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Uninterrupted Electricity Supply using Off-Grid Solar PV Systems for Remote Areas

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Abstract. Due to the intermittent electricity production, the battery takes an important role in the off-grid PV systems by storing excess electricity production. The stored electricity is then used when the PV system generates less electricity than what is demanded. However, the current price and lifetime of the battery make the electricity cost of the off-grid PV system expensive. Therefore, the capacity of components must be designed to fulfill the demand at the lowest electricity cost. In this study, two strategies in the design of off-grid PV systems to fulfill the same demand are compared. The first strategy is to employ the PV module with proper capacity, which means the annual energy production equals the annual energy demand, but it needs a huge capacity battery to store the accumulation of the excess energy. The second strategy is to use the large capacity of the PV module, which considers the lowest energy production day, but it requires the small capacity of the battery. The results show that the electricity cost of the second strategy is only 29.0 % of the first strategy. However, it dumps 50.1 % of the annual produced electricity.

Keywords: Electricity cost; Off-grid system; Sizing strategy; Solar photovoltaic

1. Introduction

The use of renewable energy (RE) as an alternative energy source is needed to prevent environmental problems caused by fossil energy (Bhayo *et al.,* 2020; Qadir, Tahir, and Al-Fagih, 2020; Malik *et al.,* 2019). The classification of regions of renewable energy is needed as a tool to minimize the risk of RE implementation (Brazovskaia and Gutman, 2021). On the other hand, energy consumption should also be predicted; thus, the dumping of energy can be avoided. The use of machine learning techniques is a promising method for predicting energy consumption (El-Hadad, Tan, and Tan, 2022). Solar energy, specifically the use of solar PV modules, is rapidly gaining popularity worldwide as a renewable energy source due to its technology development and cost effectiveness (Blakers, 2021; Jager-Waldau, 2020; Benda, 2017; Branker, Pathak, and Pearce, 2011). Moreover, the efficiency of solar PV has increased dramatically in the last two decades (Benda and Černá, 2020). The remaining problem with this technology is that electricity can only be generated when solar irradiation is available. Therefore, the battery takes an important role in the off-grid PV system, which is usually applied in remote area (Maleki and Askarzadeh, 2014; Sen and Bhattacharyya, 2014; Merei, Berger, and Sauer, 2013).

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In solar PV system applications, fluctuating and intermittent energy production is unavoidable (Poddar *et al.,* 2023; Albadi, 2020; Gowrisankaran, Reynolds, and Samano, 2011). This problem causes a mismatch between electricity production and demand. The most common solution for this issue is by using the battery as energy storage (Ekren and Ekren, 2010). However, the battery is the most expensive component in the off-grid PV system, which causes an increase in electricity cost significantly (Aneke and Wang, 2016; Hove and Tazvinga, 2012). Therefore, the capacity of the battery must be minimized to reduce the electricity cost of the solar PV system (Agarwal, Kumar, and Varun, 2019). In addition to the cost of batteries, another challenge of off-grid PV systems is the potential interruption of electricity supply to meet demand. This problem is caused by consecutive days of low insolation, during which the energy stored in the battery may not be sufficient to compensate for the deficit energy production from the PV module. As a result, electricity shortages may occur.

The economic analysis of the off-grid PV system for the remote area has been presented by various studies (Cuesta, Castillo-Calzadilla, and Borges, 2020; Jamshidi and Askarzadeh, 2019; Mandal, Das, and Hoque, 2018). Taufiqurrohman designed and evaluated the off-grid PV system to fulfill the electricity demand at 1.61 kWh/d for small houses in Indonesia (Taufiqurrohman, 2018). The resulting electricity cost was 0.30 $/kWh. Awapone presented the feasibility of the off-grid system consisting of PV, battery, and diesel generators in Ghana (Awopone, 2021). The system was designed for 80 houses with an electricity demand of 224.06 kWh/d. The electricity cost resulted at 0.4 $/kWh. Sinaga *et al.,* (2019) presented the off-grid PV system in the area of Kupang, Indonesia (Sinaga *et al.,* 2019). They claimed that the resulted in electricity cost resulted by their system ranged from 0.31-0.33 $/kWh. In the case of an on-grid system, the optimization of power generation to increase the utilization of renewable energy is very promising since it can result in an electricity cost of 0.065 $/kWh (Saroji *et al.,* 2022). The studies mentioned above did not consider to fulfill the electricity demand without interruption. Therefore, the designs had the failed potential to fulfill the electricity demand, especially on low insolation days. Based on the advantages of the PV system, the off-grid PV system is very suitable for remote areas where the electricity grid is not available. The interrupted energy supply can be solved by using the large capacity of battery as presented by Ajiwiguna *et al.* (2022). However, this strategy may create expensive electricity costs. Therefore, another strategy is needed.

