Evaluation of cost effectiveness of residential PV/BESS systems in Japan considering outage mitigation and battery degradation#

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ABSTRACT

The system with solar panels and a battery (PV/BESS system) gets residential attention as a measure against natural disasters and fluctuation of electricity costs. This paper aims to evaluate Japan's comprehensive economic profits from the PV/BESS system. This paper uses the optimization model with battery degradation and the one that keeps the state-of-charge (SoC) high. The payback period is calculated from the reduction in electricity costs. The battery's lifespan is also calculated by the operation decided by optimization. As a result, the optimization with degradation achieves the least gap between the payback period and the battery's lifespan. Including the effect of outage mitigation decreases the payback period. Considering the reduction in electricity costs and outage mitigation, introducing the PV/BESS system in a household can be economically viable.

Keywords: battery degradation, economic analysis, PV/BESS system, residential resilience

NOMENCLATURE

Abbreviations	
BESS	Battery Energy Storage System
MPC	Model-predictive Control
PV	Photovoltaics
SoC	State-of-charge
Symbols	
t	Time slot
TC	Total cost
C_{elec}	Electricity cost
C_{deg}	Degradation cost
$C_{\mathrm{deg}}^{\mathrm{cyc}}$	Degradation cost in a complete cycle
SoC	State-of-charge
PB	Payback period
L_{BT}	Battery lifespan
C_{inv}	Investment cost of PV/BESS system
P_{year}	Yearly profit of PV/BESS system
SoH^{min}	State-of-health at the lifespan
d^{cal}	Yearly degradation amount by calendar effect
d^{cyc}	Yearly degradation amount by cycle effect

1. INTRODUCTION

Blackouts caused by natural disasters get more frequent and severe. For example, in Japan, Typhoon No. 15 in 2019 caused a widespread and lengthy blackout in the Tokyo region. As well as increasing the risk of an emergency, electricity costs fluctuate because of the uncertainty of fuel costs. In the winter of 2022, energy costs significantly rose in many regions because of an increase in fuel costs. To mitigate these risks, residential systems that improve self-sufficiency get more attention.

The PV/BESS system is a popular way for households to reduce energy costs and mitigate outages. PV's generation and battery charge and discharge not only reduce the net demand but also supply electricity during outages. Thus, households profit from the PV/BESS system. However, the high investment cost makes it hard to introduce the system.

Several papers investigate the PV/BESS system in terms of cost reduction [1-3] and self-sufficiency [4,5]. The PV/BESS system helps decrease the contract capacity [1] and energy from the grid [1-5]. Deciding the optimal system size improves economic efficiency [1]. However, batteries are not economically viable based on residential behaviors [2,3]. The battery degradation impacts the battery's lifetime [3] and operation [6]. However, these studies do not include outage mitigation as an incentive for the PV/BESS system.

Other papers investigate the PV/BESS system mainly for outage mitigation [7-9]. They discuss the optimal size [7], effects of the demand profiles and weather

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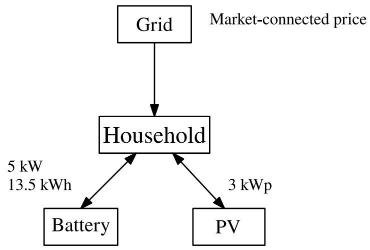

Fig. 1 Household model

conditions [8], and measures against unpredictable outages [9]. However, introducing the system against outages is rational only for the households whose willingness to pay is quite high [8,9]. Economic efficiency and outage mitigation need to be discussed simultaneously.

The residential PV/BESS system reduces electricity costs and mitigates emergency risks. Although previous research considers its economic efficiency, battery degradation, and outage mitigation, the comprehensive analysis that includes all of them has yet to be fully conducted. This paper aims to evaluate the profits of the residential PV/BESS system in Japan. The contributions of this paper are below:

- This paper evaluates the payback period and battery lifetime of the PV/BESS system by explicitly considering battery degradation in the optimization.
- This paper combines the benefits of residential outage mitigation with the economic efficiency. It utilizes actual blackout data in Japan to estimate mitigation effects.

