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Optimal Battery Energy Storage Dispatch Strategy for Small-Scale Isolated Hybrid Renewable Energy System with Different Load Profile Patterns

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Abstract: Most inhabited islands in Indonesia are powered by expensively known diesel generators and isolated from the primary grid due to either geographical or economic reasons. Meanwhile, the diesel generator can be combined with a photovoltaic (PV) system and Battery Energy Storage (BES) system to form a hybrid power generation system to reduce the energy cost and increase renewable energy penetration. For this, proper sizing of each power generation component is required, one of which is influenced by the applied control strategy. This paper proposes an optimal BES dispatch (OBD) control strategy that optimizes the power generation components' sizing. The method examines the shortcomings of the other popular control strategies, such as load following, cycle charging, or combination. The optimization objectives are to minimize the Levelized Cost of Energy (LCOE) and maximize the renewable energy (RE) penetration, which can be achieved by prioritizing the BES to supply the load over other available generations and charge the BES every time the generator operates. The proposed method is implemented at two different systems with different load profiles. As a result, the proposed control strategy provides lower LCOE while maintaining higher RE penetration than the other control strategies in both locations.

Keywords: photovoltaic (PV); battery energy storage (BES); hybrid power generation; load following (LF); cycle charging (CC); combined dispatch (CD); optimal BES discharge (OBD); isolated grid



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1. Introduction

Indonesia's geographical condition has limited electricity provision through the interconnected power grid in many locations. Thus, these isolated locations are mostly powered by diesel generators, which are known to be costly and not environmentally friendly [1–3]. Indonesia's energy cost is endorsed by the Ministerial Decree of the Ministry of Energy and Mineral Resources (MEMR) No. 55K/20/MEM/2019. It is known that in most small systems, the cost of energy is still above 0.2 \$/kWh [4] due to the utilization of diesel-fueled power generation. The CO₂ emission of a diesel generator is between 2.4–2.8 kg CO₂/L depending on the characteristics of both the engine and the fuel [5]. The average specific fuel consumption of a diesel generator is 0.33 L/kWh, so the CO₂ emission generated by a diesel generator is estimated to be 0.8–0.93 kg CO₂/kWh.

On the other hand, the Government of Indonesia (GoI) has committed to participating in the Paris Agreement to hold the global temperature rise below 2 °C and endeavor to limit it to a maximum of 1.5 °C [6]. This commitment is implemented through the issuance of Nationally Determined Contribution (NDC), which states that Indonesia will reduce the greenhouse gas emissions by 29% from business as usual on their own, which is detailed as the reduction of 314–398 Tons of CO₂ emission from the energy sector in 2030 [7]. Indonesia has targeted a renewable energy mix of 23% of the primary energy in 2025 and exceeds 31% of the primary energy by 2050 [8,9].

For this reason, it is advantageous to deploy renewable energy (RE)-based power generation in these remote locations. In addition to reducing CO₂ emission to meet the NDC target, increasing RE penetration is also expected to reduce energy costs. However, this benefit can only be obtained through appropriate planning since the implementation of REs in remote locations may require a considerable investment. Thus, RE potentials in those locations must be optimized to decrease the Levelized Cost of Energy (LCOE).

Lately, one of the massively applied REs in many countries is solar energy through photovoltaic (PV) systems, including in Indonesia. Indonesia's archipelago is exposed to sunlight throughout the year without exception, where the solar energy potential in Indonesia may reach 6 kWh/m²/day [10]. Besides, the capital investment cost for PV system installation has been significantly decreased in the past ten years [11]. Therefore, the implementation of PV systems is considered feasible to develop in Indonesia and achieve the RE mix target, as previously mentioned. Furthermore, PV systems can be combined with battery energy storage (BES) systems to supplement the existing diesel generators in an isolated area, forming a hybrid power generation. By applying a proper control algorithm to determine the optimal sizing of PV and BES systems and the dispatch strategy for each generator, the operation of hybrid power generation is proven to improve the system performance while minimizing the system cost [12]. It should be noted that the control algorithm must be suitable for the characteristics of the load in the designated location to obtain the most optimal configuration of a hybrid power generation. One control algorithm that results in good output in one isolated system may not be fitted if applied in another system.

Many works in the literature have studied the methodologies for sizing hybrid power generation in accordance with the application of different dispatch control strategies. Particularly, some of these studies applied HOMER (Hybrid Optimization of Multiple Energy Resources) to design the Hybrid Renewable Energy Resources (HRES) with optimal configuration and operation [13]. HOMER software was developed by the National Renewable Energy Laboratory (NREL) and endorsed by Underwriters Laboratories (UL) [14]. Bahramara et al. compiled studies on the optimal planning of HRES that used HOMER to obtain the most optimal sizing of HRES components in various locations [15]. They concluded that HOMER had been used mostly in developing countries, primarily to design the HRES in rural or remote areas. Some advantages of HOMER are the wide range of loads, multiple dispatchable and non-dispatchable energy resources, and a feature to apply the user's control strategy.

In HOMER, there are several options of dispatch strategy for an HRES, such as cycle charging, load following, generator order, combined dispatch, predictive dispatch, and user's own control strategy that can be developed through MATLAB Link feature. In [16], a cycle charging (CC) strategy was applied for an off-grid hybrid energy system in Iraq, consisting of diesel, hydropower, and a combined PV and BES system. Besides, Oladigbolu et al. used a load following (LF) control strategy to analyze the feasibility of HRES compared with a standalone diesel generator for a case in a remote area in Nigeria [17]. LF and CC control strategies are the two most used strategies, where the comparison and the combination of both strategies have been studied. In [18], the authors presented research for a case study in Eastern Indonesia by comparing strategies to design an HRES in a relatively high load factor system. They applied a sensitivity analysis on battery state of charge (SoC) and the fuel price, concluding that the CC control strategy was more suitable for such a system. A combined dispatch (CD) strategy of cycle charging and load following was used in the research presented by Aziz et al. [19]. The result indicated that the CD control strategy provided better system performance and a lower energy cost.

Meanwhile, Nurunnabi et al. studied the operation of HRES consisting of PV and wind power generation in grid-connected and off-grid mode, which was implemented in five regions in Bangladesh [20]. It was observed that each region had a different optimal configuration of HRES depending on the site-specific characteristics. Moreover, even

though the specific control strategy was not evident in this literature, there is an opportunity to improve the HRES performance by applying the site-specific control algorithm.

Other studies developed their dispatch strategies using other simulation tools. Torreglosa et al. proposed a simulated model predictive control (MPC)-based dispatch strategy for long-term application (25 years) using MATLAB [21]. This control strategy was verified to achieve a higher global efficiency of the HRES and ensure the off-grid load support and maintain the components parameters within the desired operating limits. Meanwhile, Velasquez et al. presented another dispatch strategy combining the concept of distributed MPC and dual decomposition, which was feasible for a short-term application and proven to provide better anticipation to the changes of the system [22]. Furthermore, Jung and Vilaran presented a Distributed Energy Resources—Customer Adoption Model (DER-CAM) technique, which was used to determine the size, type, and dispatch schedule of the distributed energy resources [23]. It was shown that the proposed technique was capable of increasing the effectiveness of RE penetration. These studies with each self-developed method have been proven to improve the performance of each system with certain benefits. Likewise, in HOMER, several control strategies aim to enhance other classic strategies, such as CD, which has the advantages of LF and CC.

For the LF control strategy, RES is prioritized to supply the load whenever the primary source is available, and the dispatchable energy sources such as a diesel generator will generate power only when RES output does not satisfy the demand. However, as the excess power produced by RES charges the BES, there might be a condition where the BES state of charge (SoC) is empty, such as during the low generation of RES. If this happens for a long duration and is repeated, it may degrade the BES lifetime. Besides, the BES is also allowed to discharge energy while the diesel generator is supplying the load. This operating condition may cause the diesel generator to run at low power, resulting in low operating efficiency.

Meanwhile, in the CC control strategy, to preserve the diesel generator operating at high efficiency, the diesel generator is run at full capacity, and it will not operate when RES output is high. The BES will be in charging mode when the diesel generator output is higher than the demand. Moreover, the BES is only allowed to start discharging at the specified SoC. Hence, the BES is not optimally used to either supply the load, although it has enough SoC since it has not reached the setpoint yet, or to charge the excess power at the lightly loaded condition, as its SoC is already full.

