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OPERATION PLANNING FOR RESIDENTIAL BATTERY ENERGY STORAGE SYSTEM WITH THE PHOTOVOLTAIC SYSTEM IN TERMS OF LIFE-CYCLE COST

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ABSTRACT

This study proposed the operation planning of the battery energy storage systems (BESS) to maximize the economic value in terms of life-cycle cost considering both the electric power self-consumption and peak load reduction. Toward this end, a bi-objective optimization model was developed in consideration of the economic net profit as well as the battery aging. An economic simulation was then conducted to create a configuration of the most cost-effective operation planning. As a result of the case study, the operation with limits on self-sufficiency rate and peak load reduction could raise the self-sufficiency rate by up to 22.1% and reduce the peak load by up to 29%, while the net present value (NPV) of the BESS was US$7,067.9 lower compared to the operation without such limits. The customers of the BESS with the PV systems can maximize their economic profits and the policy makers can establish plans for economic support schemes to improve the environmental performance of the BESS with the PV system.

Keywords: Photovoltaic system, Battery energy storage system, Life-cycle cost, Bi-objective optimization, Economic simulation

NONMENCLATURE

Abbreviations	
BESS	Battery energy storage system
PV	Photovoltaic
LCC	Life-cycle cost
REC	Renewable energy certificate
SoC	State of charge
KPX	Korea Power Exchange

Symbols	
d	Day
t	Timestep
C	Price of the electric power
P	Electric power
b	Binary variable
E	Electric Energy
η	Efficiency of a BESS
y	Year
r	Discount rate

1. INTRODUCTION

The battery energy storage systems (BESS) has been adopted with the photovoltaic (PV) systems for electricity self-consumption and peak load reduction while reducing energy costs at the level of residential customers as well as at the national level [1–3]. However, several studies have pointed out that adopting the BESS has not been able to achieve feasibility until now due to its high investment and replacement costs [4,5]. Although some studies have tried to maximize the economic profits of the BESS by means of if-then rules and optimization techniques, they did not consider the life-cycle cost (LCC) of the system, including replacement and operation & maintenance costs in their BESS operation planning models [6,7]. Moreover, maximizing the economic profit by electricity exchange has the possibility of inhibiting the self-consumption and peak load reduction of the BESS [8]. Therefore, this study proposed the operation planning of the BESS to maximize the economic value in terms of LCC considering the electric power self-consumption and peak load reduction. Toward this end, a bi-objective optimization

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model was developed, and economic simulation was conducted to determine the most cost-effective operation planning.

2. SYSTEM LAYOUT AND THE BI-OBJECTIVE OPTIMIZATION

The electric power system to be investigated is the grid-connected BESS with the PV system installed in a residential building. The electric power system consists of the BESS, PV system, residential building and the grid, and seven electric power flows exist between each component. In this study, each variable $P_{A\text{-}to\text{-}B}(d,t)$, which is the electric power flow from component A to B at day d and timestep t, was determined to maximize the economic value of the BESS with the PV system. The economic value of the BESS with the PV system includes the net profit by electric power exchange and LCC of the BESS. Accordingly, the target period intended to evaluate the economic value of the BESS with the PV system was set as the lifetime of the PV system, which is not subjected to the influence of the BESS operation [9]. In this case, it is impossible to obtain a deterministic solution to the optimization problem since setting the economic value of the BESS with the PV system during the lifetime of the PV system as an objective function requires excessive amounts of data and imposes conditional changes in the problem. Therefore, a bi-objective optimization model was formulated with the objective function of the daily economic value of the system, including daily net profits by electric power exchange and daily BESS aging costs so as to consider the LCC of the BESS. Then, the linear programming is applied to solve the optimization problem. Based on these optimization results in different optimization weights, the operation planning to maximize the economic value during the lifetime of the PV system can be determined by comparing the economic values in terms of LCC of the BESS in each optimized operation planning with different optimization weights through economic simulation.

