Optimizing Renewable Energy Share in Remote Areas Microgrids and Its Trade-off to Cost

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***Abstract*—Energy access, renewable energy share and energy efficiency are the indicators of the Sustainable Development Goal 7 for universal access to energy in 2030. This can be supported by implementing microgrids with renewable sources in remote areas. One of the issues is system oversizing, which could result in an inefficient system and high production costs. Therefore, system sizing is often correlated with cost optimization. Focusing on the other indicator, this paper investigates renewable energy share and system oversizing through power balance calculation. The study was conducted on a system with PV panels, battery energy storage system and diesel generators. It shows a nonlinear correlation between the capacity of PV, battery and the renewable energy share. Furthermore, higher load factor, higher power rating of the battery storage system and implementation of supercapacitor could increase the renewable energy share. It could also partially address the oversizing issue by reducing the curtailed power.**

Keywords—microgrid, power balance, renewable energy share, energy access

I. Introduction

The global call for Sustainable Development Goal 7 (SDG7) aims for universal access to affordable, reliable, sustainable, and modern energy by 2030 [1]. Energy access, renewable energy (RE) share and energy efficiency are the main indicators of this goal. However, there are still 759 million people without access to electricity (latest data of 2019) and only 17.1% share of energy consumption is from renewables (latest data of 2018) [2]. The data indicate that tremendous effort is still required to meet the SDG7 goal.

The implementation of microgrids with renewable sources to complement or replace existing diesel generators (DiGs) has been an engaging topic for the past few years. Introducing RE to replace DiGs requires a great effort with gradual and consistent efforts because it disrupts the technology and value chains that have been well-established for years. Nevertheless, it gives the opportunity for huge benefits. For instance, a study on 167 developing countries shows a total of 100–170 TWh of electricity generated from DiGs with the cost of more than 0.40 $/kWh in the most remote areas [3]. Implementing microgrids with RE to fully or partially replace the immense number of DiGs could significantly reduce the electricity generation cost and lower the environmental pollution. Although that may change the design choices, PV and battery costs have been dramatically dropping, making it even more attractive to replace diesel generators. Furthermore, it supports the effort for universal energy access in 2030.

One of the challenges in developing microgrids in remote areas is determining the RE generation capacity to reduce the energy from DiGs while lowering the electricity production cost. This challenge is related to the lack of practical and technical knowledge as well as an inadequate preliminary survey to estimate the demand growth, which could result in system oversizing or energy deficit and early failure [4].

Many aspects need to be considered in optimizing the capacity of battery energy storage system (BESS), which can be classified as the financial and technical criteria. Financial criteria can be described as net present value, levelized-cost of electricity and market benefit; and the technical criteria as dynamic (frequency and voltage regulation) and steady-state (reliability, curtailment, and other features e.g., peak shaving, smoothing, etc.) characteristics [5]. Depending on the application, these criteria might have higher priority than the others, which will lead to different optimal capacities. For instance, a study of a microgrid with microturbines, fuel cells, wind turbines and photovoltaic (PV) shows the optimal BESS capacity by comparing the unit commitment and BESS generation cost [6]. Another study shows the battery's optimum size depends on the capital cost that increases when higher PV capacity is allowed. The optimum sizing is constrained by the annual system cost and budget [7]. These two studies have different constraints in determining the capacity, which resulted in different optimal values.

To support SDG7, aiming for a higher RE share should be considered. This is relevant for instance in the case of Indonesia, which aims for 23% RE share in 2025 while it is still 13% of the generation capacity in 2020. One of their efforts is by replacing 5,200 DiGs [8]. In Indonesia, the implementation of PV and BESS has been rapidly growing as one of the solutions. In the context of using PV and BESS to replace DiGs in remote areas, some trade-offs need to be considered. First, higher PV and BESS capacities will increase the RE share, but after a certain point, there will be less reduction in the electricity production cost. Second, ensuring availability is easier with DiGs because it is dispatchable. However, prioritizing DiG over PV could lower PV penetration and increase the PV curtailment. These trade-offs indicate that the sizing of a microgrid generation capacity to replace DiGs is highly dependent on the priority: generation cost, RE share, or continuity of supply.