In the CD control strategy, the CC operation is applied during low net load, and the LF strategy is used for high net load [13,19]. Net load here is defined as the load demand that has been reduced by the RES output available at that time. During low net load, the BES discharges energy to satisfy the demand if its SoC is higher than its setpoint. Otherwise, a diesel generator will take over to supply the load as well as charge the BES. Whereas at high net load, the diesel generator will be run to only supply the load once the BES energy reaches its minimum SoC after being in discharging mode. Even though the CD control strategy may optimize RES output and operate the dispatchable generator more efficiently, in some cases, it is found that the BES is not optimally charged and discharged. For instance, in [24–26], the BES was left at its minimum SoC for several hours during high net load. Besides, in some particular conditions, the BES is not allowed to discharge energy although it has enough SoC, particularly during low net load. Another study also performed the CD control strategy for optimizing the HRES operation by minimizing the daily cost [27]. However, this strategy still allowed the BES to be in charging mode when the SoC reaches its maximum value and discharge energy when its SoC is low.

To overcome such drawbacks, in this paper, we developed a modification of the CD control strategy to reduce the LCOE by maximizing BES utilization. This research's contribution lies in the weakness analysis of the commonly used control strategies, such as LF, CC, and their combination or CD. The weakness of each control strategy was then solved to obtain a lower LCOE while maintaining its RE penetration ratio. In this way, we developed an optimized dispatch strategy of BES in HRES by taking advantage of the

BES's lower incremental cost than the diesel generator. The proposed algorithm has the objective of minimizing the LCOE while maintaining the high RE penetration through maximization of BES utilization. It works by optimally avoiding the idle (standby) status of BES. The proposed control strategy was developed by using MATLAB Version 2021a, Mathworks Inc., Natick, MA, USA and integrated into the HOMER Pro Version 3.14.4, HOMER Energy LLC, Boulder, CO, USA. Other HRES control strategies are presented as a comparison accordingly. By doing so, the performance of the proposed method could be appropriately compared with the other control strategies that are already available in HOMER. Furthermore, the proposed method was evaluated at different load profile patterns to investigate its robustness. The validation is performed through HOMER software to obtain uniform and consistent financial calculations for each case.

The remaining of this paper is structured as follows: Section 2 describes the technical and economic calculation, Section 3 elaborates the applicable control strategies (load following, cycle charging, combined dispatch, and optimal BES discharge). Section 4 provides simulation case studies, the results, and the discussion. Lastly, this research is concluded in Section 5.

2. Dispatch Power and Cost Calculation

2.1. BES Available Charge and Discharge Power

The available charge power (P_C) and discharge power (P_D) of a BES depends on its state-of-charge (SoC). SoC of the battery at a specified time (Q_t) is defined as the ratio between the remaining capacity at that time ($E_{bat,t}$) to the maximum capacity (E_{bat}) of the battery [28]. The discharge power of a battery is also affected by the C-rate. It is a measure of the power that can be discharged in one hour relative to the maximum capacity and was assumed to be 1-C in this research. Other than SoC and C-rate, the maximum discharge power also depends on the minimum SoC (Q_{min}) that must be maintained in the battery [29]:

$$Q_t = \frac{E_{bat,t}}{E_{bat}} \times 100\% \quad (1)$$

$$P_C = (1 - Q_t) \frac{E_{bat}}{1 \text{ h}} \quad (2)$$

$$P_D = (Q_t - Q_{min}) \frac{E_{bat}}{1 \text{ h}} \quad (3)$$

where Q_t and Q_{min} are in percentages, E_{bat} is in kWh, P_C and P_D are in kW, respectively.

2.2. Power Dispatch Setpoints

The hybrid power generation system consists of a diesel generator, variable generation of the PV system, and a BES. Each of these power generations is dispatched sequentially to meet the required load depending on the selected dispatch strategy so that the unmet load is equal to zero. First, the PV generated power is dispatched and result in the net required load (P_{net}), as follows:

$$P_{net} = P_{req} - P_{pv}^* \quad (4)$$

$$P_{pv}^* = \eta_{pvinv} P_{pv,dc} \quad (5)$$

where P_{net} is the net required load (kW), P_{req} is the required load (kW), and P_{pv}^* is the PV system setpoint (kW), η_{pvinv} is the PV inverter's efficiency (%), $P_{pv,dc}$ is the DC power generated by the PV array (kW).

The value of the net required load can be zero, negative, or positive. Zero value indicates that the required load can be satisfied precisely by the PV system. A negative value implies that the excess power produced by the PV system, which can be used to charge the battery if the battery SoC is not full. Otherwise, it will be dumped. Meanwhile, the positive value means that there is an unmet load. The unmet load can be supplied either by the BES or the generator, depending on the applied control strategy.

The battery's power setpoint (P_{bat}^*) in kW is determined as follows:

$$P_{bat}^* = \begin{cases} 0 & \text{if } P_{net} = 0 \\ -\min\left(P_D, \frac{P_{net}}{\eta_{binv}}\right) & \text{if } P_{net} > 0 \\ -\min(P_C, \eta_{brec}P_{net}) & \text{if } P_{net} < 0 \end{cases} \quad (6)$$

where η_{binv} and η_{brec} are the efficiency of the battery's inverter and rectifier (%), respectively. P_{bat}^* is negative if the battery is discharged and positive if the battery is charged.

The generator's dispatch power (P_{gen}^*) in kW is determined by the unmet load and the required power to charge the battery (if any) and compared it with the rated power of the generator ($P_{G,rate}$). It can be mathematically set as follows:

$$P_{gen}^* = \min\left(P_{G,rate}, \left(P_{net} + \frac{P_C}{\eta_{brec}}\right)\right) \quad (7)$$

At each step of dispatching the BES or the generator, the unmet load (P_u) can be calculated as follows:

$$P_u = \begin{cases} P_{net} - P_{bat}^* & \text{if BES is dispatched first} \\ P_{net} - P_{gen}^* & \text{if generator is dispatched first} \\ P_{net} - (P_{bat}^* + P_{gen}^*) & \text{if BES \& generator are dispatched} \end{cases} \quad (8)$$

2.3. Component's Marginal Cost

The order of dispatch of the power generation is decided by comparing the hourly marginal cost of energy provided by each generation system. The generation system with the lowest hourly marginal cost of energy is dispatched first and continued by the higher one. BES hourly marginal cost of energy (C_{bat}) in \$/kWh is formulated as follows [30]:

$$C_{bat} = \frac{R_{bat}}{E_{tp}\sqrt{\eta_{rt}}} \quad (9)$$

where R_{bat} is the battery replacement cost (\$), E_{tp} is the battery throughput (kWh), η_{rt} is the battery roundtrip efficiency (%).

On the other hand, the generator's hourly marginal cost of energy (C_{gen}) in \$/kWh can be formulated as follows:

$$C_{gen} = \frac{R_{gen}}{P_0 Y_{life}} + \frac{O_{gen}}{P_0} + \frac{C_f (F_0 P_0 + F_1 P_{gen}^*)}{P_{gen}^*} \quad (10)$$

where R_{gen} is the replacement cost (\$), O_{gen} is the operation and maintenance cost (\$/h), Y_{life} is the generator lifetime (hour), C_f is the fuel cost (\$/L), F_0 is the fuel curve intercept coefficient (L/kWh), F_1 is the fuel curve slope (L/kWh), P_0 is the generator rated power (kW), and P_{gen}^* is the generator dispatch power (kW).

2.4. Financial Model

The optimized configuration of the hybrid energy system is determined by the total net present cost (NPC_{tot}) and the Levelized Cost of Energy (LCOE) [31,32]. The total net present cost (NPC_{tot}) in \$ can be calculated as follows:

$$NPC_{tot} = I_{tot} + \sum_{y=1}^N \left[(1+i)^{-1} \sum_{k=1}^K (M_{y,k}) \right] \quad (11)$$

$$M_{y,k} = \sum_{y=1}^N \left[(1+i)^{-1} \sum_{k=1}^K (R_{y,k} + S_{y,k} + O_{y,k} + C_f F_y) \right] \quad (12)$$

where I_{tot} is the total initial investment for developing the hybrid energy system (\$), $M_{y,k}$ is the total marginal cost in year- y of component- k (\$), $R_{y,k}$, $S_{y,k}$, and $O_{y,k}$ are the replacement, salvage, and operation and maintenance costs in year- y of component- k , respectively, and F_y is the fuel consumption in year- y (\$). i is the real discount factor (%), N is the lifetime (year), and K is the number of components in the hybrid energy system.

