VERIFICATION OF OFF-GRID SYSTEM FOR REMOTE ISLANDS USING A RENEWABLE ENERGY AND STORAGE SYSTEM

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ABSTRACT

In this study, we inspected each generation capacity of photovoltaics power generation facilities (PVs), a battery energy storage system (BESS) and diesel engines (DEs) on a remote island. During the verification, because the unique load consumption as island, annual load current and solar radiation were measured, the combined capacity of each piece of power generator equipment that minimized the installation and operation cost were calculated.

INTRODUCTION

Off grid systems (OGS) are expected to have potential as systems supplying power system to areas with low demand density, such as remote islands or mountaintop loads, while limiting capital costs and preventing the risk of blackouts caused by natural disasters. In recent years, OGS has also been touted as a source of eco-friendly electric power using renewable energy such as photovoltaic power generation (PV), wind turbines and a battery energy storage system (BESS). However OGS is not connected with the grid system and since PVs cannot generate electricity overnight and in rainy weather, the BESS capacity must be increased at huge cost to avoid any outage. The target island is a famous sightseeing spot in Tokyo Bay, which is uninhabited and remains a historical site. Although electricity is currently supplied by DEs, we examined the potential of using PV and BESS, because of the high fuel transportation and operation costs and with the environment in mind.

ASSUMED OFF GRID SYSTEM

In this study, OFS shown in Fig. 1, it is assumed that PV, BESS and DE are applied as emergency power sources to avoid a situation where electric power is only supplied by DE, which would involve a considerable daily operational burden, encompassing a maintenance check, replacement of facilities and fuel transportation. Concretely, PV mainly supplies electric power to cover the island-wide load, while BESS compensates for any surplus or shortfall of electricity by charging / discharging. At night or on rainy days, BESS supplies electric power charged during daytime. In case PV cannot be generated for an extended period, e.g. during the rainy season and when the charging state (SOC) runs short, DE is assumed to use temporary power sources. DE output is rated and maintains a constant value for a certain period and can be used not only to cover power demand but also to charge BESS.

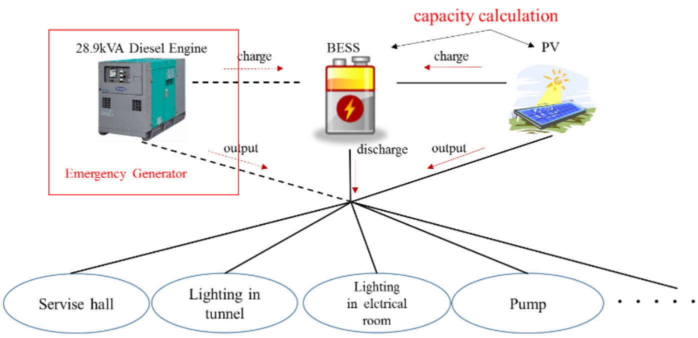

Fig. 1. Outline of the off-grid power supply system

LOAD AND PV OUTPUT ON ISLAND

Since OFS is an uninhabited island and its load usage is unique, determining the capacity of PVs and BESS to be introduced, the actual trend of load by measurement must be determined. Measuring equipment was installed on the distribution board and the load consumptions were measured on each circuit for one year from 9 July, 2016, with load data measured at nine locations each every minute. Figs. 2 and 3 show example measurement results: annual peak load and trend of daily load consumption respectively.

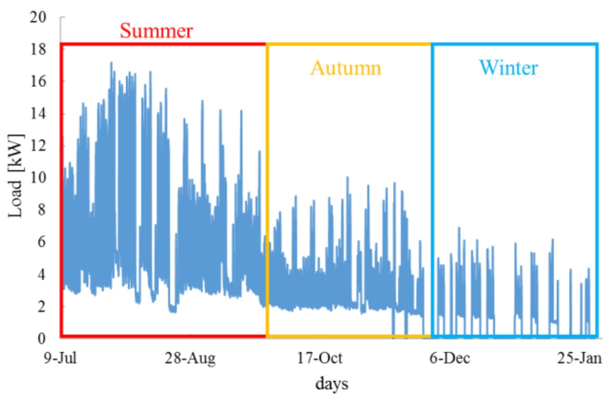

Fig. 2. Measured annual load consumption

The summer load soared, given the increased number of sunbathing island tourists and increased demand for cooling in offices and shops. After autumn, the peak load decreased and fluctuated periodically, because there were more island customers on weekends than weekdays.