This study presents a novel strategy to minimize the capacity of the battery without interrupting the electricity supply simultaneously. The proposed strategy is to consider the lowest energy production day to determine the PV capacity. By using this strategy, the battery capacity can be minimized to only one autonomous day because the daily electric energy production is always equal to or higher than the daily electric energy demand. However, it also implies that dumping energy is not avoidable. The electricity cost is then estimated as the final parameter of system performance. The proposed design system is also compared technically and economically with the design without dumping energy that was presented by (Ajiwiguna *et al.* 2022).

2. System and Case Study Description

The schematic diagram of an off-grid PV system is shown in Figure 1 (Awasthi *et al.,* 2020; Ghafoor and Munir, 2015). PV module converts solar irradiation into direct current (DC) electricity. Solar charge controller (SCC) manages the electricity by sending it to the demand, storing it in the battery, or both. If the electricity produced by the PV system is higher than the demand, the excess energy is stored in the battery (the battery is charged).

If the electricity produced by the PV system is lower than the demand, the deficit energy is supplied from energy stored in the battery (the battery is discharged). The specification of the PV module and battery used in this study is shown in Table 1 and Table 2, respectively.

Although the lifetime of PV modules was 25 years, the off-grid PV system was designed only for 20 years, considering the lifetime of other components, especially the battery. The lifetime of the components must be considered because if it is shorter than the system lifetime, the replacement cost is required. Operational and maintenance cost is mostly for the PV module for cleaning and checking the connection. For battery, its O&M cost is negligible since the battery used in this study is maintenance-free.

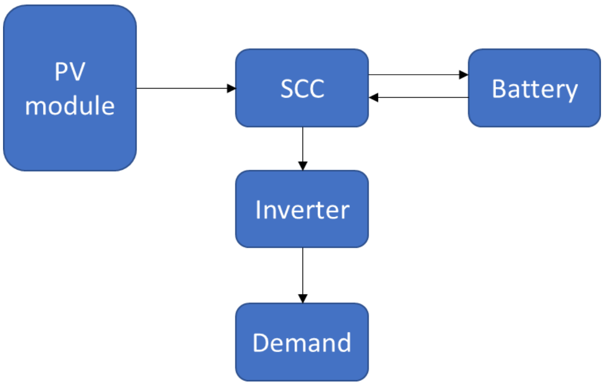

Figure 1 Configuration of off-grid PV system

Table 1 Specifications of the PV module

Maximum Power (STC), P_{STC}	375 W
Open Circuit Voltage, V_{OC}	47.6 V
Short Circuit Current, I_{SC}	9.93 A
Nominal Operating Cell Temperature, *NOCT*	41 ± 3°C
Temperature coefficient of power, γ	−0.37%/°C
Lifetime	25 years

Table 2 Specification of battery per unit

Capacity	1.2 kWh (100 Ah)
Voltage	12 V
Battery efficiency	85%
Depth of discharge	80 %
Lifetime	7 years

The case study was conducted in Cisoka Village, Indonesia, which was selected due to its potential in the tourism industry, but with limited access to electricity. The solar PV system was designed to cater to small residential buildings, with a daily electricity consumption assumption as presented in Table 3. The total daily energy consumption of 3.23 kWh is reasonable, as it falls within the range of energy consumption reported by Palaloi for small buildings in Indonesia (Palaloi, 2014). The required capacity of system components was estimated based on Typical Meteorological Year (TMY) weather data obtained from the Repository of Free Climate Data in 2019.