Furthermore, the $LCOE$ can be calculated by dividing the annualized cost spent by the hybrid energy system with the total load served by the system. The annualized cost can be calculated in order to obtain the equally annual cost throughout the lifetime [13,33]:

$$LCOE = \frac{C_{ann}}{E_{ann}} \quad (13)$$

$$C_{ann} = \frac{i(1+i)^N}{(1+i)^N - 1} NPC_{tot} \quad (14)$$

$$E_{ann} = \sum_{t=1}^{8760} P_{served,t} \quad (15)$$

where C_{ann} is the annualized cost (\$/year) and E_{ann} is the annual electrical energy served by the system (kWh/year).

3. Control Strategies

3.1. Load Following

A load following (LF) control strategy is used to optimize the utilization of energy produced by RES. LF control strategy will only allow the battery to be charged by the excess power generated by renewable energy such as PV system [18]. It prevents the diesel generator from charging the battery. Hence, the diesel generator only produced the power required to meet the unmet load.

The algorithm of the LF control strategy is presented in Figure 1. The PV is set to supply the required load. If the net required load (P_{net}) is negative, which indicates that there is excess power, then the excess power will be used to charge the battery if the SoC is less than 100% ($P_C > 0$). On the other hand, if the net required load is greater than zero ($P_{net} > 0$), the energy is available in the battery ($P_D > 0$), and the battery energy cost is cheaper than the cost to run the generator without charging the battery ($C_{bat} < C_{gen}$ (at $P_C = 0$)), then BES will be discharged. Otherwise, the generator will be dispatched to satisfy the remaining required load.

Because of the nature of the LF control strategy, it is generally suitable for the system where the PV system's power during the day is normally higher than the load demand during the same period. The LF algorithm works based on the assumption that the diesel generator is needed in the subsequent high load periods. It is unnecessary to utilize the diesel generator to charge the BES at the current time step to reduce the energy cost. However, if, in any cases the generator is still operating at the low loads in the successive periods, then the LF control strategy becomes inefficient [13].

3.2. Cycle Charging

The Cycle Charging (CC) control strategy operates the generator to supply the required and simultaneously charge the battery. It will dispatch the BES to supply the load if the battery can satisfy the load without additional power from the generator. Hence, once the generator starts charging the battery, it will continue to do so until the setpoint SoC is reached.

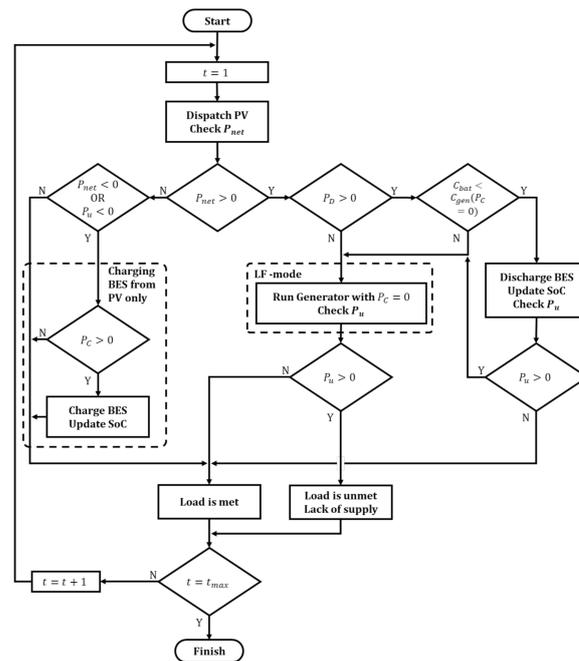


Figure 1. Load Following (LF) control strategy. This strategy does not allow the generator to charge the battery, and BES is discharged every time the SOC is greater than the SOC minimum.

The algorithm of the cycle charging (CC) control strategy is presented in Figure 2. The CC control strategy starts by setting the PV system to supply the required load. The excess power from PV (if any) will be used to charge the battery. However, if the PV cannot meet the required load alone ($P_{net} > 0$), the energy is available in the battery ($P_D > 0$), and the battery energy cost is cheaper than the energy cost of using the generator to supply the unmet load as well as to charge the battery ($C_{bat} < C_{gen}$), then the CC control algorithm will check the two following conditions:

- The battery is discharged in the previous time step ($P_{bat,t-1} < 0$);
- The SoC is higher than the setpoint SoC ($Q_t > Q_{set}$).

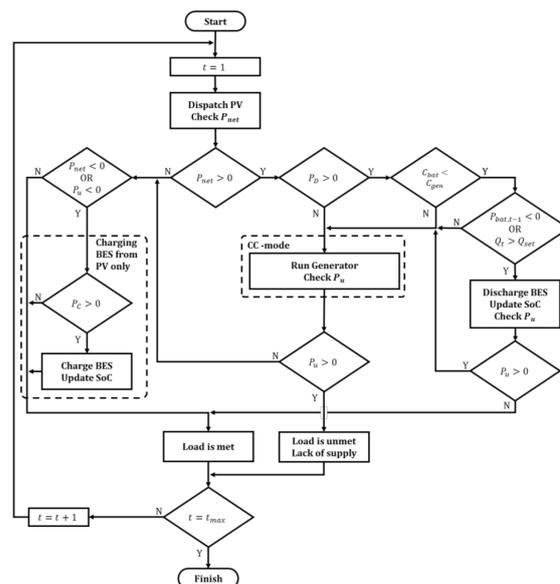


Figure 2. Cycle Charging (CC) control strategy. This strategy tends to store energy in the battery every time generator is operated. BES is only discharged when it reaches maximum SOC or has been discharged in the previous timestep.

If one of these conditions is satisfied, then the battery will be discharged. Otherwise, the controller will avoid discharging the battery at this time step.

The CC control strategy algorithm is suitable to optimize the dispatched power for the system where the power generated by the PV system during the day is lower than the required demand of a similar period. The CC algorithm works based on the assumption that the generator can be turned off in the next time steps where the load is low, and the BES can fulfill the demand, and the energy cost can be reduced. However, if the generator is still required to supply the load in any case, then the CC control strategy becomes inefficient [13].

3.3. Combined Dispatch

The energy cost of the generator operation consists of the fixed cost and variable cost, as described in (13). The variable cost incurred by running the generator depends on the produced power (P_{gen}^*). Due to the generator's no-load fuel consumption and its efficiency, it is more efficient to operate the generator at high load instead of at low load. For instance, the efficiency can be less than 20% when the diesel generator operates at 10% of rated power. In comparison, the efficiency can exceed 30% when the diesel generator operates at higher than 50% of rated power.

The combined dispatch (CD) control strategy is designed to benefit from the efficient operation of the generator. It is developed by combining the LF and CC control strategies, such that it will operate in LF mode when the net required load (P_{net}) is high and in CC mode when the net required load is low. By doing so, the CD controller can minimize the operation of the generator at a low load, which causes lower efficiency. The algorithm of the CD control strategy is provided in Figure 3.