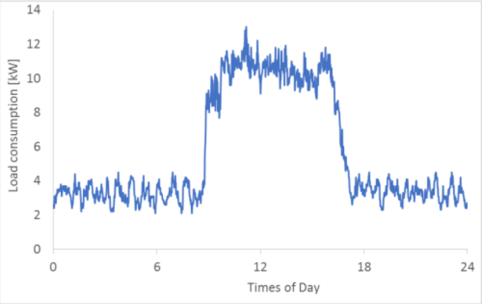

Fig. 3. Trend in daily load consumption

In other words, the island power consumption depends on the number of visitors, with both temperature and visitor numbers declining on days of bad weather and likewise the utilization rate of the electricity load. However, the electricity load did not reach 0 kW, since even while the island was uninhabited, several kW were consumed and it was necessary to consider introducing the OGS. Over winter, load consumption was relatively small and 0 kW on many days. In winter, people did not visit the island except at weekends and the generator was stopped after 17:00. Fig. 3 shows the load waveform of a typical day (July 9). The load between 8am and 5pm, the period when people enter the island, far exceeds other time zone. A load of around 2 to 4 kW was constantly drawn during periods when no-one was present on island except during the winter season.

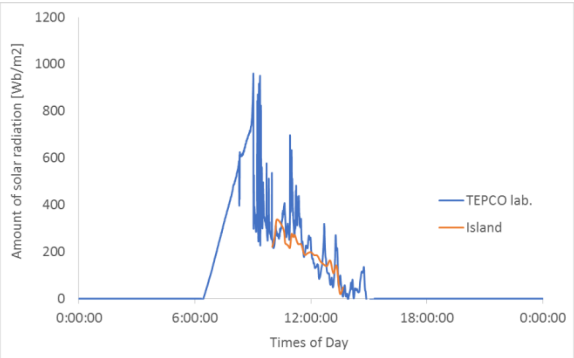

Fig. 4. Comparison of solar radiation data with island and TEPCO lab.

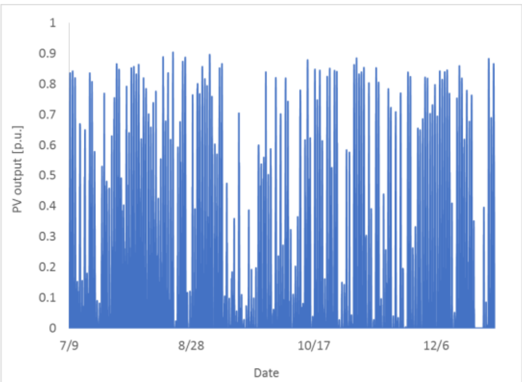

Fig. 5. Solar radiation data (July 9 to December 31 at TEPCO lab.)

For the PV output, since it was difficult to install a solar monitor on the island, we used the measurement result data of the TEPCO laboratory (TEPCO lab.) located near the island. Fig. 4 compares the solar radiation data on October 25 measured in the island and the TEPCO lab respectively. As shown in the figure, on days when clouds increased from noon, the same characteristics were confirmed from both graphs. Fig. 5 shows the PV output data from July 9 to December 31, which was the period for which the load was measured on the island.