2.1 Bi-objective function

The main target of the proposed optimization model is to maximize the daily economic value of the BESS with the PV system, including the daily net profit by electric power exchange and daily BESS aging cost. First, the daily net profit by electric power exchange was formulated. The economic net profit by electric power exchange can vary depending on the electric power business structure for electric power generation and electricity rate structure for electric power consumption. The sale price of electric power consists of electric power wholesale and renewable energy certificate (REC) transactions, and it changes every hour. In addition, the electricity rate structure for electric power consumption varies according to the amount of electrical energy purchased as progressive tariffs are applied. As a result, the daily net profit by electric power exchange can be calculated considering the electric power business and rate structure (refer to Eq. (1)). Second, the daily BESS aging cost was formulated. Since the capacity loss by the BESS cycle reduces the electrical performance of the BESS and affects the replacement period of the BESS product, the BESS aging should be calculated to maximize the economic value. In this study, the energy throughput model among the BESS cyclic aging models was used to include the BESS cyclic aging in the objective function [10]. The energy throughput model can be applied to linear programming, as the capacity of the BESS is reduced by the ratio of the current amount of the BESS charge and discharge to the maximum amount of the BESS charge and discharge during its lifetime, which can be obtained by multiplying the nominal capacity of the BESS by the maximum cycle of the BESS (refer to Eq. (3)). Lastly, the objective function was formulated. In order to normalize the daily net profit and BESS aging cost, each term is divided by the average of its absolute maximum and minimum values. The weight of each objective can then be adjusted by multiplying an optimization weight w with a range from 0 to 1 (refer to Eq. (4)). Therefore, as w approaches zero, daily BESS aging cost is minimized, and as it comes closer to 1, daily net profit by electric power exchange is maximized.

$$Net\ profit\ (d) = \sum_{t=0}^{T} (C_{sale}(d,t) \cdot P_{sale}(d,t) - C_{purchase}(d,t) \cdot P_{purchase}(d,t)) \cdot \Delta t \quad (1)$$

$$Aging\ cost\ (d) = \frac{\sum_{t=0}^{T} (P_{charge}(d,t) + P_{discharge}(d,t)) \cdot \Delta t}{E_{capacity} \cdot Lifetime\ cycle \cdot 2} \quad (2)$$

$$Objective\ function(d) = w \cdot \frac{Net\ profit(d)}{Net\ profit_{average}(d)} + (1-w) \cdot \frac{-\ Aging\ cost\ (d)}{Aging\ cost_{average}},\ \ (0 \le w \le 1) \quad (3)$$

where $Net\ profit$ is the net profit by electric power exchange, C_{sale} is the sale price of the electric power, P_{sale} is the electric power transmitted to the grid (kW), $C_{purchase}$ is the purchase price of the electric power, $P_{purchase}$ is the electric power transmitted from the grid (kW), $Aging\ cost$ is the BESS aging cost, P_{charge} is the electric power charged to the BESS (kW), $P_{discharge}$ is the electric power discharged from the BESS (kW), $E_{capacity}$ is the energy capacity of the BESS

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(kWh), $Lifetime\ cycle$ is the lifetime cycle of the BESS (cycles), $Objective\ function$ is the objective function of the optimization model, w is the optimization weight, $Net\ profit_{average}$ is the average of absolute maximum and minimum of the Net profit, and $Aging\ cost_{average}$ is the average of absolute maximum and minimum of the $Aging\ cost$.

2.2 Constraints

The electric power system and electrical energy state of the BESS is modeled in the form of constraints. The value of each variable or equation is bounded by the constraints in the format of either linear equation or inequality. First, in terms of the electric power system, the electric power generated from the PV system and the electric power consumed by the residential building can be distributed into three electric power flows, respectively (refer to Eqs. (4) and (5)). The electric power transmitted to and from the grid, bounded by the contract power, is not able to be transmitted at the same time (refer to Eqs. (6) to (8)). The developed model in this study could maximize the daily self-sufficiency rate and minimize the daily peak load by adding the constraints to set limit for each value (refer to Eqs. (9) and (10)). Second, in terms of the battery, the electric power charged to and discharged from the BESS, which is limited by the power capacity of the BESS, cannot exist at the same time (refer to Eqs. (11) to (13)). The electrical energy state of the BESS is limited to a certain state of charge (SoC) to prevent excessive aging and power failure of the BESS (refer to Eq. (14)). The electrical energy state of the BESS in the next timestep (t+1) can be calculated from that in the current timestep (t) considering the self-discharge rate, round-trip efficiency and electric power charged to and discharged from the BESS during the timestep (Δt) (refer to Eq. (15)). The maximum and minimum SoC, the self-discharge rate and the round-trip efficiency of the BESS were set with reference to the specifications of the residential BESS product currently available [11].