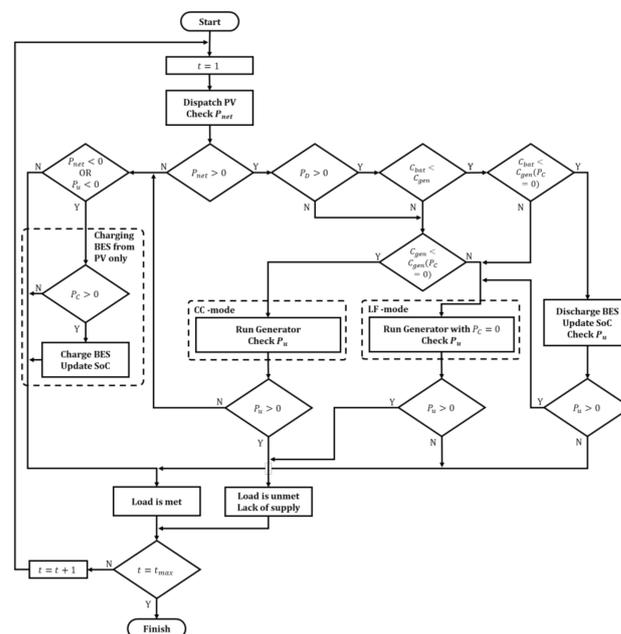


Figure 3. Combined Dispatch (CD) control strategy. The BES is charged using the excess power from the PV system or the generator during the low load period. The BES is discharged if the SOC is at maximum or if it has been discharged in the previous timestep as in CC control strategy, or if the BES can supplement the unmet power of PV system as in LF control strategy.

The CD control strategy will dispatch all of the power generated by the PV system, resulting in net required load (P_{net}). If there is excess power ($P_{net} < 0$), then it will be used to charge the battery. However, if the net required load is greater than zero, then the algorithm will dispatch the BES or the generator through the following considerations:

- BES will be discharged if the stored energy in the battery is available ($P_D > 0$) and the cost of discharging the battery (C_{bat}) is cheaper than the cost of running the generator to supply the load and to charge the battery (C_{gen}) and the cost of running the generator only to supply the load (C_{gen} (at $P_C = 0$));
- The CC mode control strategy will be applied if the cost of running the generator to supply the load and to charge the battery (C_{gen}) is lower than the cost of discharging the battery (C_{bat}) and the cost of running the generator only to supply the load (C_{gen} (at $P_C = 0$));
- The LF mode control strategy will be applied if the cost of running the generator only to supply the load (C_{gen} (at $P_C = 0$)) is cheaper than the cost of discharging the battery (C_{bat}) and the cost of running the generator to supply the load and to charge the battery (C_{gen}). Additionally, the LF mode control strategy is also applied if the BES is discharged but cannot satisfy the net required load.

3.4. Optimized BES Discharge (OBD)

The previous control strategies, such as LF, CC, and CD, were analyzed at the homogeneous system configuration to investigate their vulnerabilities. The operating characteristics at similar load profiles, solar irradiances, and component sizes were examined. The analysis results were then used to develop an enhanced control strategy that deals with the other's weaknesses. First, the LF, CC, and CD control strategies were simulated at the same load profile, solar irradiance, and the components' size (PV System, BES, and diesel generator). The annual operational characteristics, such as the schedule of generator operation and the BES charge/discharge, were analyzed to find the weaknesses. It was found that the existing control strategies sometimes simultaneously operate the generator with the BES, which causes a lower operating efficiency of the generator. Furthermore, it was observed that there was an idle operation of the BES for quite a long period, which caused a higher cost of using storage. In addition, the CC and CD control strategies tended to have the BES in full condition when there is excess power generated by the PV system so that there was wasted energy. The research framework is presented in Figure 4.

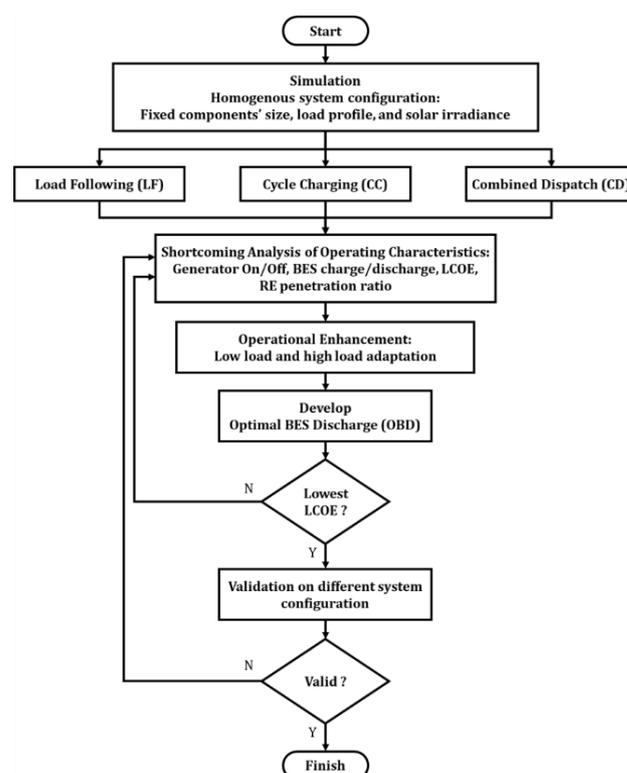


Figure 4. The research framework of the proposed control strategies.

The LF control strategy will only charge the battery by the PV system, so the battery might remain empty or at its minimum SOC during the low irradiance condition, which may occur in quite an extended period. Moreover, the LF control strategy allows the battery to discharge together with the generator, which may cause the generator to operate at low power and low efficiency. Therefore, the BES was not optimally utilized when the LF control strategy was used, as shown in Figure 5.

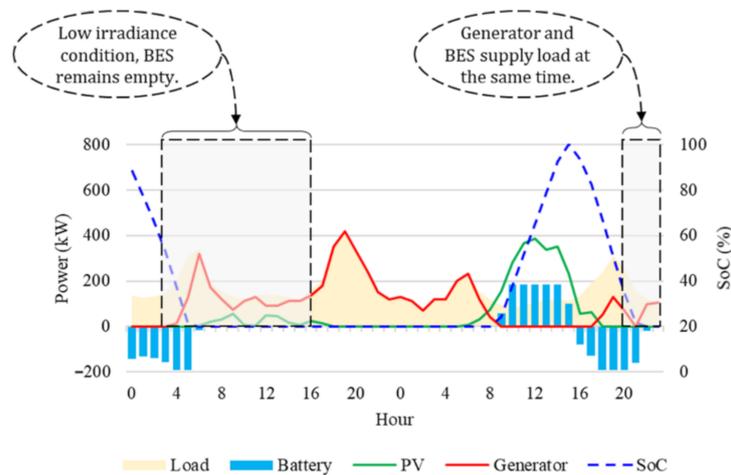


Figure 5. Analysis of LF control strategy implementation was captured on 1 and 2 January. The BES was in minimum SOC for a longer period and ran simultaneously with the generator.

The CC control strategy tended to run the generator continuously to charge the battery until it reaches its SOC setting point once it starts to operate. The battery would only be discharged if discharged in the previous timestep or at maximum SOC. This strategy might result in the condition such as the battery is already fully charged when the PV system generates excess power. Consequently, the battery may remain at maximum SOC for some periods. Hence, the BES was also not optimally utilized when the CC control strategy was applied, as shown in Figure 6.

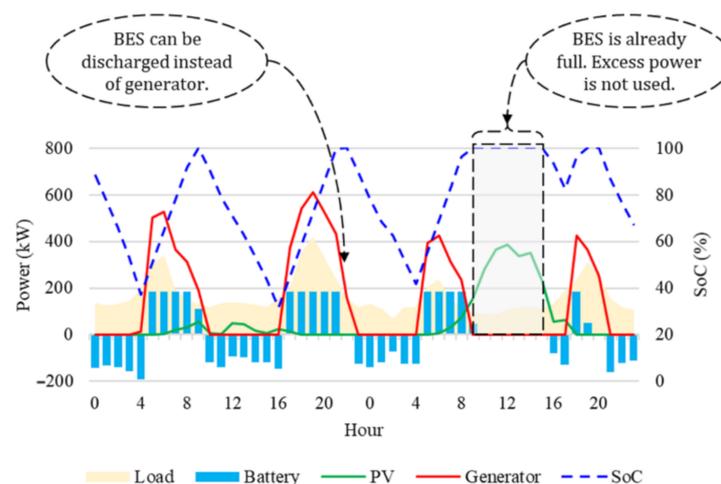


Figure 6. Analysis of CC control strategy implementation was captured on 1 and 2 January. The BES might not be discharged since it had not reached the SOC setpoint, and some excess power from the PV system could not be utilized.