CAPACITY SELECTION METHOD IN OFF-GRID

We analyzed the necessary capacities of PV and BESS and the operating number of existing DE, for installing OGS on the island using the load and solar radiation shown in the previous section. During the verification, the following four steps were considered:

Step 1: Derivation of combination that minimized cost when using only BESS and PV.
Step 2: Verification of the effect of reducing the required BESS by DE operation
Step 3: Derivation of the optimum combination to minimize the cost of introducing power and DE operation, initial SOC of BESS
Step 4: 1 year simulation of Step 3

During Step 1, using the measurement load and PV data, the usable BESS capacity for the period was calculated. At this time, the PV capacity was charged between 31 to 80 kW in 1 kW increments to calculate the minimum required BESS capacity for each PV capacity and the equation used to evaluate the cost is shown in Eq. 1.

$$\min C_{all} = \left(\frac{C_{PV}}{L_{PV}} + \frac{C_b}{L_b}\right) \times \frac{P_{sim}}{12} \quad \text{Eq. (1)}$$

where, C_{all}: total cost, C_{PV}: PV installation cost, C_b: BESS installation cost, L_{PV}: PV lifetime, L_b: BESS lifetime, P_{sim}: simulation period,

Table 1. Simulation condition (Steps 1, 2)

Initial BESS SOC	100 [%]
BESS output efficiency	85 [%]
PV output range	31 to 80 (1 kW increments)
Maximum load	21.4 [kW]
BESS capacity range	0 to 7000 [kWh]

An example simulation result is shown in Fig. 6 with PV waveform 100 patterns. Even if the PV capacity were set to 80 kW, the maximum of the current search range, 1 MWh of BESS capacity was required to supply the load. As the PV capacity increased, the BESS capacity linearly decreased and the rate of reduction in BESS capacity with respect to the increase in PV capacity declined, with a PV capacity of around 50 to 60 kW. When the PV capacity was small, the charge to the BESS by PV was small, the power to cover the load depended on the BESS capacity and during the period of “PV output < load”, the SOC of BESS showed a declining trend (Fig. 7).

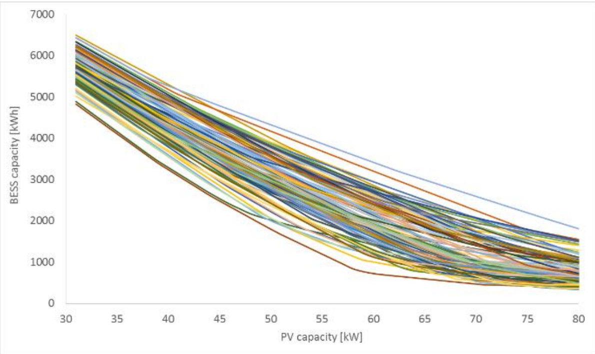

Fig. 6. Combination of operable PV and BESS capacity

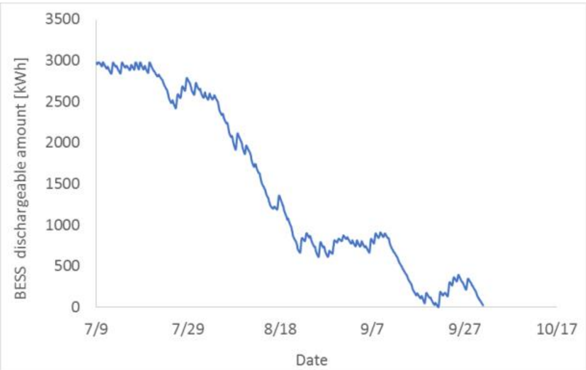

Fig. 7. Trend of BESS capacity (SOC) in the event of insufficient power generation

BESS CAPACITY REDUCTION BY DE OPERATION

In Step 2, the BESS capacity reduction effect was evaluated by performing a DE operation when the SOC of BESS decreased in the case of Step 1. Single operation of DE was set to 10 hours from 8am to 5pm daily and to determine the day that BESS capacity could be minimized using an exhaustive search for one day to operate. This procedure was carried out by changing the number of DE operation up to 10 times, whereupon the operable BESS capacity for each PV capacity was calculated.