This study focuses on trade-offs between the PV penetration (PVp) and curtailment (PVc), which are correlated with RE share and oversizing of a system, respectively. PVp is defined as the ratio between total PV energy that goes to the load (directly or through BESS) and the total energy consumption. PVc is defined as a portion of the potential PV energy that cannot be utilized to prevent oversupply. This paper investigates PVp and PVc in the context of DiGs replacement with PV and BESS.

Section II shows a demand profile that was investigated and the simulation parameters. Section III elaborates on the power balance result of PVp and PVc. Section IV analyzes the influence of the BESS power limit and load factor (LF). Section V discusses the optimization of RE share and the context of remote areas. Section VI describes the concluding remarks and suggestions for future research.

II. Power Balance Model

The investigation was conducted on a system with DiGs, PV, BESS and residential loads. The PV and BESS are separated with different inverters that are connected to a common AC bus with the DiGs and loads. The load data was obtained from a microgrid in Indonesia with an average load of 226 kW, peaked at 19:00 with 276 kW, total daily energy consumption of 5.4 MWh and LF of 82%. There are two 300 kW DiGs installed with loading that is limited between 60–90% to ensure low specific fuel consumption (SFC). Different capacities of PV and BESS were simulated to investigate the PVp and PVc. The power balance was calculated hourly throughout the year.

A. Demand and PV Production Profiles

The residential load profile is shown in the left graph of Fig. 1. Assuming there is no change in daily electricity consumption, the load profile was repeated 365 times as the hourly consumption throughout the year. This assumption is relevant because there are no significant seasonal changes and the investigated case is assumed as non-tourism remote areas in Indonesia, where load changes are only caused by a few cultural events in a year. The initial PV capacity is 660 kW with an hourly average production profile shown in the right graph of Fig. 1. The initial capacity is chosen in a way that PVp and PVc are around 40% and 20%, respectively. The potential PV power, P_{PV}, is obtained from PVsyst simulation with irradiation data from Meteonorm.

B. Energy Management

Considering the RE share target, supply from PV is prioritized over DiG. If P_{PV} is higher or equal to the demand ($P_{PV} \geq P_{load}$), then all loads are supplied by PV. However, if P_{PV} is lower than demand ($P_{PV} < P_{load}$), BESS and/or DiGs will supply the remaining required power (1).

$$P_r = P_{load} - P_{PV} \tag{1}$$

BESS is discharged when P_{PV} is not sufficient and charged when there is excess power. Charge and discharge, P_{bt}, are allowed within 10–90% state of charge (SoC) and the power is limited at the same value as the peak demand (276 kW). This BESS power limit represents the maximum power that can go through the battery and BESS inverter. This simulation used hourly data to calculate the power balance, hence the BESS SoC was calculated by assuming that the charge or discharge power is constant throughout the hour. The charge and discharge conditions are summarized in Table I. If there is excess energy but the SoC is 90%, power from PV is curtailed to prevent system oversupply. If the remaining energy in BESS is not sufficient for P_r (SoC is 10%), DiG will supply the remaining required power (2).

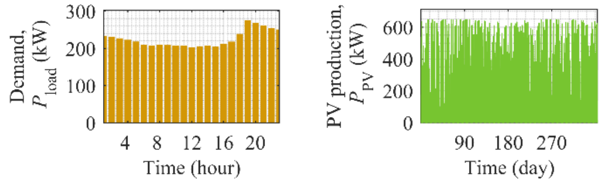

Fig. 1. Hourly power consumption profile of residential loads in a day and hourly potential power of 660 kW PV in a year

$$P_r' = P_{load} - P_{PV} - P_{bt} \tag{2}$$

There are three P_r' conditions for DiGs with supply values listed in Table II. DiG min and max is the minimum and maximum loading limit, which are 60% and 90%.

