Study on optimum configuration of off-grid systems from the viewpoint of renewable energy ratio and investment cost

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***Abstract*—In this paper, the optimum configuration of DC off-grid systems from the viewpoint of renewable energy ratio and the installation cost has been studied. The DC off-grid system is assumed to consist of power loads for 50 three-person-households, solar panels and storage batteries installed in each house, an emergency power generator, and a DC bus-line that electrically connects them. The power flow of the DC off-grid system is numerically simulated over a period of one year and the renewable energy ratio and the installation cost is estimated. Based on the simulation, the optimal configuration and installation cost of the grid components required to achieve a given value of the renewable energy ratio has been derived.**

***Index Terms*—off-grid, optimum, renewable energy ratio, investment cost**

I. Introduction

Several environmental issues brought on by global warming have raised significant concerns about energy use. The Paris Conference encouraged Japan, which is heavily reliant on fossil fuels, to set a goal towards becoming carbon neutral by 2050, which Prime Minister Yoshihide Suga announced in October 2020.This initiative has driven a series of energy policy and institutional reforms in Japan, including the expansion of renewable energy, the restoration of nuclear power, and the decarbonization of the power sector [1].

As a power system independent of the system grid, off-grid system is one of the important ways to promote energy saving and CO_2 emission reduction on the one hand, and on the other hand, the development of off-grid technology is inevitable for areas or buildings that cannot be connected to the system grid due to geographical constraints. Numerous studies have been carried out to demonstrate the feasibility, viability, financing index and risk factors of off-grid systems [2], [3]. In off-grid systems, the reasonable configuration of backup power is inevitable to effectively reduce the system cost and improve the stability of system power supply.

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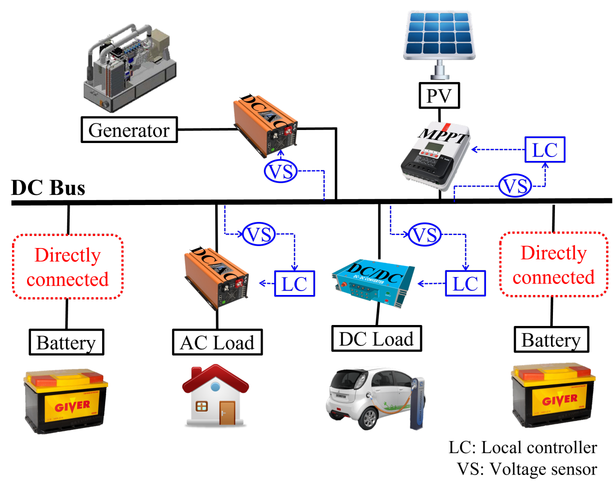

Fig. 1. Configuration of off-grid system based on ADCC.

This paper focus on the annual power variation under the proposed ADCC-based off-grid system and numerically derive the maximum generator power that can be adapted to this system to obtain the optimal generator power configuration. In order to figure out the optimal grid design and investment cost for various system goals, simulations of various combinations of important system components, including PV cells and generators, have also been performed in terms of feasibility, renewable energy ratio, and installation cost.

II. Design of ADCC-based Off-grid Systems

Autonomous decentralized coordination control (ADCC), a DC bus voltage control technique based on DC bus signaling [4]–[6], has been demonstrated in simulations [7], [8]. The batteries of ADCC-based off-grid systems are directly connected to the bus line and have the same terminal voltage as the reference voltage on the bus-line as shown in Fig. 1. By utilizing the battery's droop characteristics and electrical inertia, the bus-line voltage can be stabilized. Compared

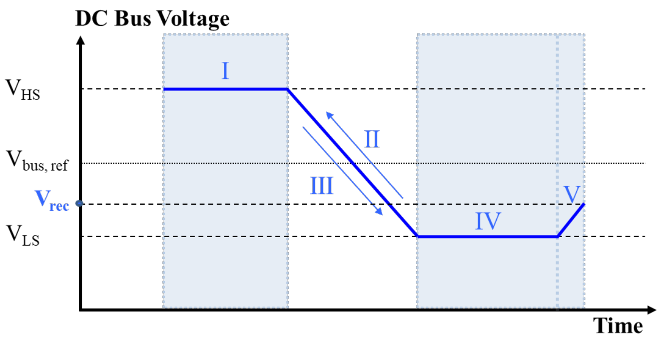

Fig. 2. Bus-line voltage control method for off-grid systems.

to other three main microgrid control methods (centralized control, decentralized control and distributed control [9]–[11]), the ADCC strategy has advantages in terms of simplicity of control (spontaneous control) and disaster resilience, etc [8]. In this paper, the ADCC strategy is improved and applied to an off-grid system, and the optimal configuration for each component in the off-grid systems are designed by evaluating the renewable energy utilization and the installation cost. The control strategy of DC bus voltage in ADCC based off-grid systems is shown in Fig. 2.