$$P_{pv}(d,t) = P_{pv\text{-}to\text{-}ess}(d,t) + P_{pv\text{-}to\text{-}grid}(d,t) + P_{pv\text{-}to\text{-}building}(d,t) \quad (4)$$

$$P_{building}(d,t) = P_{ess\text{-}to\text{-}building}(d,t) + P_{pv\text{-}to\text{-}building}(d,t) + P_{grid\text{-}to\text{-}building}(d,t) \quad (5)$$

$$P_{purchase}(d,t) = P_{grid\text{-}to\text{-}ess}(d,t) + P_{grid\text{-}to\text{-}building}(d,t) \leq b_{purchase}(d,t) \cdot P_{contract} \quad (6)$$

$$P_{sale}(d,t) = P_{pv\text{-}to\text{-}grid}(d,t) + P_{ess\text{-}to\text{-}grid}(d,t) \leq b_{sale}(d,t) \cdot P_{contract} \quad (7)$$

$$b_{sale}(d,t) + b_{purchase}(d,t) \leq 1 \quad (8)$$

$$Self\text{-}sufficiency\ rate\ (d) = \frac{\sum_{t=0}^{T}(P_{building}(d,t) - P_{purchase}(d,t))}{P_{building}(d,t)} \cdot 100 \geq Self\text{-}sufficiency\ rate\ limit \quad (9)$$

$$Peak\ load\ (d) = \frac{P_{building}(d,t)}{P_{contract}} \cdot 100 \leq Peak\ load\ limit \quad (10)$$

$$P_{charge}(d,t) = P_{pv\text{-}to\text{-}ess}(d,t) + P_{grid\text{-}to\text{-}ess}(d,t) \leq b_{charge}(d,t) \cdot P_{capacity} \quad (11)$$

$$P_{discharge,t}(d,t) = P_{ess\text{-}to\text{-}building}(d,t) + P_{ess\text{-}to\text{-}grid}(d,t) \leq b_{discharge}(d,t) \cdot P_{capacity} \quad (12)$$

$$b_{charge}(d,t) + b_{discharge}(d,t) \leq 1 \quad (13)$$

$$E_{capacity} \cdot SoC_{minimum} \leq E(d,t) \leq E_{capacity} \cdot SoC_{maximum} \quad (14)$$

$$E(d,t{+}1) = (1-\eta_{self}) \cdot E(d,t) + \left\{(1-\eta_{round}) \cdot P_{charge}(d,t) - \left(\frac{1}{1-\eta_{round}}\right) \cdot P_{discharge}(d,t)\right\} \cdot \Delta t \quad (15)$$

where $P_{A\text{-}to\text{-}B}$ is the electric power flow from component A to B (kW), P_{pv} is the electric power generated from the PV system (kW), $P_{building}$ is the electric power consumed in the residential building (kW), $P_{contract}$ is the contract power, which is 3 kW in South Korea, b_{sale} and $b_{purchase}$ are the binary variables of the electric power transmitted to and from the grid, $Self\text{-}sufficiency\ rate$ is daily self-sufficiency rate of the building (%), $Self\text{-}sufficiency\ rate\ limit$ is the limit of daily self-sufficiency rate set as the model input parameter (%), $Peak\ load$ is daily peak load (kW), $Peak\ load\ limit$ is the limit of daily peak load set as the model input parameter (kW), b_{charge} is the binary variable of the electric power charged to the BESS, $P_{capacity}$ is the power capacity of the BESS (3kW), $b_{discharge}$ is the binary variable of the electric power discharged from the BESS, $E_{capacity}$ is the energy capacity of the BESS (3.3kWh), $SoC_{minimum}$ and $SoC_{maximum}$ are the minimum and maximum state of charge of the BESS (20 and 90%), E is the energy state of the BESS (kWh), η_{self} is the self-discharge rate of the BESS (5%/30days), and η_{round} is the round-trip efficiency of the BESS (5%).

