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Impact of Battery Energy Storage System Operation Strategy on Power System: An Urban Railway Load Case under a Time-of-Use Tariff

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Abstract: Customer-owned battery energy storage systems (BESS) have been used to reduce electricity costs of energy storage owners (ESOs) under a time-of-use (TOU) tariff in Korea. However, the current TOU tariff can unintentionally induce customer's electricity usage to have a negative impact on power systems. This paper verifies the impact of different BESS operation strategies on power systems under a TOU tariff by analyzing the TOU tariff structure and the customer's load pattern. First, several BESS operation strategies of ESO are proposed to reduce the electricity cost. In addition, a degradation cost calculation method for lithium ion batteries is considered for the ESO to determine the optimal BESS operation strategy that maximizes both electricity cost and annual investment cost. The optimal BESS operation strategy that maximizes ESO's net benefit is illustrated by simulation using an urban railway load data from Namgwangju Station, Korea. The results show that BESS connected to urban railway loads can negative impact power system operation. This is due to the high BESS degradation costs and lack of incentive of differential rates in TOU tariff that can effectively induce proper demand response.

Keywords: price-based demand response; time-of-use tariff; urban railway load; energy storage owner (ESO); battery energy storage system (BESS); operation strategy

1. Introduction

Over the past decades, demand response (DR) has been studied and implemented in many power systems. The studies show that appropriate changes of demand are more efficient in contrast to traditional philosophy that electricity demands should be fully supplied only by controlling generation units [1]. Price-based DR programs induce customers to change their electricity usage through price signals that reflect volatility of wholesale market prices. Customers respond to the price signals to reduce their energy cost by changing demand patterns, such as peak load shaving, which affects the overall power system. The tariff structure and level of the rates will directly affect the amount of changes in demand and resulting benefits over the system. Therefore, tariff system should be carefully designed to maximize the system-wide benefits while the customers make strategies to minimize their energy costs.

The change in demand can only be achieved by price-elastic customers, and customers' utility is essentially reduced when customers change their demand. In fact, price-elastic customers are confined to only some part of the total customers and the price elasticity of the system demand is known to be very low. In contrast, by owning a battery energy storage system (BESS), every customer is able to be price-elastic and demand can be changed without reduction of the customer's utility. Therefore, operation of BESS for participating in DR programs is one of the options that customer can use to reduce their electricity cost, and it has already been studied in [2–4]. Although performance of its application on DR programs is verified in previous studies, the economic value of BESS operation is still controversial due to the high installation costs and short life time of BESS.

The system peak load shaving and/or load leveling offers system-wide benefits in the aspect of economical operation and avoidance of additional capital expenditure of supply units [5,6]. Many studies verified that BESS are successfully operated to flatten the load pattern and, thus, achieve the aforementioned benefits. In spite of the technical suitability of BESS on peak load shaving, however, practical issues related to the inconsistency between system operators and energy storage owners (ESOs) arise [7]. In other words, ESOs are likely to operate their BESS to maximize their own benefits regardless of its impact on the power system. Therefore, proper signals are required to induce ESOs to have a positive effect on the overall power system as a result of ESO's optimal BESS operation for their economic purpose.

A time-of-use (TOU) tariff is subdivided into demand and energy charges. Customer's demand charges can decrease by reducing their peak demand, while energy charges can be reduced by shifting demand from high to low price time periods. According to previous studies, shaving the customer's peak load to reduce demand charges is considered an effective way to reduce the electricity bill on account of the high proportion of demand charges to the entire charges [8,9]. For this reason, most of the previous studies on utilization of BESS to reduce energy costs under a TOU tariff has only considered demand charge reduction, thereby confining the contribution of the research to no more than the decrease in energy charges. In some studies, research on determination of an optimal BESS size [2], and its operation [3,4,10], which could also minimize energy charges along with demand charges have been conducted. However, the results appeared to be similar to the peak shaving operations since a normal demand pattern in which the peak occurs in a time period of a high rates is used, and it did not practically reflect the customer loads in reality, which may have various patterns.