On the other hand, the combination of LF and CC control strategies, the so-called CD control strategy, delivers more efficient results. It was considered the most optimized control strategy [19]. The CD control strategy tends to charge the battery in two conditions: using the excess power from the PV system and using the generator during the low load period. The first one follows the logic of the LF control strategy, while the latter works based on the algorithm of the CC control strategy. This strategy does not use the generator to charge the battery during the high load period simultaneously. The CD control strategy commands the BES discharging when the BES's SOC is at maximum setpoint, or the BES has been discharged in the previous timestep (as in the CC control strategy), or the BES can supplement the unmet power generated by the PV system (as in the LF control strategy). The analysis of the CC control strategy operation is illustrated in Figure 7.

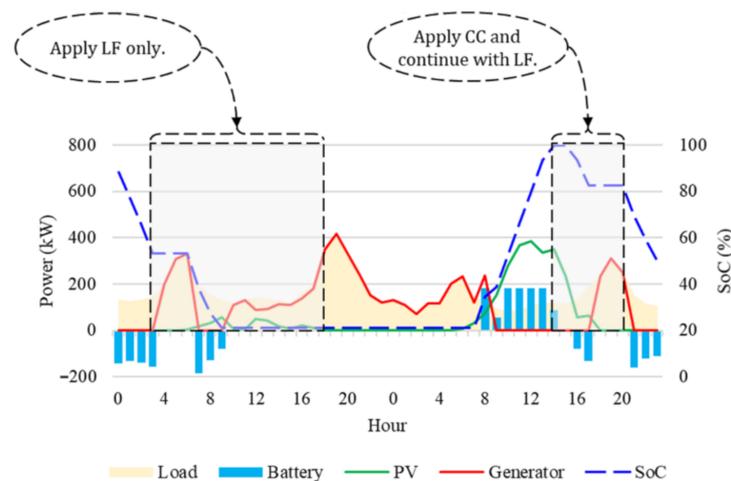


Figure 7. Analysis of CD control strategy implementation was captured on 1 and 2 January. It works as an LF control strategy in the low load period and as a CC control strategy in the high load period.

This paper proposes modifying the CD control strategy, namely Optimal BES Discharge (OBD) control strategy, as presented in Figure 8. OBD control strategy does not decide the BES discharging operation based on the availability of the stored energy, BES's maximum SOC, or charge/discharge status of the previous timestep. The BES discharging operation is determined based on the BES capacity to supply the net required load solely ($P_D > P_{net}$). If the stored energy in BES is greater than the net required load, then the BES will be discharged. The BES can immediately be discharged once its available energy can supply the load. Otherwise, the generator will be operated to supply the load as well as to charge the battery. By doing so, this control strategy can optimize the utilization of the BES. Another benefit obtained from the proposed control strategy is that the generator will consistently operate at a high load and deliver higher operating efficiency. Lastly, the low load period will be satisfied either by the PV system, BES, or both.

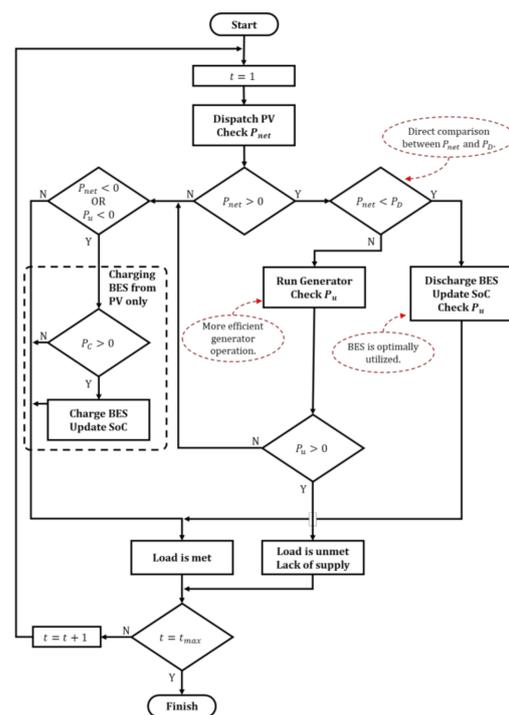


Figure 8. Optimal BES Discharge (OBD) control strategy. The decision to utilize BES is by directly comparing P_{net} to the available BES power (P_D) instead of examining the BES's SOC, such as in other control strategies. The generator is always set to charge the BES every time it operates to supply the load, resulting in a more efficient operation. BES is always ready to be discharged every time it can supply the load alone, resulting in a more optimized utilization.

4. Simulation and Results

4.1. Systems' Profile

We used a two-hybrid power generation system in this paper to validate the proposed predictive dispatch control. The system data used for validation was obtained by observing and summarizing the small-scale isolated grids in Indonesia. Each system had a unique load pattern, daily average energy consumption, peak load, and average load.

System-1 had an average energy consumption of 4000 kWh/day, an annual peak load of 529 kW, and an hourly average load of 167 kW. It was supplied by diesel generators with a total installed capacity of 1000 kW with specific fuel consumption (SFC) defined as $(0.03 + 0.28 P_{gen}^*)$ L/hour. The Levelized Cost of Energy (LCOE) of System-1 was 0.2500 \$/kWh. Meanwhile, System-2 consumed about 5000 kWh/day of energy, 504 kW of annual peak load, and 208 kW of hourly average load. System-2 was fed by a 1200 kW diesel generator with SFC defined as $(0.025 + 0.26 P_{gen}^*)$ L/hour. The LCOE of System-2 was 0.1920 \$/kWh. Table 1 summarizes the data of both systems, and Figure 9 presents their load profiles.

Table 1. Data summary of System-1 and System-2. System-1 had lower energy consumption and hourly average load but higher peak load compared to System-2. System-1 had a lower load factor than System-2.

Description	Unit	System-1	System-2
Energy consumption	kWh/day	4000	5000
Annual peak load	kW	529	504
Hourly average load	kW	167	208
Load Factor	%	32	41
Diesel generator rating	kW	1000	1200
SFC	-	$0.03 + 0.26 P_{gen}^*$	$0.025 + 0.25 P_{gen}^*$
Existing LCOE	\$/kWh	0.2500	0.1920

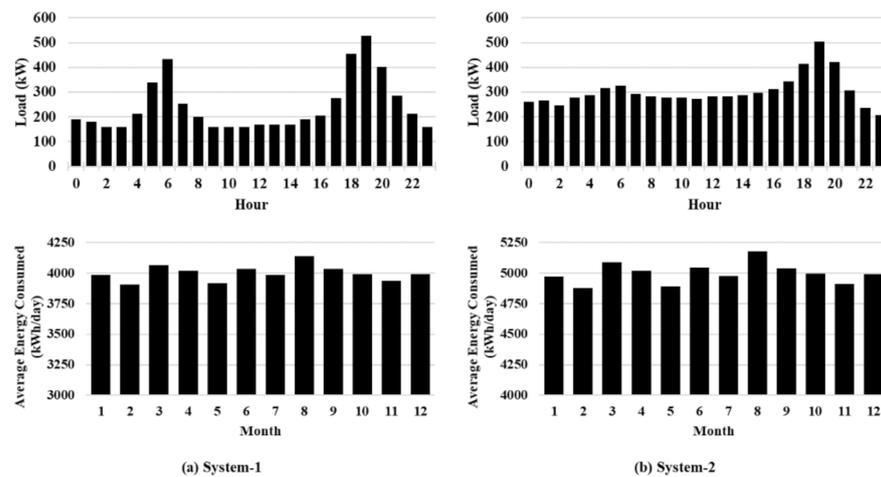


Figure 9. Load profiles of System-1 and System-2. The deviation between peak load and the hourly average load in System-1 was greater than in System-2.

4.2. Hybrid System Configuration and Component’s Unit Cost

The schematic of the hybrid power generation system of both systems is presented in Figure 10. The additional components include the solar PV system and BES system, in which the sizing would be determined through an optimization process in accordance with the applied dispatch control strategy.