Table 3 Appliances and estimation of daily energy consumption

No	Appliance	Quantity	Effective operation hour (h/d)	Wattage (W)	Energy consumption (kWh)
1	Lamp 1 (outdoor)	3	12	18	0.65
2	Lamp 2 (indoor)	5	10	12	0.60
3	Refrigerator	1	8	110	0.88
4	Rice cooker	1	2	300	0.60
5	Pump	1	2	100	0.20
6	Washing Machine	1	1	300	0.31
	Total daily energy consumption				3.23

3. Methods

3.1. Sizing components method

The capacity of PV modules and batteries should be determined thus the electricity demand can be fulfilled perfectly. Before determining the capacity of those components, the estimation of electricity production must be performed. Equation (1) and (2) were used to estimate the DC electricity generated by single PV module (Riffonneau *et al.*, 2011).

$$P_{pv} = [P_{STC} \frac{G_T}{1000} (1 - \gamma (T_j - 25))] \tag{1}$$

$$T_j = T_{amb} + \frac{G_T}{800} (NOCT - 20) \tag{2}$$

where P_{pv} is DC power produced by PV modules, P_{STC} is the power produced by the PV module at standard test conditions, γ is the temperature dependence coefficient of power, T_j is a module or cell temperature, T_{amb} is the surrounding temperature, and NOCT is the nominal operating cell temperature. This calculation requires data from the specification of PV modules and weather data (especially solar irradiation and ambient temperature).

Since the electricity demand is in the form of AC electricity, the losses from the inverter and wire must be considered. Moreover, not all electricity supplied to the battery can be stored, and not all electricity from the battery can be utilized. Battery has an efficiency that must be considered. Therefore, the usable electricity from the off-grid PV system is calculated by using Equation (3).

$$P_{AC} = \eta_{bat} (1 - L) P_{pv} \tag{3}$$

where η_{bat} is battery efficiency, and L is the overall losses of the system. By using the procedure above, the hourly data for a year are obtained because the weather data used in this study is also hourly data.

In this study, the comparison of two different design strategies to fulfill the same electricity demand was conducted. The strategies presented in this study aim to supply electricity to the demand without interruption while the weather and season are not constant. To obtain this purpose, two different strategies can be applied. The first strategy is to minimize the PV capacity thus, the annual electricity production is as same as the annual electricity demand. This option needs the huge capacity battery to store the excess electricity production on the consecutive sunny days and to use it on cloudy or rainy days. The second strategy, our proposed strategy, is to use the worst weather day of electricity production as the basis for determining the capacity of the PV system. By using this option, the PV capacity must be huge because it must produce the electricity as much as demand on the worst production day. However, the battery capacity can be reduced to only one day's worth of autonomy, as the system does not need to store excess electricity production for consecutive days. This allows the system to efficiently supply electricity to meet demand without encountering any problems on the following day. The differences between the two design strategies are summarized in Table 4.

In the first strategy (Strategy A), the PV module capacity was determined so that the annual electrical energy production was as same as the annual demand. The flow chart for determining the PV capacity is shown in Figure 2. Since the weather is not constant, the battery capacity was determined by considering the accumulation of storing excess electricity production. Generally, Indonesia has two seasons: Dry and Rainy. In the dry season, solar irradiation is very high; thus, the electricity production from the PV system is also high. Most of the excess electricity production is in this period. To accommodate the accumulation of stored energy from consecutive days, a huge capacity battery is needed. The methods used to calculate the capacity of PV modules and batteries were based on the study presented by Ajiwiguna *et al.* (2022).

Table 4 Design characteristics of the two strategies

	Strategy A	Strategy B
PV module capacity	Determined by calculating the annual electrical energy production as same as athe nnual demand	Determined by using the worst daily weather in a year to produce electrical energy
Battery capacity	Considering the accumulation of energy storage and/or energy deficit in a year	One autonomous day
Dumping energy	No (or minimum)	Yes

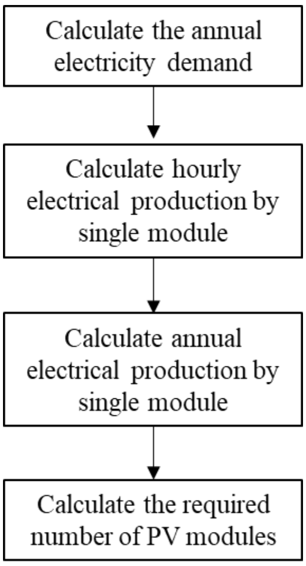

Figure 2 Flowchart to determine the capacity of PV module for strategy A

In the second strategy (Strategy B), the PV module capacity was determined by considering the lowest electricity production day. In this day, the PV module capacity was calculated so that it must be able to produce electricity as much as the daily demand. By using this strategy, daily energy production always equals or is higher than demand. The process to determine PV capacity is shown in Figure 3. First, hourly usable electrical power produced by the PV system was calculated by using Equations (1) to (3). Then, to calculate the daily energy production, the hourly data was integrated every 24 hours, as shown in Equation (4):