Urban railway loads, whose patterns are different from general loads, have been growing more important in the wake of accelerating urbanization. In consideration of its large implications on power systems made by its large amount of power consumption, a number of efforts for energy saving have been put forth in various aspects [11]. Several studies reflect the methods that save braking energy in ESS for acceleration time requiring a large amount of power supply due to its energy cost reduction effect [12–14]. Additionally, economic viability and benefits from peak-power management of urban railway loads with BESS were analyzed [14] and an optimal capacity of BESS is determined [15]. The established studies that have been used for a single purpose such as reduction of energy consumption or decrease of peak load will be able to be more economically used through analysis on load properties and the tariff systems.

The main goal of this paper is to analyze the impacts of customer-owned BESS operation strategies under a TOU tariff on the power system. Four types of ESO's BESS operation strategies are established by considering the structure and properties of a TOU tariff system. In order to predict the impacts of demand changes resulted from each strategy on the overall power system, the patterns of the TOU rates, system load, and urban railway load are comparatively investigated. Furthermore, in order to facilitate the determination of ESOs on the optimal BESS operation strategy that maximizes their net benefit, a method to calculate annual investment costs that can reflect the influence of ESO's strategies is proposed. This is because different charging/discharging strategies affect the degree of degradation of the BESS, which determines the life of BESS, and the lifespan is inversely proportional to annual investment costs. The optimal BESS operation strategy is determined from the simulation using an urban railway load data from Namgwangju Station, Korea. In addition, countermeasures against negative impacts of customer-owned BESS operation on the power system are discussed.

2. Background

BESS operation strategies aiming at electricity bill minimization have a direct relation with composition and features of the electricity tariff system and load. Moreover, the operations are expected to bring in diversified social benefits, as well as a reduction of the ESOs' electricity bill.

2.1. Time-of-Use Tariff

A TOU tariff system consists of "demand charges" and "energy charges". Normally, these charges are devised to cover fixed costs and variable costs for power supply, respectively. As one of the price-based DR programs, TOU tariff provides pre-set differential rates by pre-set time intervals which leads to changes of customers' demand patterns. The customers' demand change affects the system demand pattern and brings in considerable impacts on the power system. Therefore, the tariffs are designed to induce the customer to respond to price signals and to maximize the social benefits thereof.

Likewise, the Korean industrial electricity tariff consist of demand charges and energy charges. The demand charge, which is charged monthly, is a demand charge rate (KRW/kW per month) multiplied by the demand for applying to the demand charges, which is defined as a maximum demand out of December, January, February, July, August, September, and the month of meter reading amongst 12 months before, and including, the month of meter reading. Accordingly, the maximum demand affects the electricity bill every month for up to a year, whereas the energy charge rates apply differential rates depending on season and time. Table 1 below is an example of a TOU which is one of the present Korean industrial electricity tariff systems. Of many tariffs, it shows the Industrial Power at Class A High Voltage A option II-type tariff. The tariffs are classified according to three attributes—contract power, standard voltage, and level of rates of demand charges and energy charges. *Classes* are classified into two types according to contract power: Class A and Class B; *Voltages* are divided into three types according to standard voltage: Low Voltage, High Voltage A, and High Voltage B; *Options* consist of two types that are different in level of rates of the charges: options I and option II [16].

Table 1. An example of the industrial electricity TOU tariff in Korea.

Rate Period	Demand Charge Rate (KRW/kW per Month)	Energy Charge Rates (KRW/kWh)		
		Summer	Spring/Autumn	Winter
Off-peak	7470	55.6	55.6	63.0
Shoulder		81.4	60.4	79.9
Peak		114.9	79.6	109.3

The energy charge rates shows a similar pattern with the entire power system load. In the case of a cost-based pool market, like Korea, a generator with the highest marginal cost determines its market price in the wholesale electricity market, which is called the system marginal price (SMP). An amount of demand affects SMP; in other words, more demand requires a more expensive generator, raising SMP. Hence, SMP results in having a very similar pattern to the entire demand pattern. Energy charge rates are generally designed to reflect the variability of the wholesale market to the retail market, so their patterns really approximate the SMP. Therefore, the energy charge rates, SMP, and the entire demand display a similar pattern (Figure 1). Both SMP of whole electricity market acting on the pricing of power suppliers and energy charge rates levied on end-users offer a proper remuneration for supplied electricity, and an inducement to shift the demand from a high to a low demand area at the same time.