The reference voltage of DC bus ($V_{bus,ref}$) is set to 400 V. V_{HS} and V_{LS} represent the maximum ($V_{bus,ref}$ $\times$ 105%) and minimum ($V_{bus,ref}$ $\times$ 95%) values of the permissible range of the bus-line voltage for realizing stable operation of microgrids, respectively.

The off-grid system is designed to process three operating modes (ADCC mode, over voltage protection and under voltage protection modes) and five voltage variation states can be classified according to the different operating states of each component, which are summarized in Table. I. The details of the three operating modes in this control strategy are described as follows:

A. Over voltage protection mode

Over voltage protection mode (state I) prevents overcharging of batteries and maintains the DC bus voltage at +5% of the reference voltage $V_{bus,ref}$. Charge controller operates in float mode, maintaining the battery's state of charge (SoC) at 100%. Only the amount of power needed by the load will be produced and any additional power generated will be discarded. The power flow in this mode is shown in eq. (1).

$$P_{Cons} = P_{PV}^{Float} \tag{1}$$

B. ADCC mode

ADCC mode is active when the bus-line voltage is within $\pm 5\%$ of $V_{bus,ref}$. In this mode, II and III representing for the charging and discharging of batteries are considered. The bus-line voltage increases as the battery charges, approaching the maximum value of V_{HS}, corresponds to a battery SoC of 100%. Additionally, when the battery is being discharged, the bus-line voltage drops until it reaches a minimum point V_{LS}, which corresponds to the battery SoC is 10%. In ADCC mode, only PV and batteries are involved in supplying power to the load, and the PV operates at the maximum power point tracking (MPPT) mode. In this mode voltage of the bus-line is stabilizing by electrical inertial force and droop characteristics of batteries as shown in eqs. (2) and (3), respectively.

$$P_{Cons} + P_{Batt}^{Charge} = P_{PV}^{MPPT} \tag{2}$$

$$P_{Cons} = P_{PV}^{MPPT} + P_{Batt}^{Discharge} \tag{3}$$

C. Under voltage protection mode

Under voltage protection mode exists to protect batteries from excessive discharging. The bus-line voltage in this mode is mainly operated by the emergency generator. The emergency generator will enter standby mode and prepare to provide power when the bus-line voltage approaches to its lower limit. Additionally, the generator will attempt to maintain the bus-line voltage by changing the output on its own when the bus-line voltage drops below the lower limit. At this point, the emergency generator and PV power generation are providing all of the power needed to run the total loads, and the battery discharge has stopped (state IV). The energy flow for state IV is shown in eq. (4).

$$P_{Cons} = P_{PV}^{MPPT} + P_{Generator} \tag{4}$$

When the power generated by the PV devices exceeds the total power consumption of the loads, the surplus power charges the battery and the emergency generator shifts to standby (state V). After the battery is sufficiently charged and the bus-line voltage recovers from the lower limit, the system switches to ADCC mode and shuts off the backup generator. The energy flow in state V is shown in eq. (5).

$$P_{Cons} + P_{Batt}^{Charge} = P_{PV}^{MPPT} \tag{5}$$

In both states of the battery protection mode, the PV operated in MPPT mode.

III. Simulation Analysis of ADCC Based Off-grid System

A battery plays a key role in controlling the baseline voltage in an ADCC-based off-grid system. In a typical lithium-ion battery, the terminal voltage has a nearly linear relationship with the SoC, within a certain range. When the battery voltage is 3.4 V, for instance, the SoC for lithium-iron phosphate ion batteries is roughly 80%, but it is just 5% when the battery voltage is 3.1 V. Multiple batteries should be run in series and parallel for a 380 V system in order to provide sufficient voltage. To load a Li-ion iron phosphate battery with a terminal voltage of about 3.2 V per cell, 60 cells should be connected in series to achieve a terminal voltage of about 192 V, where the battery SoC is about 50%.