1 : DiG_1 min ≤ P_r' < DiG_1 max

2 : DiG_1 max ≤ P_r' < DiG_1 max + DiG_2 min

3 : DiG_1 max + DiG_2 min ≤ P_r' < DiG_1 max + DiG_2 max

This energy management maximizes the utilization of solar energy and minimizes diesel supply by prioritizing battery over diesel when solar energy is low or not available. The power balance was calculated hourly for one full year and the outputs are the hourly profile of PV power that goes directly to the load, curtailed PV power, charging and discharging power of BESS and DiGs supply.

TABLE I. BESS Charge and Discharge Conditions

Charge	$P_{PV} \geq P_{load}$	Load supplied fully from PV and the excess PV power goes to BESS
	$P_{PV} < P_{load}$ and P_r' < DiG_1 min	DiG_1 generates minimum power and the PV excess power goes to BESS
Discharge	$P_{PV} < P_{load}$	All PV power goes to the load and the remaining demand is supplied by BESS

TABLE II. P_{DiG} Supply on Different P_r Conditions

Conditions	P_{DiG_1}	P_{DiG_2}
1	P_r'	OFF
2	P_r' – DiG_2 min	DiG_2 min
3	DiG_1 max	P_r' – DiG_1 max

III. Simulation Results

A. Hourly Power Balance

The power balance result of the system with 660 kW PV, 1 MWh BESS with a power limit of 276 kW, and 5.4 MWh daily demand with 82% LF is shown in Fig. 2 for low and high PV production. On the 18th day, the PV generation was low, the BESS only charged up to about 20% SoC, and discharged at 13:00 when the DiG can be turned off. On the 300th day at 06:00, DiG supply was at the minimum (60%) to ensure low SFC, hence there was excess PV power to charge BESS. At 09:00–10:00, the PV potential energy was curtailed because it exceeded the BESS power limit. At 11:00–15:00, the BESS reached 90% SoC so PV power was curtailed to prevent system oversupply. DiG was turned OFF from 07:00–19:00 because the energy from PV and BESS was sufficient to supply the load.

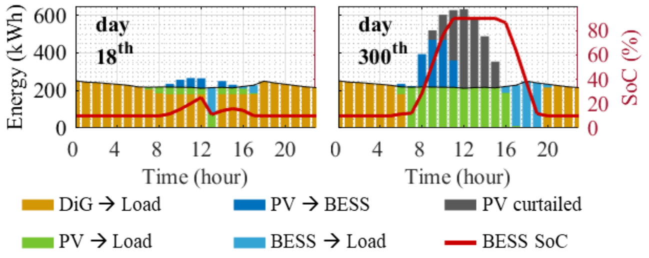

Fig. 2. Power balance for low (18th day) and high (300th day) levels of potential PV production

B. PV Penetration and PV Curtailed Energy

Higher PVp means a higher RE share, which is important to fulfilling one of the SDG7 indicators. Higher PVc means higher potential energy that is available but cannot be utilized, which also indicates oversizing of a system. Fig. 3 shows PVp (solid lines) and PVc (dashed lines) throughout the year with PV capacity ranging from 0.66–5.94 MW and BESS capacity ranging from 1–8 MWh. It shows that higher PV capacity increased PVp and PVc. However, with the increase of BESS capacity, the PVp increased while the PVc decreased. At a certain value of BESS, the increase of its capacity was no longer giving a significant change in PVp and PVc (the optimal point for RE share). This is because the BESS power limit reduces the PV energy that can be stored during the day.