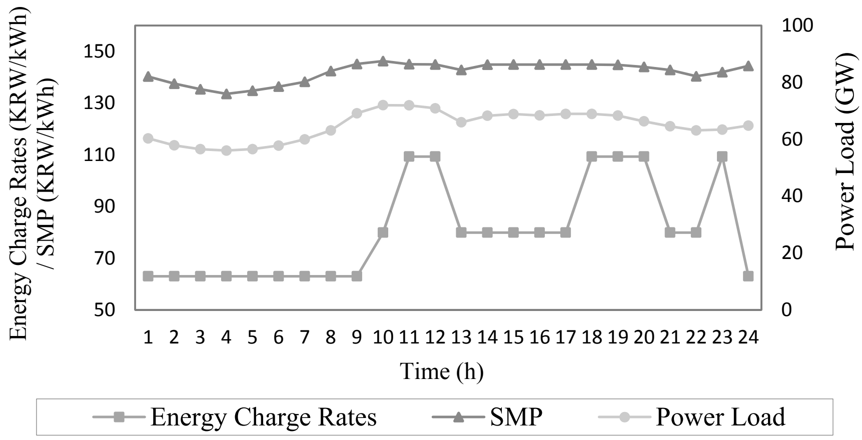

Figure 1. Pattern comparison of energy charge rates, SMP, and entire power load (average figure of January 2015).

2.2. Features of an Urban Railway

The different pattern of an urban railway load presents diverse characteristics. This paper defined "general load" as the loads with the equal pattern to the entire power system load pattern to explain the features of urban railway loads. Figure 2 shows typical day patterns of general and urban railway loads, respectively. The urban railway load was the daily data of 12 January 2015 recorded at Korea Namgwangju Substation, whereas the general load was the average data of weekdays in January 2015, in Korea. Both are normalized with a maximum value.

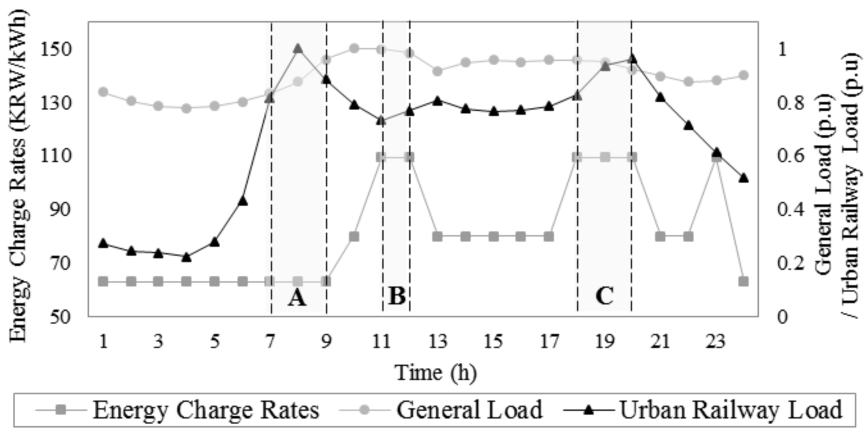

Figure 2. Impact of Load shift on power systems according to relations between urban railway loads and energy charge rates.

Urban railway load patterns havehas different features from general loads in terms of peak time, peak time duration, load variance, and accuracy of peak time prediction: (1) as the peak time of the general load are business hours (11 a.m.–noon, noon–5 p.m.), while that of the urban railway load are commuting hours (7 a.m.–9 a.m., 6 p.m.–8 p.m.) when train use increases; (2) the peak duration of urban railway load is shorter than that of general load; (3) unlike the general load that has a steady demand during a day, the urban railway load has a considerable gap between peak and off-peak time, and the least load for station operation is in the early hours when the train does not run; and (4) the urban railway load is greatly influenced by the number of trains in operation and heating, ventilating, and air-conditioning (HVAC), and its peak time is easily predictable from the train operation schedule. These features, large variances, and short peak duration, can contribute to peak load reduction per BESS capacity [17], and another feature, relatively precise prediction of demand, can help to determine timing of charging and discharging in operation of the ESS. However, if a peak appears at a different time than general loads, the BESS operation method may undermine social benefits, such as peak aggravation in the entire load of the power system.