Since the internal transformation of a lithium-ion battery involves complex chemical processes, fitting experimental data

TABLE I
OPERATING MODES IN ADCC BASED OFF-GRID SYSTEM

DC bus operation mode	State	Battery		Charge Controller (PV)	Generator	Voltage Status	Power Characteristics
		Charge	Discharge				
Over Voltage Protection Mode	I	×	O	Float	Stop	$V_{bus} = V_{HS}$	$P_{Cons} = P_{PV}^{Float}$
ADCC Mode	II	O	×	MPPT	Stop	$V_{bus} \uparrow \& V_{LS} < V_{bus} < V_{HS}$	$P_{Cons} + P_{batt}^{Charge} = P_{PV}^{MPPT}$
	III	×	O	MPPT	Stop	$V_{bus} \downarrow \& V_{LS} < V_{bus} < V_{HS}$	$P_{Cons} = P_{PV}^{MPPT} + P_{batt}^{Disharge}$
Under Voltage Protection Mode	IV	×	×	MPPT	Operating	$V_{bus} = V_{LS}$	$P_{Cons} = P_{PV}^{MPPT} + P_{Generator}$
	V	O	×	MPPT	Stop	$V_{LS} < V_{bus} < V_{rev}$	$P_{Cons} + P_{batt}^{Charge} = P_{PV}^{MPPT}$

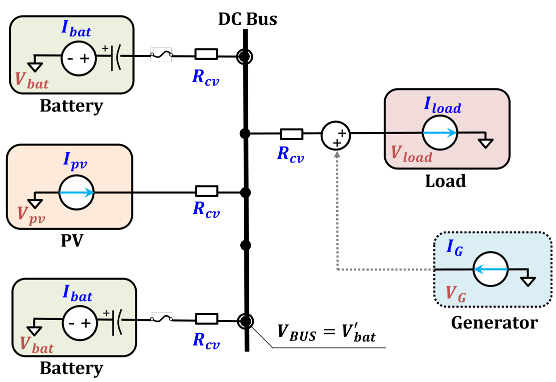

Fig. 3. Simulation model diagram of the off-grid system.

to construct a model that matches its charging and discharging characteristics is a common modeling technique. The battery is modeled in the simulation as a capacitor connected in series to a voltage source, with the output voltage of the voltage source derived by fitting the data to the capacitor using a look-up table obtained in experiment. In the designed off-grid system, over-discharge recovery voltage (V_{rec}) was set to -2.5% of the reference voltage (the battery SoC is approximately 20%).

PV and load have been constructed based on current source, where daily irradiance data of Sendai City, Japan for 2019 was used as input data to calculate the output power of PV. The irradiance data is multiplied by the entire system efficiency at 70% taking into consideration the impacts of shadowing, the inclination and orientation of the installation and the imbalance of the PV module, etc. In addition, PV module conversion efficiency was set at 15%. The load model was assumed to contain fifty three-person households, where the power consumption of each household is a random number satisfying a normal distribution. Besides, the generator is designed to compensate the load demand directly, so it is designed as a current compensation model located at the load. Based on above, simulation model of the ADCC based off-grid systems is built in MATLAB/Simulink according to Fig. 3. This abbreviated model is appropriate for this simulation because our goal is to optimize the capacity of the components in the system over a long time horizon (in years), so the sacrifice in simulation time due to an overly detailed model will not be considered in this model.

Due to geographical constraints and other natural considerations, off-grid systems differ from on-grid systems in that they are not connected to the utility grid. Due to unpredictable generation brought on by rainy weather, it becomes challenging to maintain DC bus voltage stability in off-grid systems, particularly in stand-alone PV systems.

Two options can be taken into consideration to address the unstable nature of renewable energy in PV-based off-grid systems: (1) increasing the PV generation power and battery capacity in the grid; (2) adding an emergency generator. Given the yearly variance in daily power generation and the load's consumption patterns, the equipment capacity in the first way has to be increased significantly. As a result, higher initial investment costs are a consequence of larger equipment. In the second strategy, however, lowering carbon emissions or even achieving zero emissions is a crucial indicator for a successful transition of the power system.

Therefore, in a system that assumes a diesel generator as a backup power source, the optimal configuration of the off-grid system can be obtained by analyzing its renewable energy ratio as well as the investment cost, using the generator power required for different combinations of PV and batteries as variables.

