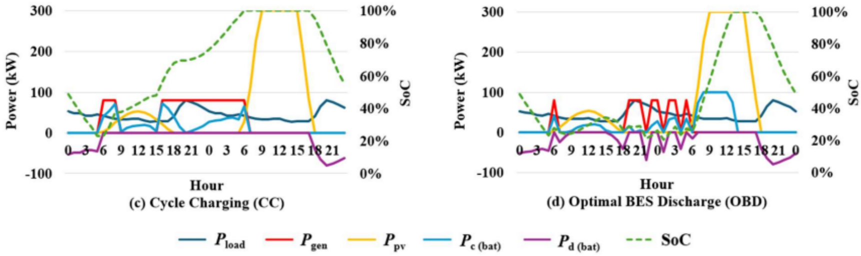


Figure 7. The system operation pattern in Mei 2029 (80 kW peak load) condition in four different dispatch strategies

While this strategy guarantees DG at regular intervals, it lacks responsiveness to actual load and battery *SoC* conditions. As a result, several lack of supply period were observed, particularly during periods of high evening demand when the load exceeded the available DG and the battery *SoC* had dropped below its minimum threshold. Since the DG units are not dispatched based on real-time conditions, the system occasionally fails to supply enough power, despite having surplus energy at other times of the day. This highlights a critical flaw in fixed-schedule dispatching, especially for systems with intermittent renewable sources and variable loads.

The LF strategy improves upon CM by dynamically operating DGs only when the load exceeds what can be met by PV and BES. This reduces unnecessary generator runtime and prioritizes renewable energy usage. The simulation shows that LF achieves a higher f_{RE}(approximately 59.6%) and a lower *LCOE* than CM. However, due to the absence of predictive SoC management, LF occasionally suffers from supply shortages, especially during evening on high peak load operations when the BES is depleted and diesel generators are not yet activated. Additionally, Diesel 1 operates for over 80,000 hours, raising concerns regarding maintenance frequency and operational use. Although LF improves DG efficiency by operating only when necessary, it introduces a trade-off in reliability. The strategy occasionally results in a temporary lack of supply, particularly during early evening hours when solar output drops sharply and the battery is already partially or fully discharged. Since DGs are only triggered when demand exceeds current supply, there is a lag in system response, especially when the battery's SoC is too low to meet the sudden demand surge or highest peak load. This issue is exacerbated in systems without predictive load management or advanced SoC forecasting.

Moreover, during extended cloudy days, the PV contribution declines, and LF may delay DG activation until the load gap becomes critical. This reactive behavior contrasts with preemptive charging seen in CC or SoC-optimized dispatch in OBD, emphasizing the need for anticipatory control strategies in hybrid systems.

The CC strategy prioritizes BES charging whenever diesel generators are running, ensuring that excess DG capacity is utilized efficiently. This approach reduces DG start-stop cycles and stabilizes battery SoC. However, the strategy results in higher DG fuel consumption due to prolonged generator operation even when the load is relatively low. As a result, the LCOE becomes the highest among all strategies, and the fRE is reduced, as DG becomes the dominant supply. Despite these drawbacks, CC effectively eliminates the lack of supply events, indicating improved supply reliability at the expense of economic and environmental performance.

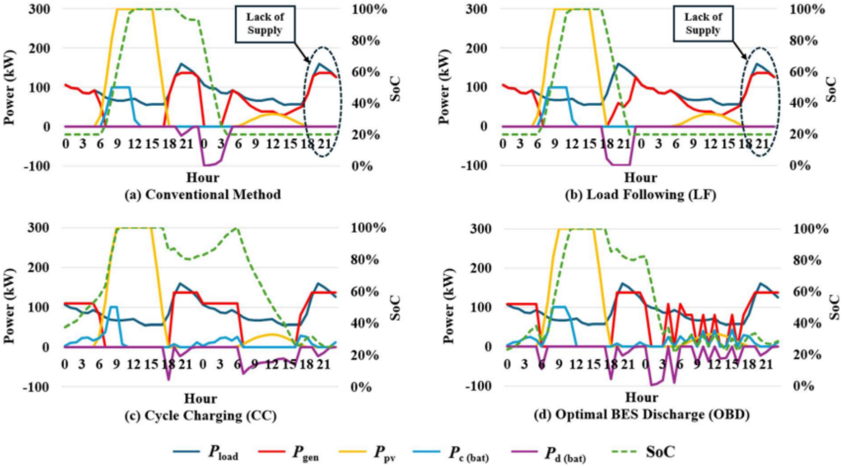


Figure 8. The system operation pattern in October 2045 (160 kW peak load) condition in four different dispatch strategies

The OBD strategy introduces an intelligent dispatch algorithm that prioritizes battery discharging over generator activation, unless the battery is insufficient to meet demand. This method allows the system to maximize PV utilization during the day and optimize batterydischarge during the night, significantly minimizing diesel operation. The results show that OBD achieves the lowest LCOE (Rp 5825/kWh) and highest operational efficiency, while also eliminating any lack of supply scenarios. DG runtime is optimally distributed, reducing wear and maintenance needs. Furthermore, OBD maintains SoC within safe thresholds, ensuring system resilience and sustainability in long-term operation.

From this comparative analysis, it becomes clear that the evolution from rigid to intelligent dispatch strategies brings significant improvements in system performance. The CM and CC methods are associated with higher fuel use and cost, while LF and OBD strategies enable higher integration of renewable energy. Among all, OBD proves to be the most balancedstrategy, excelling in both technical reliability and economic viability. This underscores the critical role of optimization-based energy management in the design and operation of modern hybrid renewable energy systems, particularly in off-grid or remote applications.

5. Conclusion

This paper investigates how dispatch strategies influence different results. This study compared four dispatch strategies—CM, LF, CC, and OBD—for a PV–Diesel hybrid system. The results show that while CM and CC provide system stability, they incur high fuel costs and low renewable utilization. LF improves efficiency but suffers from supply interruptions. The OBD strategy offers the best balance, achieving the lowest LCOE (Rp 5825/kWh), high fRE (57.24%), and eliminating lack of supply events through adaptive BES and DG management control. Thus, optimized dispatch plays a key role in enhancing both economic and technical performance of hybrid systems. In the configuration system of Dulah Laut location, the OBD dispatch strategy is the best and the most suitable to be applied.

Future work may explore integrating load forecasting, real-time control, and additional renewable sources that found in different areas. Applying stochastic or AI-based optimization could further improve adaptability and system resilience under uncertainty.

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