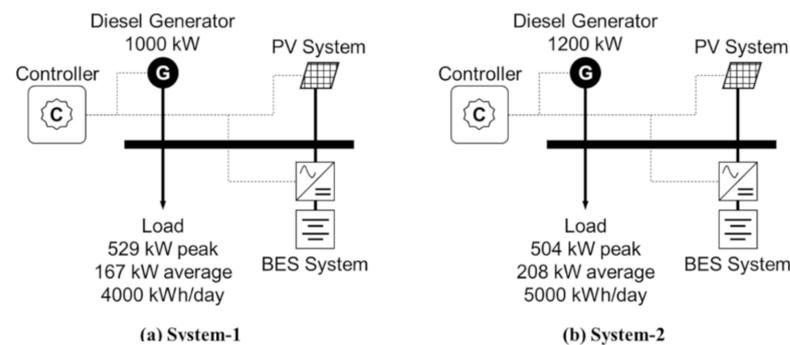


Figure 10. Configuration of the hybrid power generation system. Both systems have typical configurations but with different characteristics. System-1 with a higher peak load had a lower generator capacity than System-2.

The profile of solar irradiance in both locations is provided in Figure 11. The average solar irradiance in the System-1 location was 4.8 kWh/m²/day, and in the System-2 location was 5.6 kWh/m²/day. The maximum energy per day occurred in March (5.17 kWh/m²/day) and in October (6.5 kWh/m²/day) for System-1 and System-2, respectively.

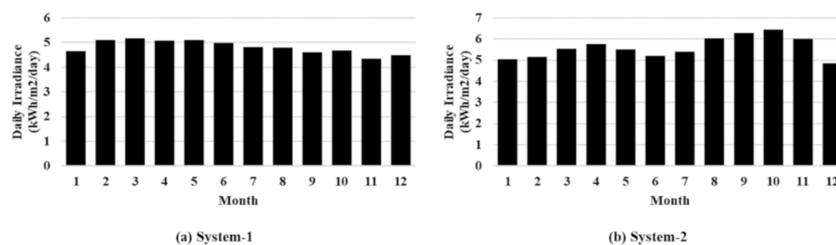


Figure 11. Daily solar irradiance profile. System-1 had peak daily irradiance in March, and System-2 had peak daily irradiance in October.

The costs incurred in the development of solar PV system was estimated based on the previous projects and global trend studied by International Renewable Energy Agency (IRENA) [34]. The investment cost of the solar PV system applied in this paper was \$760/kWp, and the replacement cost was estimated at \$152/kWp. The operation and maintenance cost was assumed to be 1% of the investment cost per year. On the other hand, the investment cost of the BES system included the cost of the battery pack, cost power conversion system, and balance of the system. The total installation cost of the BES system applied in this paper was \$420/kWh [35,36]. The replacement cost of the BES system was associated with the cost of the battery pack, which was estimated to be \$150/kWh [37], and the operation and maintenance cost was assumed to be 1% of the capital cost annually. In addition, the fuel price considered in this study was \$0.5/L, and the operation and maintenance cost of a diesel generator was \$0.005/kWh.

4.3. Simulation Result

The performance of the control strategy is validated through the 25-year of simulation concurrently with the other control strategies to obtain comparable results. The simulations are carried out by using HOMER software. The proposed method was implemented through the MATLAB Link feature, enabling the users to apply their dispatch strategy [13]. HOMER determines the optimized component's sizing through a derivative-free optimization algorithm, which does not require defining an objective function and its derivative [11,38]. Therefore, the sizing optimization results could be acknowledged to be comparable between the control strategies. The optimized sizing results for each type of dispatch algorithm are presented in Table 2. The PV system size required by the OBD control strategy was relatively smaller, being 610 kWp in System-1 and 1081 kWp in System-2. Similarly, the optimized BES capacity obtained by the OBD control strategy was 1273 kWh and 2177 kWh for System-1 and System-2, respectively.

The LCOE of System-1 was \$0.1874/kWh, which could compete only with the CC control strategy (\$0.1914/kWh). However, the ratio of renewable energy by using the OBD control strategy was higher (34.0%) than the CC control strategy (22.4%). Even though the renewable energy fraction in other control strategies, such as LF and CD, was higher than the OBD control strategy (74.7% and 72.6%, respectively), they come with a higher LCOE of \$0.2028/kWh and \$0.1994/kWh, respectively. System-2 results in the LCOE of \$0.1637/kWh if the OBD control strategy was used, which is the lowest among the other control strategies. The renewable energy fraction could also be considered sufficiently high (59.9%), particularly by considering its low LCOE.

The optimal operation of the proposed control strategy could also be evaluated by looking at the ratio of excess electricity. It could be seen that the OBD gave the lowest excess electricity compared to other control strategies in System-1 and second-lowest in System-2. Furthermore, the proposed method was also more robust for a system with different load profile patterns. The OBD control strategy delivered a consistent benefit in terms of the low LCOE, satisfactorily high renewable energy penetration, and low excess electricity (wasted energy) for different load profiles.

The snapshots of the operation pattern for all control strategies are presented in Figure 12 for System-1 (two consecutive days in March) and Figure 13 for System-2 (two consecutive days in September). The OBD control strategies regularly charge the BES by using the generated power from the PV systems or using a generator during the high load period. In contrast, the other control strategies did not charge the battery during the high load period (between 05:00 to 07:00 and between 18:00 to 22:00) in both systems.

Table 2. Optimized Simulation Results. The results compare the PV and BES size, Net Present Cost (NPC), LCOE, renewable fraction, and excess electricity between the control strategies applied in System-1 and System-2.

Parameter	Control Strategy	System-1	System-2
PV system size (kWp)	LF	1234	1405
	CC	550	966
	CD	1268	1396
	OBD	610	1081
BES system size (kWh)	LF	2981	3614
	CC	524	3021
	CD	2922	3357
	OBD	1273	2177
Net Present Cost (NPC) (\$)	LF	3.83 M	4.05 M
	CC	3.61 M	4.26 M
	CD	3.76 M	4.02 M
	OBD	3.53 M	3.87 M
LCOE (\$/kWh)	LF	0.2028	0.1718
	CC	0.1914	0.1804
	CD	0.1994	0.1704
	OBD	0.1872	0.1640
Renewable Energy Fraction (%)	LF	74.7	83.8
	CC	22.4	56.3
	CD	72.6	79.2
	OBD	34.0	58.1
Excess Electricity (%)	LF	13.7	11.2
	CC	12.5	6.7
	CD	16.7	14.2
	OBD	8.37	9.9

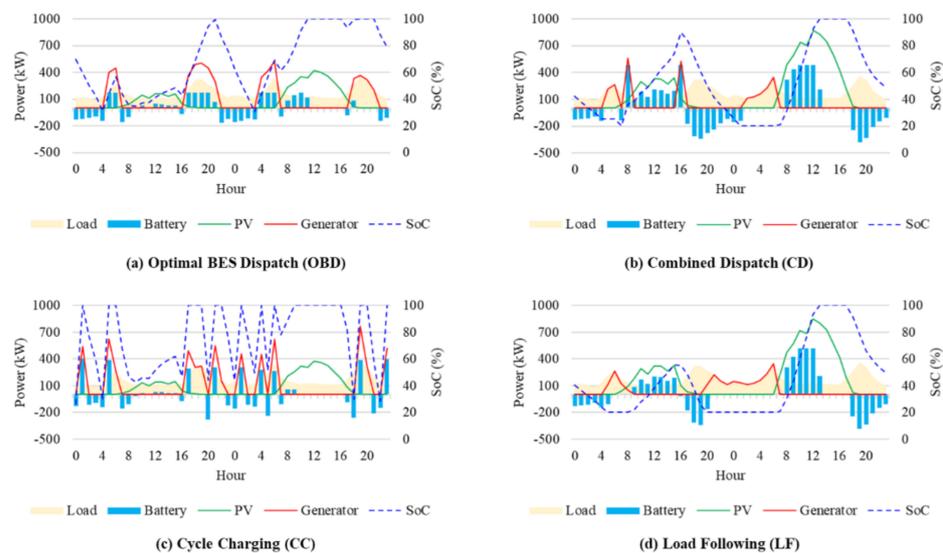


Figure 12. The operation pattern in System-1 for all control strategies in two consecutive days in March. BES was constantly discharged at the low load period, or every time there was a lack of supply from the PV system.