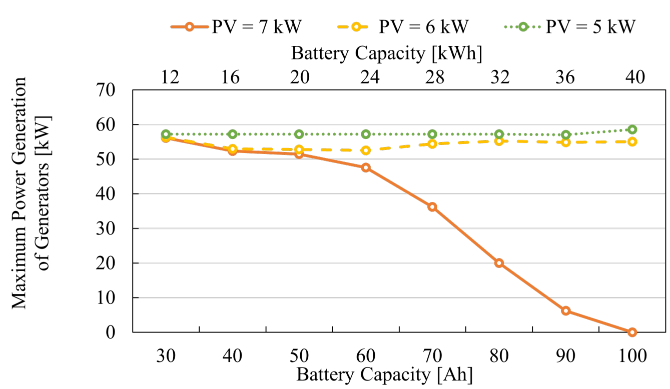

Fig. 4. Required maximum power for generators under different combination of PV and battery

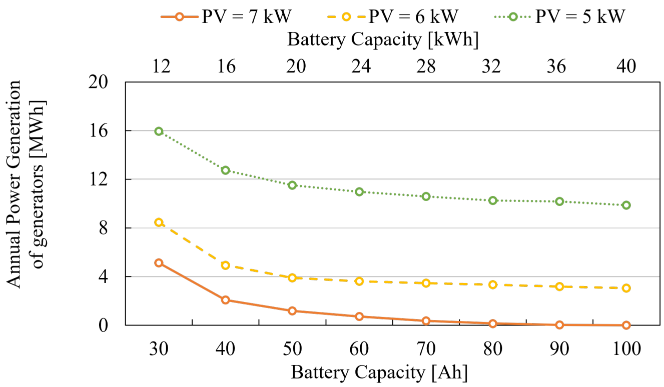

Fig. 5. Annual power generation of generators under different combination of PV and battery

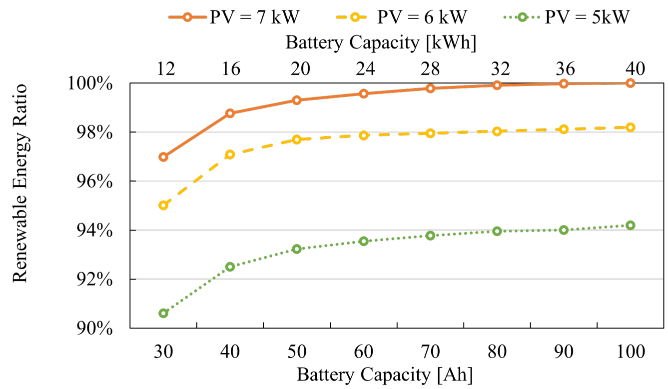

Fig. 6. Renewable energy ratio at different combination of PV and battery capacity

In order to prevent blackouts, the emergency power generator's maximum output power must be greater than the maximum power demand during peak hours. With the combination of various PV output powers (5-7 kW) and battery capacities (30-100 Ah), which were achieved under ten different sets of load data, we simulated the maximum power generation and required output power of the generator. The maximum generator power needed for 5 kW and 6 kW PV systems, shown in Fig. 4, is nearly identical to one another, at 53 kW and 57 kW, respectively, and remains basically the same as the battery capacity increases. In contrast, the maximum generator power needed in the case of 7 kW PV reduces as the battery capacity increases.

Generally, the maximum generator power is determined by the maximum power demand throughout the year (which generally occurs in January and February during the winter months). Due to the insufficient power generation at a small PV (5 kW or 6 kW), the maximum power demand can only be met by the generator, despite increasing the battery capacity. As a result, the generator's maximum power output is nearly unchanged at 5 kW and 6 kW PV. The maximum load requirement can be partially satisfied by the PV generation when it is large enough (7 kW), however this is constrained by the battery capacity. Even though the PV power generation is large while the battery capacity is low, only a tiny fraction of it is really used because of the battery capacity restriction, and the generator is still required to handle the maximum load. When the battery capacity becomes large enough, the maximum load can be met entirely by PV generation, so the maximum generator power generation tends to decrease as the battery capacity increases.

As can be seen in Fig. 5, the annual generated energy produced by the generator decreases as the battery capacity increases, and the rate of decline slows. This is due to larger batteries have better solar power storage capabilities, which minimizes the amount of electricity needed by loads. Every 1 kW increase in PV results in a reduction of the generator's annual power output by almost half for the same battery capacity and varying PV power. However, the maximum generator capacity (26 MWh at PV of 5 kW and battery of 30 Ah) is still small compared to the annual load demand (approximately 180 MWh).