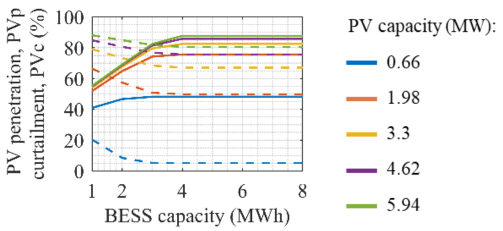

Fig. 3. PVp (solid) and PVc (dashed) with different PV and BESS sizes

IV. Influence of BESS Power Limit and Load Factor

PVp and PVc are dependent on the capability of the system to store the excess PV energy (for indirect use of PV energy through BESS) and the load during the day (for direct use of PV energy to load). To investigate these factors, simulations with different BESS power limits and different LFs were performed. In terms of the BESS power limit, a higher value means that higher power can be sent or drawn from the BESS. The BESS power limit is indicated as a factor of peak load, so it is more practical for sizing.

Fig. 4 shows that at low PV and/or low BESS capacities, higher BESS power limit did not result in significant improvement of PVp and PVc because there was not enough PV energy to be stored and curtailment was mainly because the BESS is full. At higher PV and BESS capacities, higher BESS power limit resulted in a noticeable change in PVp and PVc because it reduced the power curtailment, hence more energy can be stored to BESS. However, after a certain BESS power limit value, the change was no longer significant. This is because, even though the PV and BESS capacity was sufficient to provide daily energy consumption, there were periods within the year when the supply from DiGs was required, which were during the consecutive low irradiation days. Fully replacing DiGs requires high PV and BESS capacities to provide a large energy reserve for those consecutive days. This is shown by the slow change in PVp and PVc at increasing BESS capacity. In practice, this is not cost-efficient since the increase in system cost will be enormous compared to the improvement of PVp and PVc.

Another factor that affects PVp and PVc is LF, which is defined as the ratio between the average to the peak load. By keeping the daily total energy consumption at 5.4 MWh, part of the energy consumption during off-peak (00:00–18:00) was shifted to the peak (19:00–23:00) to obtain different LF. The influence of LF on PVp and PVc of a system with low (left) and high (right) BESS power limit is shown in Fig. 5. In the case of a low BESS power limit with low BESS capacity, the PV energy that can be stored was limited. With lower LF, there was less PV energy that can be used directly for the load during the day. Therefore, lower LF resulted in lower PVp. In contrast with high BESS capacity, although lower LF resulted in less direct PV energy for the load, there was more PV energy that can be stored during the day. Therefore, fewer DiGs energy is required during the night, which resulted in higher PVp at lower LF. The result also shows that with a low BESS power limit, lower LF shifted the optimal point to the higher BESS capacity. In the case of a high BESS power limit, a similar trend to the case with low BESS capacity was found i.e., lower LF resulted in lower PVp. However, this trend continued to a higher BESS capacity because there was more PV energy that can be stored during the day with the higher BESS power capability. Furthermore, in contrast with the sensitivity of the BESS power limit at high BESS capacity, LF did not affect the portion of DiGs energy during consecutive low irradiation days. This is due to the assumption of constant total daily energy for different LFs.

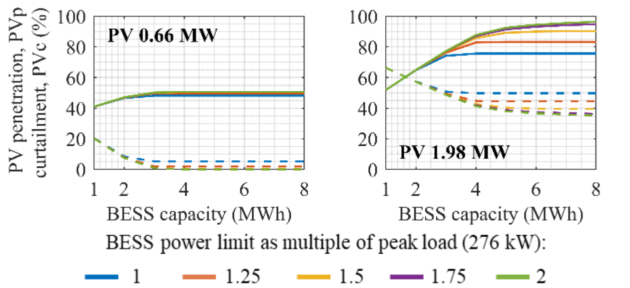

Fig. 4. PVp (solid) and PVc (dashed) with different BESS power limits

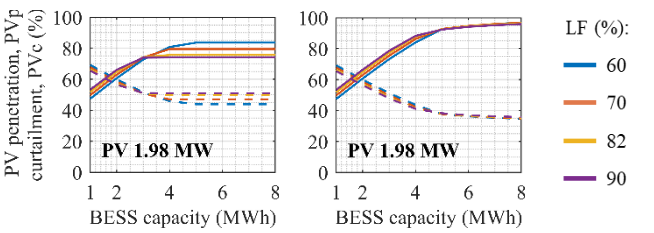

Fig. 5. PVp (solid) and PVc (dashed) with different LFs and a BESS power limit equal to one (left) and two (right) times the peak load