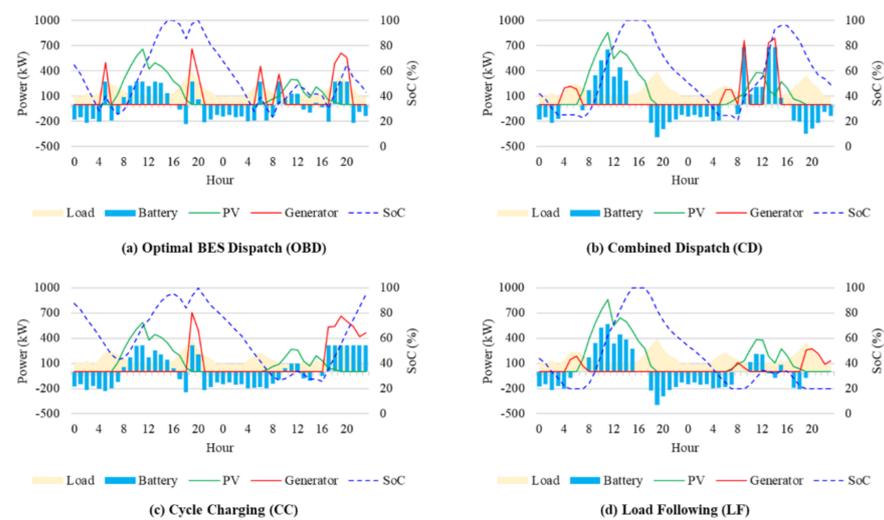


Figure 13. The operation pattern in System-2 for all control strategies in two consecutive days in September. BES was constantly discharged at the low load period, or every time there was a lack of supply from the PV system.

On the other hand, the OBD control strategy consistently discharged the BES at low load conditions, such as seen during the period between 00:00 to 04:00 and after peak load period (22:00 or 23:00) in both systems. The BES was also discharged when the solar PV energy production was insufficient (day one at 07:00–08:00 in System-1 and day two at 13:00–14:00 in System-2). Whereas, the discharging schedule happened every time there was available power in the battery in LF, once the BES's SOC exceeded the setpoint SOC in CC and CD, or if the BES was already discharged in CC and CD.

The proposed control strategy provided the sizing of the PV system and BES that result in the lowest LCOE and sufficiently higher renewable energy penetration compared with other control strategies. The operation of the generator was also more efficient when the OBD control strategy was applied. The generator operated at a lower frequency and shorter period but with higher power compared with the other control strategies. This operating characteristic resulted in lower fuel consumption and led to a lower LCOE. Moreover, it performed more robustly than the others in terms of the trade-off between the LCOE, the percentage of renewable energy penetration, and the excess electricity for any system with different load and solar irradiance profiles.

4.4. Discussion

The simulation results showed that the proposed control strategy had the lowest LCOE among the other control strategies. Nevertheless, the resulting RE penetration was still lower than the control strategy where the LF is applied (i.e., LF and CD). For instance, the LCOE in System-1 with the OBD is \$0.1872/kWh, and its RE penetration was 34.0%. On the other hand, the LCOE when the LF was applied was as high as \$0.2028/kWh (7.7% higher), and its RE penetration could be more than twice the one with the OBD control strategy. The RE penetration by using the CD control strategy was 72.6%. However, its resulted LCOE is \$0.1994/kWh, which was 6% higher than the OBD. Another example was presented in System-2. The LCOE in System-2 with the OBD was \$0.1640/kWh, with an RE penetration of 58.1%. The LF and CD control strategy results in a higher LCOE such as \$0.1718/kWh (LF) and \$0.1704/kWh (CD) and provides a higher RE penetration, such as 83.8% (LF) and 79.2% (CD).

The results of LF and CD implementation were consistent because, in the LF control strategy, the system required a higher capacity of the PV system and BES. By using OBD, the required capacity of the PV system was only 610 kW_p (System-1) or 1081 kW_p (System-2), and the required capacity of BES was 1273 kWh (System-1) or 2177 kWh (System-2). By applying the LF and CD control strategies, the sizes became one-and-a-half to twice the

one with the OBD control strategy. Hence, a higher RE penetration ratio in the LF control strategy comes with a huge investment and results in a higher LCOE.

On the other hand, the CC control strategy had the lowest RE penetration among other control strategies, including the OBD. It could only reach 22.4% (System-1) and 56.3% (System-2). Meanwhile, the LCOEs were still higher than the proposed control strategy, such as \$0.1914/kWh (System-1) and \$0.1804/kWh (System-2). The CC control strategy required a smaller capacity of PV system in both System-1 and System-2. It also needed a lower BES capacity in System-1 but a higher BES capacity in System-2. The CC control strategy often operates to maximize diesel generator utilization. This result shows that the CC control strategy was load profile dependent, which means the resulted LCOE could be lower or higher than the LF and CD control strategies in other locations. Hence, it is less robust than the OBD, LF, and CD.

It is worth noting that the development of HRES is considered capital investment-sensitive. Hence, the capacity of the PV system and BES are expected to be as low as possible so that it needs lower capital investment, and thus, the total life-cycle cost and LCOE can be reduced. On the contrary, a lower capacity may result in a lower RE penetration, as described above. Therefore, still and all, the cost-benefit decision depends on the stakeholder whether to achieve a low LCOE or to achieve the RE penetration target. For the remote or isolated grids in Indonesia, the lower LCOE with sufficiently higher RE penetration is preferable, which can be obtained by implementing the proposed control strategy.

5. Conclusions

Expensive diesel generators are predominantly used in remote and isolated areas. The application of the hybrid system consisting of the PV system and BES can bring two-fold benefits, such as reducing the LCOE and increasing the renewable energy penetration. The most popular generation dispatch control strategies, namely load following, cycle charging, and combined dispatch can be implemented as the energy management system algorithm in a hybrid system. However, these algorithms still have disadvantages, and their performance depends on the system characteristics like the load profile and local solar irradiance.

This paper presented an improved control strategy algorithm, the so-called Optimal BES Discharge (OBD), enhancing the combined dispatch control strategy. The OBD was designed to operate a hybrid system (generator-PV-BES) with a smaller PV and BES system size. Hence, the LCOE could be reduced by doing so but still maintaining a higher percentage of renewable energy penetration. Moreover, it was also aimed at minimizing the excess electricity generated by the hybrid system.

The results show that the proposed control strategy could work better than the other control strategies, which can be evaluated through the resulting LCOE, renewable energy penetration ratio, and excess electricity. The LCOE of an HRES could be lower by 2.2–9.1% when the OBD is implemented. The RE penetration ratio was comparable to the second-lowest LCOE, which could be lower by only 3.1%, but it could be higher by 35.3%. The excess electricity of the OBD implementation could be reduced below 10%, while the other control strategies mostly have excess electricity above 10%. Furthermore, the proposed OBD control strategy also consistently performed satisfactorily in different load and solar irradiance profiles.

Although this paper has shown some improvements, such as the LCOE reduction, the resulted RE penetration ratio was still lower than the original CD control strategy. Therefore, further research can be performed to increase the RE penetration with a lower LCOE. The improvement can be executed by implementing the scheduled dispatch control strategy for specific site characteristics or the predictive control strategy through well-known machine learning algorithms.