A. Renewable energy ratio analysis

The renewable energy ratio (η_{re}) is an indicator that characterizes the proportion of renewable energy consumed at the load as in eq. (6). For a power system composed entirely of renewable energy, the renewable energy ratio is 100%. However, the economic efficiency of a system with 100% renewable energy ratio is very low, and this is the result of sacrificing economy for environmental benefits, which makes the balance between the two an inescapable issue. In the off-grid system proposed in this paper, the expression of renewable energy ratio is as follows:

$$\eta_{re} = 1 - \frac{P_{Generator}}{P_{Cons}} \tag{6}$$

This value can be calculated from the data obtained in Fig. 6, and the result is as follows.

As can be seen in Fig.6, η_{re} increases with increasing battery capacity non-linearly, and leveling off at higher battery capacities. At PV of 7 kW, the maximum renewable energy ratio achievable is 100% and the minimum value is about 97%. The reduction in capacity of 70 Ah brings about a 3% decrease in renewable energy ratio compared to the maximum battery capacity. When the PV power is reduced from 7 kW to 6 kW, the overall renewable energy ratio decreases by about 2%. The ratio of renewable energy decreased considerably, by around 4%, from 6 kW to 5 kW. Nevertheless, the observed minimum renewable energy ratio is greater than 90%.

Further, the configuration of PV and battery and generator can be obtained for systems that require various renewable energy ratios to be obtained from Fig. 6. For example, there are a total of 13 sets of data that can be met when the renewable energy ratio is required to be at least 98%, and in all combinations, the battery capacity is at least 40 Ah and the PV power is at least 5 kW, which can be used as a reference for system design.

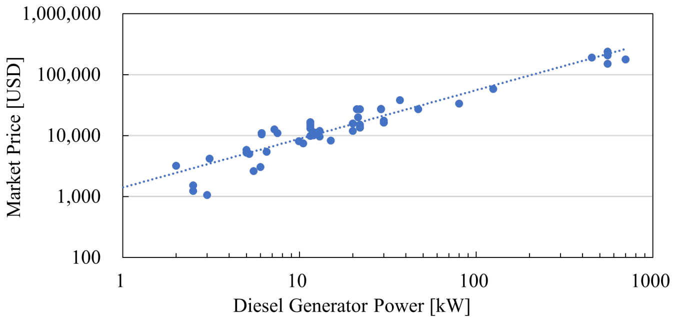

Fig. 7. The relationship between the rated power of diesel power generator (kVA@50Hz@Single-phase and the selling price (excluding tax)

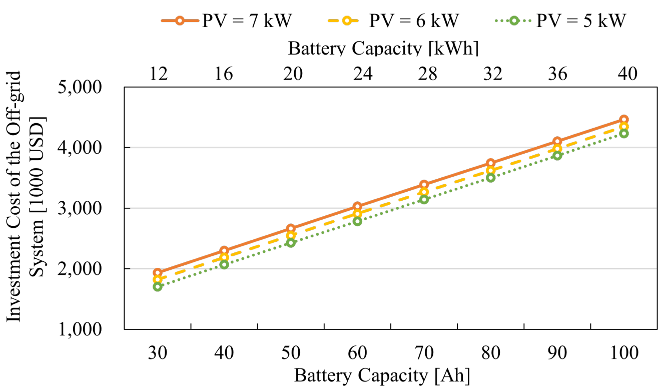

Fig. 8. Investment cost at different combination of PV and battery capacity.

B. Investment costs analysis

The cost of an off-grid system based on emergency generators includes investment cost, operation cost, maintenance cost, replacement cost and fuel cost of the component [2], [3]. However, except for the investment cost, other costs including maintenance and replacement vary greatly from country to country and even from company to company, and the analysis without the support of a large amount of data is not sufficient as a reference, so only the investment cost of key devices (PV, battery, and emergency generator) is discussed in this paper which can be expressed in eq. (7):

$$C_{Invest} = C_{PV} + 2 \times C_B + C_G \tag{7}$$

Here, a diesel power generator is considered as an example for investment cost analysis, considering that it is very common as an emergency generator and many related studies have been implemented [12]–[16].

Considering that both PV and diesel generators have a maximum life cycle of 20 years, it can be assumed that the whole system has an evaluation cycle of 20 years. Most of the current battery life is 10 years, which means that the battery needs to be replaced once in the life cycle of the system. Therefore the installation cost of the battery is multiplied by 2, without considering the effects of inflation and discount rate here.