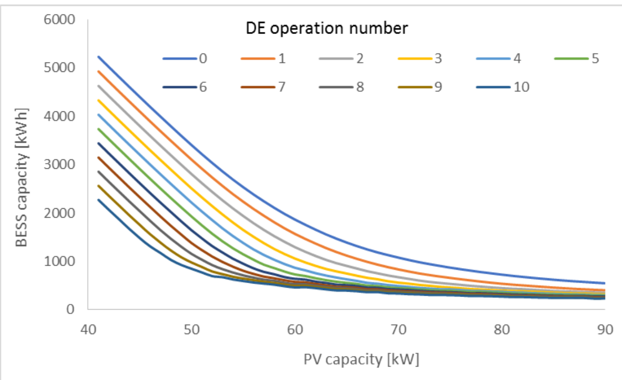

Fig. 8. Relation between PV capacity, number of DE operations and required BESS capacity

Fig. 8 shows the required BESS capacity for PV capacity and the number of DE operation. When the PV capacity was small, the required BESS capacity was proportionally related to the DE operation number and the required BESS capacity decreased with increasing PV capacity.

OPTIMUM COMBINATION TO MINIMIZE INTRODUCTION COST

In addition to the BESS capacity that minimized cost for each PV capacity, the number of DE operations, a combination of initial SOC of BESS as a new parameter, was derived.

1. At first, with initial SOC set to 50%, the required BESS capacity was calculated assuming a fixed PV capacity.
2. By decreasing the BESS capacity by 1kWh from the calculated minimum required BESS capacity, under circumstances of insufficient BESS capacity and where electric power could not be supplied, the DE was started for 10 hours to supply a load and charge to BESS.
3. Similarly, procedures 1 and 2 were performed by changing the PV output by 1kW increments.
4. With the PV output in mind, BESS capacity and DE operation number obtained in 3, the initial cost and operation costs such as fuel and maintenance, were taken into account and expenses for the verification period were calculated. The equation used for cost evaluation is shown in Eq. 2.

$$\min C_{all} = \left(\frac{C_{PV}}{L_{PV}} + \frac{C_b}{L_b}\right) \times \frac{P_{sim}}{12} + DE_{count} \times \left(C_{carry} + C_{fuel} + \frac{C_{DE}}{L_{DE}}\right) + C_{ini} \quad \text{Eq. (2)}$$

where, C_{all}: total cost, C_{PV}: PV installation cost, C_b: BESS installation cost, L_{PV}: PV lifetime, L_b: BESS lifetime, P_{sim}: simulation period, DE_{count}: number of DE operation, C_{fuel}: fuel cost per one operation, C_{carry}: transportation cost each time, C_{ini}: initial installation cost such as EMS, C_{DE}: DE installation cost, L_{DE}: DE lifetime,

5. The BESS capacity selected for each pattern was extracted and the number of DE operations was calculated by changing the PV capacity to 30 to 80 kW and the initial SOC to 30 to 100% respectively.
6. In 5, combinations that minimized the cost for the PV of each capacity were calculated.

Simulations were carried out using data of load and PV waveforms measured for one year. Fig. 9 shows the calculation results of the relation between PV and BESS capacities as the parameter of DE operation number, while Fig. 10 shows the relation between PV capacity and minimum cost as the parameter of DE operation number. Amid limited DE operation numbers, the total cost was decreased by increasing PV capacity, because it cost more to introduce BESS than PV. With the DE operation number unrestricted, the total cost remained almost constant, even if the PV capacity were increased.