$$EP_{day} = \int_0^{day} P_{AC}\, dt \approx \sum_0^{24} P_{AC}\, \Delta t \tag{4}$$

where EP_{day} is daily energy produced by a PV system using a single module, and Δt is a time interval of data. Next, the minimum daily energy production, $\left(EP_{day}\right)_{min}$, is chosen as the basis for determining the capacity of the PV module. The required number of PV modules was calculated by using Equation (5).

$$N_B = \frac{\left(EP_{day}\right)_{min}}{ED_{day}} \tag{5}$$

where ED_{day} is daily energy demand. Then the PV capacity for strategy B is calculated by using Equation (6).

$$\left(PV_{cap}\right)_B = N_B P_{STC} \tag{6}$$

By using that capacity, the electricity demand on the other days was fulfilled because the weathers were better than that worst day. Since the daily energy production was always equal to or higher than daily demand, the battery didn't need to store the excess energy for consecutive days. It also meant the required capacity of the battery was only one autonomous day. However, dumping energy in this strategy was unavoidable. One of the functions of a solar charge controller is to stop the charging process when the battery is already full. Therefore, the overcharging of the battery can be avoided.

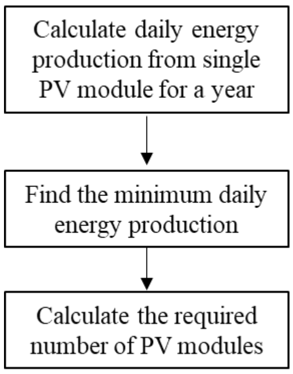

Figure 3 Flowchart to determine PV module capacity for strategy B

3.2. Electricity cost estimation method

Electricity cost was calculated as the ultimate parameter for comparison between the two strategies. It considered capital cost, operational and maintenance cost, and replacement cost. The total capital cost (CC_{Total}), PV module capital cost CC_{PV}, Inverter capital cost (CC_{inv}), Solar charge controller capital cost CC_{SCC}, and battery capital cost CC_{batt} were calculated by using Equations (7) to (11).

$$CC_{Total} = CC_{PV} + CC_{inv} + CC_{SCC} + CC_{batt} \tag{7}$$

$$CC_{PV} = 1.15 \times TP_{PV} \tag{8}$$

$$CC_{inv} = TP_{inv} \tag{9}$$

$$CC_{SCC} = TP_{SCC} \tag{10}$$

$$CC_{batt} = TP_{batt} \tag{11}$$

where TP_{PV}, TP_{inv}, TP_{SCC}, and TP_{batt} are the total price of the PV module, inverter, solar charge controller, and battery, respectively. For the PV module, it considered 15% of the installation cost (Mohamed and Papadakis, 2004). This installation cost is included in the installation of other components. Therefore, the other components' capital costs were only the total price of components.

Annual operational and maintenance cost (OnM) was assumed to be 11.5 $/kWp (Fu, Feldman, and Margolis, 2018). Since the PV system was designed for 20 years of operation, the replacement cost must be considered for the components, which have a lifetime of less than 20 years. The components replacement cost is the frequency of replacement multiplied by the component capital cost. In this case, the battery was replaced two times since its lifetime was only 7 years. Operational and maintenance cost and total replacement cost (RC_{Total}) was calculated by using Equations (12) and (13).

$$OnM = 11.5 \times PV_{cap} \tag{12}$$

$$RC_{Total} = RC_{inv} + RC_{SCC} + RC_{Batt} \tag{13}$$

where PV_{cap} is the total capacity of PV modules, RC_{inv} is the replacement cost of the inverter, RC_{SCC} is the replacement of the solar charge controller, and RC_{Batt} is the replacement of the battery.

The annualized capital and replacement cost, called annual fixed charge *(AFC),* was then calculated by considering the amortization factor (α). This factor considers the inflation rate and lifetime of the PV system. Equations (10) and (11) were used to calculate the amortization factor and annual fixed charge, respectively. In these equations, *i* is the inflation rate, and *n* is the lifetime of the PV system.