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Nomenclature

BES	Battery Energy System
CC	Cycle Charging
CD	Combined Dispatch
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy System
LCOE	Levelized Cost of Energy
LF	Load Following
NPC	Net Present Cost
OBD	Optimal BES Discharge
PV	Photovoltaic
RE	Renewable Energy
SFC	Specific Fuel Consumption
SOC	State of Charge

References

- Budiyanto, A.; Kamil, M.I.; Aryani, D.R.; Jufri, F.H.; Ardita, I.M. Performance analysis of a hybrid natural gas generator/photovoltaic system for residential use. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *599*, 012018. [CrossRef]
- Aprilianti, K.P.; Baghta, N.A.; Aryani, D.R.; Jufri, F.H.; Utomo, A.R. Potential assessment of solar power plant: A case study of a small island in Eastern Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *599*, 012026. [CrossRef]
- Garniwa, I.; Herdiansyah, H. Sustainability Index of Solar Power Plants in Remote Areas in Indonesia. *Technol. Econ. Smart Grids Sustain. Energy* **2021**, *6*, 1–14.
- Government of Indonesia. *Keputusan Menteri Energi dan Sumber Daya Mineral Republik Indonesia No. 55K/20/MEM/2019 tentang Besaran Biaya Pokok Penyediaan Pembangunan PT Perusahaan Listrik Negara (Persero) Tahun 2018*; Government of Indonesia: Jakarta, Indonesia, 2019; p. 7.
- Jakhrani, A.Q.; Rigit, A.R.H.; Othman, A.K.; Samo, S.R.; Kamboh, S.A. Estimation of carbon footprints from diesel generator emissions. In Proceedings of the 2012 International Conference on Green and Ubiquitous Technology, Bandung, Indonesia, 7–8 July 2012; pp. 78–81. [CrossRef]
- Government of Indonesia. *Undang-Undang Republik Indonesia No. 16 Tahun 2016 Tentang Pengesahan Paris Agreement to the United Nations Framework Convention on Climate Change*; Government of Indonesia: Jakarta, Indonesia, 2016; p. 71.
- BPPT. *Indonesia Energy Outlook 2020—Special Edition*; BPPT: Jakarta, Indonesia, 2020.
- Government of Indonesia. *Peraturan Pemerintah Republik Indonesia No. 79 Tahun 2014 Tentang Kebijakan Energi Nasional*. Indonesia; Government of Indonesia: Jakarta, Indonesia, 2014; p. 36.
- Government of Indonesia. *Peraturan Presiden Republik Indonesia No. 22 Tahun 2017 Tentang Rencana Umum Energi Nasional*; Government of Indonesia: Jakarta, Indonesia, 2017; p. 227.
- Morrison, G.L.; Sudjito. Solar radiation data for indonesia. *Sol. Energy* **1992**, *49*, 65–76. [CrossRef]

11. Baghta, N.A.; Aprilianti, K.P.; Aryani, D.R.; Jufri, F.H.; Utomo, A.R. Optimization of Battery Energy Storage System (BESS) sizing for solar power plant at remote area. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *599*, 012030. [CrossRef]
12. Nejabatkhah, F. Optimal Design and Operation of a Remote Hybrid Microgrid. *CPSS Trans. Power Electron. Appl.* **2018**, *3*, 3–13. [CrossRef]
13. HOMER Energy Homer Pro Knowledgebase. Available online: https://www.homerenergy.com/products/pro/docs/latest/viewing_the_knowledgebase.html (accessed on 29 October 2020).
14. Sureshkumar, U.; Manoharan, P.S.; Ramalakshmi, A.P.S. Economic cost analysis of hybrid renewable energy system using HOMER. In Proceedings of the IEEE-International Conference on Advances in Engineering, Science and Management (ICAESM-2012), Nagapattinam, Tamil Nadu, India, 30–31 March 2012; pp. 94–99.
15. Bahramara, S.; Moghaddam, M.P.; Haghifam, M.R. Optimal planning of hybrid renewable energy systems using HOMER: A review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 609–620. [CrossRef]
16. Aziz, A.S.; Tajuddin, M.F.N.; Adzman, M.R.; Azmi, A.; Ramli, M.A.M. Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq. *Renew. Energy* **2019**, *138*, 775–792. [CrossRef]
17. Oladigbolu, J.O.; Ramli, M.A.M.; Al-Turki, Y.A. Feasibility Study and Comparative Analysis of Hybrid Renewable Power System for off-Grid Rural Electrification in a Typical Remote Village Located in Nigeria. *IEEE Access* **2020**, *8*, 171643–171663. [CrossRef]
18. Azahra, A.; Syahindra, K.D.; Aryani, D.R.; Jufri, F.H.; Ardita, I.M. Optimized configuration of photovoltaic and battery energy storage system (BESS) in an isolated grid: A case study of Eastern Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *599*, 012017. [CrossRef]
19. Aziz, A.S.; Tajuddin, M.F.N.; Adzman, M.R.; Ramli, M.A.M.; Mekhilef, S. Energy management and optimization of a PV/diesel/battery hybrid energy system using a combined dispatch strategy. *Sustainability* **2019**, *11*, 683. [CrossRef]
20. Nurunnabi, M.; Roy, N.K.; Hossain, E.; Pota, H.R. Size optimization and sensitivity analysis of hybrid wind/PV micro-grids—A case study for Bangladesh. *IEEE Access* **2019**, *7*, 150120–150140. [CrossRef]
21. Torreglosa, J.P.; García, P.; Fernández, L.M.; Jurado, F. Energy dispatching based on predictive controller of an off-grid wind turbine/photovoltaic/hydrogen/battery hybrid system. *Renew. Energy* **2015**, *74*, 326–336. [CrossRef]
22. Velasquez, M.A.; Barreiro-Gomez, J.; Quijano, N.; Cadena, A.I.; Shahidehpour, M. Distributed model predictive control for economic dispatch of power systems with high penetration of renewable energy resources. *Int. J. Electr. Power Energy Syst.* **2019**, *113*, 607–617. [CrossRef]
23. Jung, J.; Villaran, M. Optimal planning and design of hybrid renewable energy systems for microgrids. *Renew. Sustain. Energy Rev.* **2017**, *75*, 180–191. [CrossRef]
24. Ramesh, M.; Saini, R.P. Dispatch strategies based performance analysis of a hybrid renewable energy system for a remote rural area in India. *J. Clean. Prod.* **2020**, *259*, 120697. [CrossRef]
25. Das, B.K.; Zaman, F. Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection. *Energy* **2019**, *169*, 263–276. [CrossRef]
26. Murugaperumal, K.; Srinivasn, S.; Satya Prasad, G.R.K.D. Optimum design of hybrid renewable energy system through load forecasting and different operating strategies for rural electrification. *Sustain. Energy Technol. Assess.* **2020**, *37*, 100613. [CrossRef]
27. Obaro, A.Z.; Munda, J.L.; Siti, M.W.; Yusuff, A.A. Energy dispatch of decentralized hybrid power system. *Int. J. Renew. Energy Res.* **2018**, *8*, 2131–2145.
28. Sundén, B. Thermal management of batteries. *Hydrog. Batter. Fuel Cells* **2019**, 93–110. [CrossRef]
29. Mu, H.; Xiong, R. *Modeling, Evaluation, and State Estimation for Batteries*; Elsevier Inc.: Amsterdam, The Netherlands, 2018; ISBN 97801281131091.
30. Larsson, P.; Borjesson, P. Cost models for battery energy storage systems. Bachelor’s Thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden, 2018; p. 31.
31. Das, I.; Canizares, C.A. Renewable Energy Integration in Diesel-Based Microgrids at the Canadian Arctic. *Proc. IEEE* **2019**, *107*, 1838–1856. [CrossRef]
32. Rendall, C.O. Economic feasibility analysis of microgrids in Norway: An application of HOMER Pro. Master’s Thesis, Norwegian University of Life Sciences, Ås, Norway, 2018.
33. Saputra, Y.T.W.; Garniwa, I. Techno-economy study of battery energy storage system for electricity grid peak generation. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *716*, 012070. [CrossRef]
34. Taylor, M.; Ralon, P.; Anuta, H.; Al-Zoghoul, S. *IRENA Renewable Power Generation Costs in 2019*; IRENA: Abu Dhabi, United Arab Emirates, 2020; ISBN 978-92-9260-244-4.
35. Asian Development Bank. *Handbook on Battery Energy Storage System*; Asian Development Bank: Mandaluyong, Philippines, 2018; ISBN 9789292614713.
36. Mongird, K.; Fotedar, V.; Viswanathan, V.; Koritarov, V.; Balducci, P.; Hadjerioua, B.; Alam, J. *Energy Storage Technology and Cost Characterization Report*; Pacific Northwest National Laboratory: Richland, WA, USA, 2019; pp. 1–120.
37. BloombergNEF. A Behind the Scenes Take on Lithium-ion Battery Prices. Available online: <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/> (accessed on 29 October 2020).
38. HOMER Energy. *LLC HOMER Pro Version 3.7 User Manual*; HOMER Energy: Boulder, CO, USA, 2016; p. 416.