Table 2. Simulation condition (Steps 3, 4)

Initial BESS SOC	30 to 100 [%]
BESS output efficiency	0.85 × 0.95 × 0.95
PV output range	31 to 80 (1 kW increments)
Load data (1 year)	Measured in the island
PV data (1 year)	Measured in the TEPCO lab.
Maximum load	21.4 [kW]
BESS capacity range	0 to 7000 [kWh]
DE rated output	28.9 [kW]
DE operating time	10 [hours]
Priority of power supply	1. PV, 2. BESS, 3, DE
Remarks	1. PV excessive power suppression 2. Surplus DE is charged to BESS, further suppression

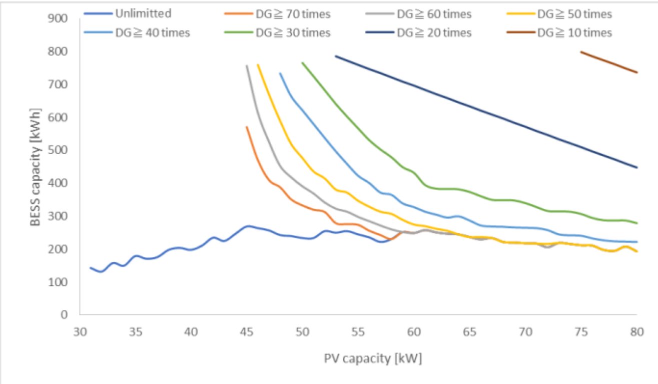

Fig. 9. Relation between PV output and BESS capacity

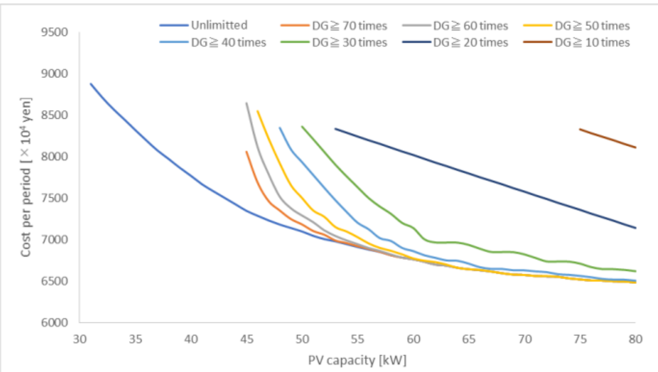

Fig. 10 Relation between PV output and annual cost

The following four patterns were calculated after considering the desire to reduce the number of DE operations with the environment in mind. When the upper limit of the search range of BESS was up to 800 kWh, the condition that enabled load operation for one year could not be obtained in the OGS of only PV and BESS of ①. In ② and ③, the result showed the potential to introduce PV capacity at below the current cost when introducing 80 kW.

In particular, when using the maximum number of DE operations, it is possible to suppress it to about 79% of the present condition. In addition, from Table 3, introducing OGS of PV + BESS in each case paves the way to reduce the maintenance cost to the same level or less and CO_2 emissions can be greatly reduced, even given limited PV capacity and number of DE operations.

①The combination with which the cost is minimized using only PV and BESS.
②The combination with which the cost is minimized using PV, BESS and DE.
③The combination with which cost is minimized using PV, BESS and DE (fewer than 30 days/year)
④The combination with which cost is minimized using PV (less than 50 kW), BESS and DE (fewer than 30 days/year)

Table 3. Simulation result under each limitation condition

Proposal	Annual cost [€/year]	PV output [kW]	BESS capacity [kWh]	DE operation number [Days/year]	CO_2 emission [kg-CO_2]
Original	8,222.6	–	–	365	32256.8
①	–	–	–	–	–
②	6,485.4	80	193	47	3054.1
③	6,620.4	80	279	30	1949.4
④	8,361.3	50	432	30	1949.4

CONCLUSION

This research presented in this paper focused on the selection method for the introduction capacities of PV and BESS and the number of DE operations capable of realizing the lowest operation cost to remote islands considering the introduction of OGS. Simulation results using one year of measurement data show the potential to reduce the operating cost to the same level or less by introducing OGS, which, in turn, shows how CO_2 emissions can be drastically reduced.

REFERENCES

[1] S. Kama, J. Yoshinaga, W. Hirohashi, M. Watanabe, H. Takigasaki, Y. Hayashi, 2017, "Installed generator capacity determination method with variable weather-based SOC operation for island-alone off-grid system", ISGT Asia 2017