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{14}$$

$$AFC = \alpha \times (CC_{Total} + RC_{Total}) \tag{15}$$

The electricity cost (C_{el}) was then calculated by using Equation (12):

$$C_{el} = \frac{AFC + OnM}{ED_{ann}} \tag{16}$$

where ED_{ann} is annual electricity demand.

Table 5 shows the assumptions of the prices of each component. The price information was obtained by surveying the market, and their reasonability was checked by comparing it with the report from NREL (Cole and Frazier, 2019; Fu, Feldman, and Margolis, 2018). The specific price is needed to check the reasonability of the price used in this study because most of the statistical report shows specific prices.

Table 5 Price list of main components

No	Component	Capacity/unit	Price ($)	specific price
1	PV module	375 W	307.5 $	0.82 $/W
2	Battery	1.2 kWh	200 $	166.67 $/kWh
3	Inverter	500 W	30 $	0.06 $/W

4. Result and Discussion

Figure 4 shows the sample simulation results of usable power production from a single PV module for two consecutive days. The usable power production strongly followed global solar irradiation. The usable power production is the AC electric power that considers the losses of inverter and battery efficiency. Based on technical data of PV module, the temperature coefficient of power is only -0.37 %/°C. Moreover, the temperature fluctuation is not that significant, ranging from 16 °C to 28 °C. This ambient temperature profile is typical for highlands in tropical country. Therefore, the ambient temperature didn't affect the power production significantly.

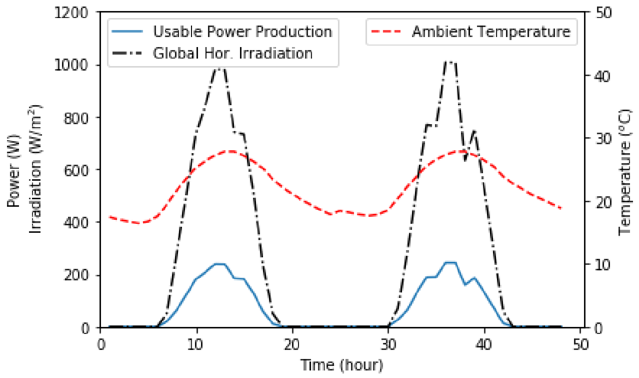

Figure 4 Simulation result of the usable power production based on the weather conditions

Figure 5 displays the daily usable energy production of a single PV module, which varies between 0.93 kWh and 1.91 kWh, with an average of 1.61 kWh. These data were then used for the sizing capacity of the PV module. In strategy A, the capacity of the PV module was determined based on the annual energy production. The number of PV modules was determined; thus, the system produces annual energy as same as the annual demand. All the excess energy production was stored in the battery, and it was used when the daily energy production was less than the daily demand. In strategy B, the capacity of the PV module was determined based on the minimum daily energy production day. The PV system must be able to produce energy as much as demand, even though at the lowest production day. Therefore, the battery capacity can be minimized to only one autonomous day. However, dumping energy was inevitable in this strategy.

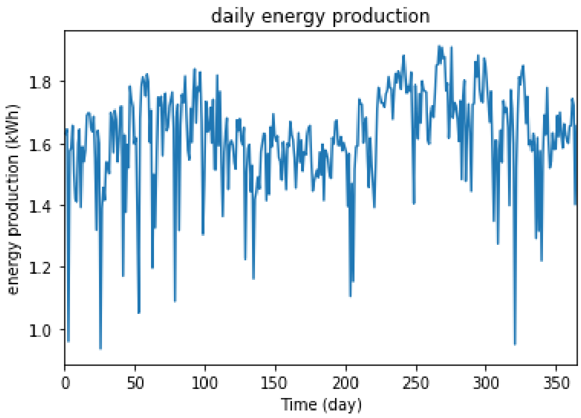

Figure 5 Simulation result on daily usable energy production from a single PV module for a year

Table 6 compares the sizing capacity of the PV system between the two strategies. As electricity production from the PV system is intermittent and fluctuating, a proper strategy is necessary to address any potential mismatch between electricity production and demand. The strategies discussed in this study aim to ensure uninterrupted electricity supply to fulfill the electricity demand.