The above-mentioned characteristics of urban railway loads will clearly result in different optimal BESS operation strategies and impacts on the power system from general loads. Furthermore, urban railway loads have grown in importance because of a large amount of power consumption of urban railways and their growing demand in the wake of accelerating urbanization.

2.3. ESO's BESS Operation Strategies

In order to reduce electricity bills, ESOs can establish BESS operation strategies according to their demand patterns and the rates of energy charge. Demand charges can decrease by customer's peak load shaving, and so can energy charges by shifting demand from high to low price time period. To determine the timing of charging and discharging, ESOs can choose one of the followed strategies:

- Case 1: No BESS operation
- Case 2: Demand charges minimization only
- Case 3: Both demand and energy charges minimization
- Case 4: Energy charges minimization only

2.3.1. General Load Case

Each BESS operation for demand charge minimization and energy charge minimization can have similar results of charging and discharging strategy when the customer's load pattern is similar with the system load pattern. Since the customer's peak occurs when high rates are applied, which is shown as B and C parts in Figure 2, ESO will shift demand of B and C parts into the time of low demand (Case 2) or the time of low rates are applied (Case 4). That is, by only reducing the load of B and C parts, ESOs are able to reduce both demand and energy charges, which is an expected operation result of Case 3.

2.3.2. Urban Railway Load Case

The charging and discharging strategies of BESS installed in an urban railway load differs from those of the general load case, since the pattern of the urban railway load and the system load pattern are different. While load reductions in A and C parts of Figure 2 can reduce the demand charges (Case 2) by reducing the customer's peak loads, shifting demands of B and C parts to the time of low rates reduces the energy charges (Case 4). In order to minimize electricity bills of the urban railway load, unlike the general load case, not only the demands of B and C parts, but also those of A part, need to be changed (Case 3).

Not only can the urban railway loads, but any load whose demand pattern is different from the general load pattern—for example, load's peak demand regularly occurs during non-peak price time (illustratively, A part in Figure 2)—be similarly analyzed like this.

2.4. Impact of BESS Operations on Power Systems

Operation of customer-owned BESSs to maximize the ESO's economic benefits will have an effect throughout the power systems. As the increase of the operation of the BESS will bring profound impact on the power system, system operators are in need of analyzing ESOs' incentives and establishing measures to avoid adverse impacts.

Load changes led by BESS operation can be divided into classifications of local load change (distribution system load) and the load change of the entire power system. In the case of an urban railway load, the customer's peak load reduction (Figure 2A,C) offers economic benefits by impeding or hindering expansion of the infrastructure of the distribution systems [4]. On the other hand, the entire load reduction in a power system (Figure 2B,C) encourages operation of generators with low variable costs, reducing the use of those with a high variable cost to allow a low cost operation in a power system [5], as well as the mentioned benefit brought by employing the peak load reduction. Application of BESS for demand charge minimization to general loads (Figure 2B,C) can provide all of the aforementioned system-wide benefits with the ESO's bill reduction. Contrarily, such an attempt made on urban railway loads (Figure 2A,C) may possibly trigger a rise in a peak load of the entire power system, hampering acquisition of all of the benefits. Shifting demand of A part into B part to reduce peak demand can bring an effect of demand charge reduction from the peak reduction from the perspective of the distribution system, but it can also raise energy charges on account of the load shift. Therefore, building a BESS plan in light of both peak load reduction and energy charge minimization for ESOs is expected to produce greater economic advantages.

3. Methodology

3.1. Calculation of BESS Degradation Costs

The life of the BESS declines by time of use as it consists of numerous cells that react chemically. Therefore, indiscriminate use of BESS incurs replacement costs, which is inefficient as a whole. To avoid this, we should consider BESS degradation and subsequent expenses when determining BESS operation strategies in light of its relatively high installation costs. By applying degradation cost calculations as per the strategy, ESOs will be able to choose a most economical strategy.