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3. ECONOMIC SIMULATION

In this study, the net present value (NPV) of the BESS with the PV system during the PV system lifetime was calculated based on the one-year optimization results to compare the economic values of the BESS with the PV system considering its LCC according to different scenarios and optimization weights. As a result, the NPV was calculated by applying a discount rate to the value obtained by deducting the total cost for installing and operating the BESS from the total profit derived by operating the BESS with the PV system for 25 years (refer to Eq. (16)). The total profit represents the net profit by electric power exchange (i.e., installation, operation & maintenance, and replacement cost) and can be obtained through optimization results. The installation cost was set at US$700/kWh [12,13], while the operation & maintenance cost was set to incur annually at 2.2% of the installation cost [12]. The replacement cost was set to ensure an 8% reduction per year so as to consider that the installation cost decreases every year [12]. In addition, the replacement period of the BESS was set as the lifetime of the BESS which ends when the capacity of the BESS is 80% or less [14]. The discount rate was set to an average discount rate of 2.73% over 10 years [15].

$$NPV = \sum_{y=0}^{25}\left(\frac{Total\ profit_y - Total\ cost_y}{(1+r)^y}\right) \quad (16)$$

where NPV is the net present value of the BESS with the PV system for 25 years (US$), $Total\ profit_y$ is the total profit over a year y (US$), $Total\ cost_y$ is the total cost over a year y (US$), and r is the discount rate (%).

4. RESULTS AND DISCUSSION

To validate the proposed method in this study, a case study was conducted. This study assessed the economic value of two scenarios: (i) scenario 1 has no limit on the self-sufficiency rate and peak load reduction; and (ii) scenario 2 has limits to maximize the self-sufficiency rate and peak load reduction. The target power system of the case study was of the residential building where the 3kWp PV system is installed located in Chungbuk, South Korea. In order to conduct the case study, the hourly electric power generation and consumption data of one year (i.e., from April, 2018 to March, 2019) were obtained from the target power system so the timestep of the optimization model is set to an hour. The electric power price data were collected from the Korea Power Exchange (KPX) [16].

4.1 Optimization results

Fig. 1 shows the results of the bi-objective optimization of the case study. In both scenarios, as the optimization weight increased, the capacity loss of the BESS and net profit by electric power exchange also increased at the same time. This suggests that the BESS cycle is increased to raise the net profit by electric power exchange, and the lifetime of the BESS can be further reduced as the BESS cyclic aging accelerated. In scenario 1, when the optimization weight was changed from 0 to 1, the net profit by electric power exchange increased by US$317.1, and the capacity loss increased by 1.921%, when the peak load was constant at the contract power of 3kW, and the self-sufficiency rate decreased by 10.5%. On the other hand, in scenario 2, when the optimization weight was changed from 0 to 1, the net profit by electric power exchange increased by US$61.3, and the capacity loss increased by 0.249%, showing a smaller increase than in scenario 1. The peak load was constant at 2.13kW, and the self-sufficiency rate remained constant, and this indicates that the peak load further decreased, and the self-sufficiency increased compared to scenario 1. However, the net profit by electric power exchange that can be obtained in scenario 2 further decreased than scenario 1 in all optimization weights. In addition,

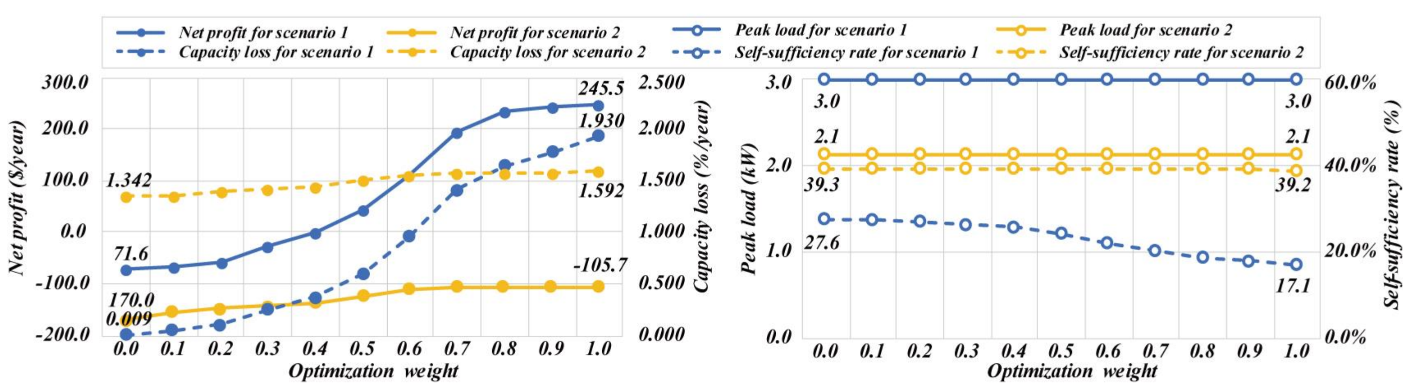

Fig 1 The results of the bi-objective optimization in scenario 1 and 2.