Table 6 Comparison of PV module, battery, and energy between the strategies

No	Parameter	Strategy A	Strategy B
1	PV module Capacity	0.75 kW	1.5 kW
2	Battery capacity	27.2 kWh	4.0 kWh
3	Annual energy demand	1180 kWh	1180 kWh
4	Annual energy production	1181.8 kWh	2363.8 kWh
5	Annual dumped energy	1.8 kWh	1183.7 kWh

Strategy A required 0.75 kW of PV module capacity and 26.8 kWh of battery capacity. The PV module capacity was determined by estimating the annual energy production so that it was as same as the annual energy demand. Therefore, the mismatch between daily energy production and demand was unavoidable. This strategy required a huge capacity of battery to accommodate the accumulation of excess energy production in the dry season and deficit energy production in the rainy season. Without considering the recommended DoD, the required capacity of the battery is 6.6 autonomous days. It meant that the battery was enough to supply electricity to the demand for 6.6 days without interruption, even if the production from the PV system was zero. The dumped energy was very low, which is 1.8 kWh, because almost all the excess daily energy production is stored in the battery. The PV capacity of the PV module is slightly oversized because the number of PV modules must be an integer.

In strategy B, the PV module and battery capacities were 1.5 kW and 4.0 kWh, respectively. The PV capacity is determined by choosing the lowest energy production day as the basis calculation. Therefore, it required a relatively huge capacity of PV modules. By using this strategy, the daily energy production was always equal to or higher than the energy demand. This strategy allowed the system not to store the accumulation of consecutive excess daily energy production. It implied that the required battery capacity could be minimized to only one autonomous day. However, dumping energy was not unavoidable due to the limitation of battery capacity. The annual dumped energy was 50.1 % of annual energy production. It was reasonable since the energy must be dumped almost every day (except the lowest energy production day).

Those two strategies discussed above were the only options if the demand must be fulfilled without interruption for a whole year. Reducing the capacity of the PV module or battery caused energy shortage conditions for some hours. From the energy point of view, strategy A is the most optimum strategy because, theoretically, the dumped energy can be avoided. In other words, all the energy produced by the PV module is used to supply energy demand.

Table 7 shows the economic comparison between the two strategies. The capital costs of the components were proportional to their capacity. It is worth noting that the capital cost is the initial cost for the system to work properly during the first operation. Therefore, the replacement cost is not included in the capital cost. It also meant that the capital cost of the battery was only for the first seven years of operation. For the whole designed operation time (20 years), the battery must be replaced twice. The replacement costs were considered for calculating the electricity cost as expressed in Eq. 16. The most expensive capital cost for strategy A was for the battery, which takes 80.9 % of the total capital cost. Contrarily, 67.2 % of the total capital cost was for the PV module in strategy B which made it the highest capital cost of the component. The total capital cost of strategy B was only 52.5% of the total capital cost of strategy A. In the case of the electricity cost, strategy B also resulted in much lower costs which only 29 % of the cost resulting from strategy A. Based on this economic analysis, it implies that strategy B was more feasible than Strategy A to fulfill the same electricity demand.

Table 7 Economic aspect comparison

	Strategy A	Strategy B
Capital cost of PV module ($)	707.25	1414.5
Capital cost of Battery ($)	4600	800
Capital cost of Inverter ($)	60	90
Total Capital cost ($)	5367	2304.5
Electricity cost ($/kWh)	1.00	0.29

4. Conclusions

The problem of off-grid PV system are the expensiveness of battery and the interruption electricity supply. To overcome those two problems, certain design strategy is needed. In this study, two different strategies for designing the off-grid PV system to fulfill the same demand were compared. The first strategy uses the optimum number of the PV system, so the dumped energy can be minimized. However, it needs a large capacity battery to accommodate the difference between electricity production and demand. The second strategy uses a minimum capacity of the battery. The capacity of the PV module is determined by considering the lowest energy production day. Therefore, this strategy dumps a lot of energy produced by the PV system. Strategy B uses a larger capacity PV system but a smaller capacity battery than Strategy A. Even though the capacity of the PV system is larger, strategy B is more feasible than strategy A since the total capital cost and electricity cost are only 42.9 % and 29.0 % of strategy B, respectively. However, strategy B dumped 50.2% of the energy produced by the PV system because the capacity of the battery is small. In the future, the design concept for harnessing the dumped energy should be investigated thus the system may have additional economic value.

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