2. MATERIAL AND METHODS

2.1 Household model

Fig. 1 shows the household model. The household has a battery and PV panels. The grid supplies electricity at a price connected to the wholesale market. Fig. 2 shows the electricity prices in the yearly optimization. It is based on the clearing prices in the Kansai region [10].

2.2 Battery degradation model

The battery degrades due to the deep charging and discharging cycle. Such degradation is called the cycle effect. The degradation includes the capacity fade and power fade. This paper focuses on the capacity fade because the reduction in the capacity significantly affects the operation. Fig. 3 shows the relation between the bottom SoC in a complete cycle and the degradation cost based on the model in [11]. The degradation cost is non-linear against the SoC change. Segmentation into eight segments linearizes it. Each segment has the width of a

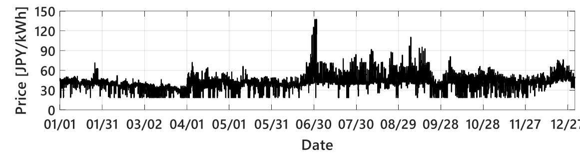

Fig. 2 Electricity price in 2022 [10]

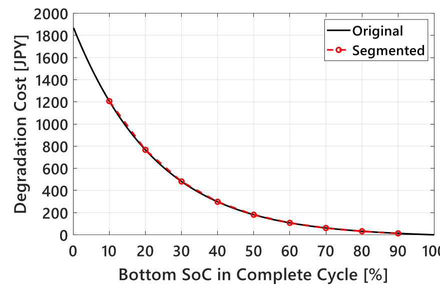

Fig. 3 Degradation cost per complete cycle and its segmented linearization

10% SoC. $C_{\text{deg}}^{\text{cyc}}$ denotes the segmented degradation cost in Fig. 3.

Battery degradation also occurs due to the calendar effect. The speed of the calendar effect depends on the years of use, temperature, and SoC [6]. For simplicity, we use the experimental data on the battery of EVs [12]. The calendar effect degrades the battery capacity by 1.2%/year, not depending on temperature and SoC.

The cumulative degradation caused by the calendar and cycle effects decides the battery lifespan. This paper assumes that a 30% decrease in capacity is the end of the lifespan. The degradation and lifespan of solar panels are not considered.

2.3 Optimization model

The optimization problem decides the battery operation. The overall structure is similar to our previous work [9]. This paper does not include outage occurrence, so the objective function excludes outage costs.

This paper includes the degradation costs in the objective function to protect the battery from the intense cycle effect. In our previous work [9], the optimization in the normal state minimizes the electricity costs. In contrast, this paper minimizes the sum of electricity costs and battery degradation costs. The optimization problem includes linearized degradation costs using the method in [13]. It assumes that the degradation occurs only when the SoC decreases. In each time step, the degradation costs are calculated by subtraction of costs in a complete cycle as shown below:

$$C_{\text{deg},t} = C_{\text{deg}}^{\text{cyc}}(SoC_t) - C_{\text{deg}}^{\text{cyc}}(SoC_{t-1}) \ (\text{if } SoC_t < SoC_{t-1})$$

$$C_{\text{deg},t} = 0 \ (\text{if } SoC_t \geq SoC_{t-1})$$

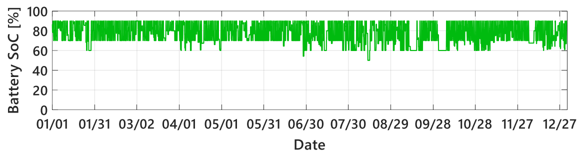

Fig. 4 Battery SoC in the optimization with degradation

When considering degradation, the objective function is to minimize the sum of the electricity and degradation costs.

$$\min TC = \sum_t (C_{\mathrm{elec},t} + C_{\mathrm{deg},t})$$

In contrast, the objective is to minimize electricity costs without considering degradation. Instead of explicitly expressing degradation, the SoC margin restricts deep discharging. We compare the cases with and without degradation and different margin settings. The detail on the SoC margin is expressed in [9].

Electricity prices affect battery operation, but the household does not know future prices. This paper adopts model-predictive control (MPC) to handle this limitation. One optimization problem decides a daily operation, considering the electricity price until the next day. This paper decides on yearly operations using 365 optimization problems.