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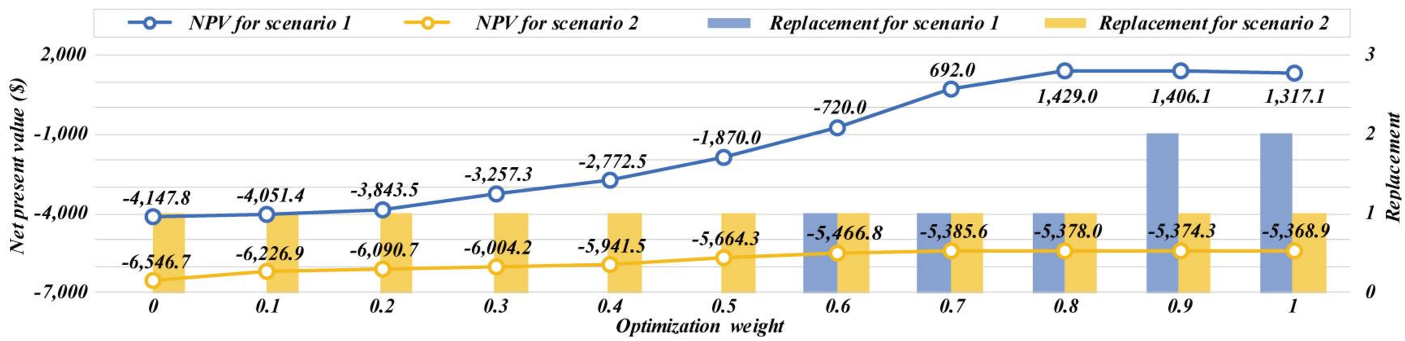

Fig 2 NPV for each optimization weight and scenario.

the capacity loss of the BESS was relatively higher in scenario 2 than in scenario 1 when the optimization weight was 0.7 or less, but it was lower in scenario 2 than in scenario 1 when it was 0.8 or more. This suggests that if the peak load and self-sufficiency rate are limited, the cycle of the BESS does not greatly increase, thereby limiting the increase of the net profit by electric power change.

4.2 Optimization results

The economic value of the BESS with the PV system considering its LCC was calculated based on the result of the optimization. As shown in Fig. 2, the NPV of different optimization weights varied significantly according to each scenario. In scenario 1, the NPV increased with the increasing optimization weight, but decreased after reaching the maximum value of US$1,429 when the optimization weight was 0.8. This indicates that a decrease in the replacement cost of the BESS by reducing the cycle of the BESS is a more economical operation in terms of LCC, even if the net profit by electric power exchange is slightly reduced accordingly, rather than maximizing the net profit by electric power exchange. On the other hand, in scenario 2, the NPV increased as the optimization weight rose, and the maximum NPV was US$-5,368.9 when the optimization weight was 1. This means that the maximization of the net profit by electric power exchange can be the most economical operation in terms of LCC since there is a limit to the increase in the cycle of the BESS when the self-sufficiency rate and peak load are limited. As a result, the maximum economic value of the BESS with the PV system considering its LCC was achieved when the optimization weight was 0.8 in scenario 1, and the optimization weight was 1.0 in scenario 2. In addition, customers who have installed the PV system can obtain economic profits as the NPV is greater than or equal to zero through proper operation planning when the BESS are built in scenario 1. However, in scenario 2, as the NPV continues to be negative, additional subsidies and incentives must be provided to the customer to obtain economic profits.

5. CONCLUSION

This study proposed the method of operation planning for the residential BESS considering its LCC. Toward this end, the bi-objective optimization model was developed, and economic simulation was conducted to determine the most economic operation. The results of the case study showed that the customer could obtain US$1,429 of NPV at most during the lifetime of the PV system through the proposed operation planning of the BESS which considered to reduce the replacement cost of the BESS as well as to increase the net profit by electric power exchange. On the other hand, the customer could not obtain economic profit but at least US$5,368.9 of cost occurred through the operation planning of the BESS which only considered to increase the net profit by electric power exchange. Based on the proposed methods and results of this study, the customers who have installed the residential the BESS with the PV system can reduce their energy cost and maximize their economic profit during the whole lifetime of the PV system. Moreover, the additional support schemes for the BESS with the PV system by imposing subsidies and incentives should be considered by the policy makers to improve the environmental performance of the BESS with the PV system.

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