V. Discussion

The simulations show that the change in both PVp and PVc was not linear with the increase of either PV or BESS capacities. Furthermore, after a certain value of BESS, the increase of its capacity no longer resulted in a significant change in PVp and PVc. In terms of electricity generation costs in Indonesia's remote areas, reducing the supply from DiGs with PV could reduce the total generation cost because it is more expensive than PV. DiGs cost more than 0.21 $/kWh in most small systems in Indonesia [9] with 80% cost coming from the operational expenditure [10]. BESS is required to maximize the reduction of DiGs with PV and there is an optimum BESS capacity that can be estimated through cost-benefit analysis by comparing the cost of unit commitment and BESS [6]. However, this cost-based optimum BESS capacity does not reflect the optimum BESS capacity for PVp and PVc. Considering the target of the RE share, higher production costs might be necessary.

Taking into account the RE share, not only the capacity but also the BESS power capability to transfer power is important. The BESS cost of a PV and BESS standalone system in Indonesia is 45–77% of the total system cost [11], which is largely associated with the capacity rather than the power rating [12]. Therefore, at a certain BESS capacity, increasing the BESS power limit could be done to gain a higher RE share at a lower cost. However, a higher power rating means a higher current and results in faster aging, which also eventually become a trade-off to cost.

Considering the high current and the intermittency of PV, a supercapacitor (SC) could be added to transfer short-time high PV power and minimize PV curtailment due to the BESS power limit, hence improving PVp. SC can be used to reduce the required power ramping rate of BESS [13] and to support BESS in providing ancillary services (e.g., frequency and voltage control), which will lower the degradation rate of BESS [14]. Moreover, the implementation of SC could also reduce the fuel consumption of DiG [15].

In the case of remote areas that are dominated by residential loads, the demand is most likely to have low LF. Although lower LF could result in lower PVp, it allows more power to be stored. Therefore, a high BESS power limit is better to maximize the PVp. If the BESS power limit is set close to the peak load, lower LF shifts the optimal value of PVp to a higher BESS capacity.

VI. Conclusion and Recommendation

Apart from providing energy access in remote areas with RE microgrids, aiming for a higher RE share is also important to support SDG7 and the government's policy targets. However, it may complicate the microgrid generation sizing due to its potential trade-off with the generation cost. This study investigates the relation between RE share, PV and BESS capacity by analyzing the power balance of a system that consists of DiGs, PV, BESS and residential loads. PVp and PVc were investigated as the indication of RE share and system oversizing.

The results showed the relation between PV and BESS capacities was not linear with PVp and PVc. There was an optimal value in which the increase of its capacity no longer resulted in a significant improvement in PVp and PVc. At this optimum value, it was better to increase PVp by increasing the BESS power capability by more than 1.5 peak load rather than increasing the capacity. The improvement in PVp and PVc will be high if the level of PV power curtailment due to the BESS power limit is relatively high. This could also be further improved by implementing SC in the system. Moreover, in the context of DiG replacement with PV and BESS in remote areas, lower LF shifted the optimal value of PVp to a higher BESS capacity when the BESS power limit is set close to the peak load.

From this paper, the following are suggestions for future improvement of the research.

- Analysis of SC in improving total system efficiency and sizing optimization.
- Implementation of SC for ancillary service in remote areas and the trade-off between cost and RE share.

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