2.4 Economic evaluation

This paper compares several optimization models in the payback period and battery lifespan. The payback period depends on the initial cost of the PV/BESS system and its yearly profit. It is defined as follows:

$$PB = \frac{C_{\mathrm{inv}}}{P_{\mathrm{year}}}$$

The yearly profit of the PV/BESS system is the cost reduction from the household not having either solar panels or batteries. The battery lifespan depends on the amount of yearly degradation. It is defined as follows:

$$L_{\mathrm{BT}} = \frac{1 - SoH^{\min}}{d^{\mathrm{cal}} + d^{\mathrm{cyc}}}$$

The calendar effect is constant in all cases, but the cycle effect depends on the operations. If the payback period is shorter than the battery lifespan, introducing the PV/BESS system is economically viable.

3. RESULTS AND DISCUSSIONS

3.1 Analysis without outage mitigation

First, we compare the yearly SoC locus. Fig. 4 shows the SoC locus during yearly operation, considering battery degradation. The electricity prices connected to the wholesale market (Fig. 2) stimulate charge and discharge. However, the battery avoids deep discharge because it incurs significant degradation costs. The SoC stays higher than 60% most of the time.

Table 1 Yearly electricity cost and degradation

Case	Elec. Cost [JPY] (Diff)	Degradation [%/year]
No PV/BESS (Baseline)	214600 (-)	-
Margin 0%	66200 (−148400)	7.86
Margin 40%	83400 (−131200)	1.43
Margin 60%	103600 (−111000)	0.47
Deg. Model	101700 (−112900)	0.44

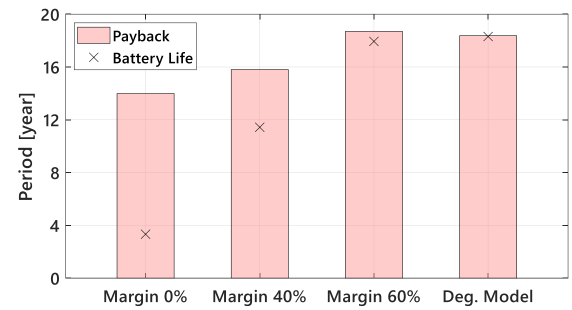

Fig. 5 Comparison between the payback period only considering a reduction in electricity costs and the battery lifetime with different cases

Next, we analyze the payback period and the battery lifespan. Table 1 shows the yearly electricity costs and the degradation amount. Fig. 6 shows the payback period and the battery lifespan. When the battery can discharge deeply, its payback period gets short. At the same time, the battery lifespan also gets short due to the cycle effect. The payback periods are longer than the lifespan in all cases. However, the optimization considering battery degradation achieves the least gap between the payback period and the lifespan.

The PV/BESS system has social and environmental benefits, such as increasing energy independence and reducing CO_2 emissions. We calculate the self-sufficiency rate. The self-sufficiency rate is a reduction in energy from the grid divided by the original demand. Fig. 6 shows the self-sufficiency rates in each case. If the household has only PV, the rate is around 30%. The battery increases the rate up to 60%. The optimization considering battery degradation achieves a 46.6% self-sufficiency rate. Residential CO_2 emissions come from electricity from the grid. We use a constant emission coefficient (0.445 kg-CO_2/kWh). This coefficient equals that of electricity from the market from April 2022 to

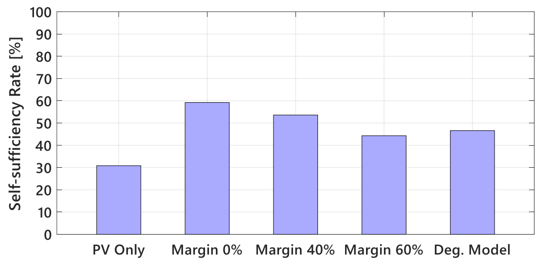

Fig. 6 Comparison of yearly self-sufficiency rates

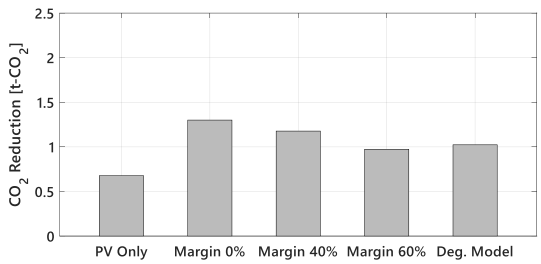

Fig. 7 Comparison of a reduction in CO_2 emissions from the baseline (no PV/BESS) case