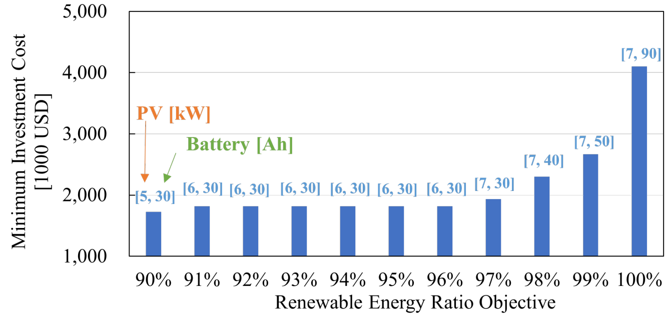

Fig. 9. Minimum investment costs and corresponding system configurations for different renewable energy objectives.

The equipment cost of residential PV systems is based on the average price of 2,100 USD/kW (including installation costs) for new installations across Japan in 2021. By calculating the annual selling price capacity of lithium-ion battery systems in Japan, the investment per kWh of battery can be derived, as about 915 USD/kWh. Besides, the investment cost of diesel power generators C_g (USD/kW) is derived from a statistical survey of diesel generators currently on the Japanese market, which is depicted in Fig.7. The slope of the price versus power curve of diesel generators is less than , which means that the price per kW of diesel generators shows a tendency to decrease as the kW increases and this result is consistent with the description by Eskenazi et al [17].

Based on the results of the maximum power of the generator for different combinations of PV and battery in the previous subsection, its investment cost is calculated as shown in Fig. 8.

As can be seen from Fig. 8, the investment cost for PV of 5 kW and battery of 30 Ah is the smallest of all PV and battery combinations, at approximately 1.7 million USD. The system cost basically tends to increase linearly with increasing battery capacity, while the impact of the diesel engine on the system cost is very limited. This is because the emergency generator has essentially the same rate power for majority combinations of PV and battery, meaning that investment cost of the diesel generator has little impact on the overall system investment cost.

Since emergency generators balance the annual variation of renewable energy sources and the load power demand of the grid, they have a significant economic advantage over off-grid microgrids without them, and effectively reducing the equipment size of off-grid microgrids.

Based on the calculation of the renewable energy ratio in the previous subsection, the optimal investment cost and the corresponding optimal configuration for each renewable energy ratio objective can be obtained, as shown in Fig. 9, respectively. The investment cost of the system increases non-linearly with the increase of the renewable energy ratio. In contrast to the slower increase in investment cost for η_{re} at smaller amounts, the increase for η_{re} at larger amounts and close to 100% is very significant. It is noteworthy that for the system with the renewable energy ratio objective of η_{re} = k (k=92%-94%), the lowest investment cost occurs at 95% of 6 kW PV and 30 Ah (12kWh) battery. Therefore, the objective of renewable energy ratio between 91%-95% is the same for this off-grid system's optimum configuration with the lowest investment cost. The investment cost increases non-linearly with the increase of renewable energy ratio objective. The investment cost is lowest for η_{re} = 90% when the required PV and Battery are 5 kW and 30 Ah, respectively, while the investment cost becomes 2.5 times higher if the η_{re} equals to 100% (2.5 times higher than for η_{re} of 90%). In comparison, instead of aiming for a high investment cost for a 100% renewable energy ratio, it may be acceptable to aim for a 90% system design, since 90% renewable energy ratio is also a fairly high value. This method can be used to obtain specific system configurations for different renewable energy ratio objectives, serving as a guide for off-grid system design.

IV. Summary

In the proposed ADCC-based off-grid system, the maximum generation capacity of the required standby generator was obtained by numerically simulating different PV and battery combinations for the power demand of 50 households, and it was further concluded that an off-grid system equipped with at least 7 kW of PV and more than 100 Ah (40 kWh) of battery is fully feasible to operate independently without standby power.

In addition, by calculating the annual generation capacity of the backup generator in the simulation, the renewable energy ratio was calculated and evaluated, and the relationship between the renewable energy ratio and the equipment configuration was obtained.

Further, by investigating the investment cost of each component, the off-grid system configuration with the minimum investment cost per renewable energy ratio was calculated. For systems with renewable energy ratio requirement above 90%, the system configuration with PV at 5 kW and battery at 30 Ah is optimal, and the optimal system configuration for other renewable energy ratio objectives can also be derived by referring to the chart. Therefore, this method can be used to obtain specific system configurations for different renewable energy ratio objectives, which provides a reference for the design of off-grid systems.

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