March 2023 [10]. The yearly emission in the baseline case is 2.20 t-CO_2. Fig. 7 shows the reduction in yearly CO_2 emissions in each case. A yearly emission decreases by 0.68 t-CO_2 when the household has only PV. Considering battery degradation, the optimization reduces a yearly emission by 1.02 t-CO_2 (46.6% reduction).

3.2 Analysis with outage mitigation

The residential PV/BESS system reduces electricity costs and mitigates outages. The mitigation effect depends on the frequency of outages. Fig. 8 shows the average length of outages per household in the Kansai region. In most of the years, the length is less than 10 minutes. The peaks of outage lengths correspond to large blackouts by typhoons. From 2001 to 2023, large typhoons caused ten blackouts, interrupting electricity at more than 100,000 households [12]. Using this data, this paper assumes that a household experiences typhoon outages once every three years. In addition, outages for other reasons occur once every ten years. This paper also assumes that households can predict outages. Thus, the battery charges to its maximum SoC (90%) before outages. It reduces supply shortages by 9.72 kWh (= 13.5 kWh×0.8×0.9) at maximum.

The average effect of outage mitigation is the product of the reduced supply shortages and the household's outage unit costs. The supply shortages reduced are 4.21 kWh/year (= 9.72 kWh×(1/3+1/10)) at maximum. The outage unit costs are different for households. We consider four cases ranging from 100 JPY/kWh to 5000 JPY/kWh.

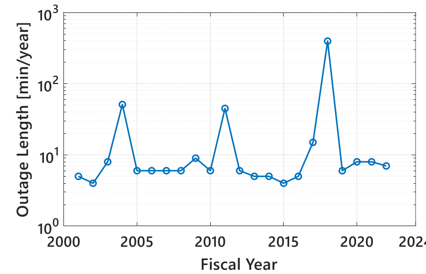

Fig. 8 Yearly outage length per household in the Kansai region [14]

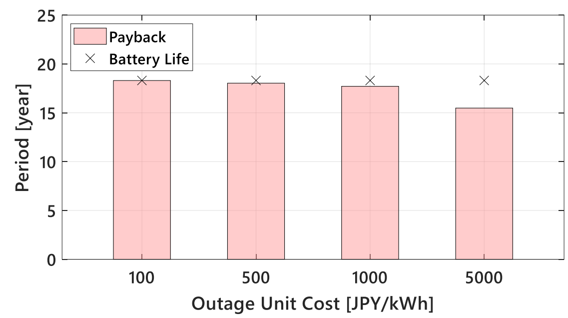

Fig. 9 Payback period of the PV/BESS system considering outage mitigation with different outage unit costs

Fig. 9 shows the payback period considering the effect of outage mitigation. The period is based on the optimization result considering battery degradation. The payback period considering only the reduction in electricity costs is longer than the battery lifespan (Fig. 5). However, the payback period becomes shorter than the lifespan considering the effect of outage mitigation, even if the outage unit cost of a household is 100 JPY/kWh. It implies that considering battery degradation and outage mitigation makes introducing a residential PV/BESS system economically viable.

4. CONCLUSIONS

The residential PV/BESS system is essential to tackle an increase in the frequency of natural disasters and uncertainty of electricity prices. This paper develops the optimization model, including battery degradation, to estimate the profit and lifespan of the PV/BESS system. In addition, this paper combines the effect of outage mitigation with the reduction of electricity costs. The optimization shows that the lifespan is shorter than the profit. However, considering outage mitigation and battery degradation realizes the shorter payback period than the lifespan, which is economically viable. This paper also confirms that the PV/BESS system achieves a 46.6% self-sufficiency rate and CO_2 reduction by 46.6%.

We separate the procedures to estimate electricity cost reduction and the effect of outage mitigation. The analysis of the SoC locus enables a precise estimation of the outage mitigation. This is our future work.

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