3.1.1. BESS Degradation Model

Ref. [18] suggests a new empirical model to calculate degradation and life of a lithium ion battery. Superposition theory cannot be used in arbitrary depth of the state-of-charge (SoC) cycle due to the nonlinearity of the existing degradation models, and is only applicable to simple and full depth of cycle, such as an electric vehicle. However, Ref. [18] shows the linear degradation model could be applied to various forms of identical cycles with the fact that the degradation is affected by SoC deviation and the average of the cycles. Through this, degradation of a BESS with arbitrary use in a short interval cycle could be modeled. Other types of ESS, such as lead-acid batteries, vanadium redox flow batteries, and thermal storage systems, can be used for the same purpose [9,19] and studies on efficiency and lifespan analysis [20] and SoC estimation [21] are expected to encourage development of their degradation models.

Battery degradation occurs due to stress by time, heat, and charging and discharging cycle. State-of-health (SoH), which represents the status of battery degradation, can be expressed as a single lumped damage parameter, L, which can be expressed as a function of the average and deviation of SoC and thermal parameters. Additionally, the definition of two variables relating to SoC is shown in Equations (1) and (2) [18]:

$$\mathrm{SoC_{avg}} = \int_0^{\tau} \mathrm{SoC}(t)\mathrm{d}t/\tau \tag{1}$$

$$\mathrm{SoC_{dev}} = 2\sqrt{3\int_0^{\tau} (\mathrm{SoC}(t) - \mathrm{SoC_{avg}})^2 \mathrm{d}t/\tau} \tag{2}$$

BESS degradation can be modeled as Equations (3)–(6):

$$L_1 = K_{\mathrm{co}} \cdot N \cdot \exp[(\mathrm{SoC_{dev}} - 1) \cdot T_{\mathrm{ref}}/K_{\mathrm{ex}}/T_{\mathrm{B}}] + 0.2\tau/\tau_{\mathrm{life}} \tag{3}$$

$$L_2 = L_1 \cdot \exp[4K_{\mathrm{SoC}} \cdot (\mathrm{SoC_{avg}} - 0.5)] \cdot (1 - L) \tag{4}$$

$$L_3 = L_2 \cdot \exp[K_{\mathrm{T}} \cdot (T_{\mathrm{B}} - T_{\mathrm{ref}}) \cdot T_{\mathrm{ref}}/T_{\mathrm{B}}] \tag{5}$$

$$L(J) = \sum_{j=1}^{J} L_3(j) \tag{6}$$

where J is the set of time interval of j-th cycle; N is the effective throughput number of cycle ($=\int_0^{\tau}|I(t)|\mathrm{d}t/2Q_n$); $I(t)$ is the charging and discharging current; Q_n is the nominal charge capacity of the battery; K_{co}, K_{ex}, K_{SoC} and K_T are the battery specifications; T_{ref} and T_B are reference and operation battery temperatures, respectively; and τ_{life} is the calendar life to 80% SoH.

The normalized value $L = 0$ indicates no occurrence of degradation and $L = 1.0$ no remaining capacity. As calendar life to 80% SoH is, in general, regarded as the end of life, $L = 0.2$ indicates an expiration of life

3.1.2. Degradation Cost Calculation of Identical Charging and Discharging Cycle

A level of BESS degradation and subsequent life decline are derived from Equations (3)–(6). Based on these models, we propose a calculation method of degradation costs by each identical charging and discharging cycle. Most BESS operations conduct arbitrary charging and discharging per purpose, rather than repeating simple charging and discharging from the maximum to the minimum SoC. This paper considers similar BESS operation methods, where a total degradation level is a sum of each degradation level in a time interval, like Equation (6). Degradation cost calculation by each cycle is described by Equation (7):

$$L_3(j)/0.2 \cdot IC_{BESS} \tag{7}$$

where IC_{BESS} are the BESS installation costs. This is divided by 0.2 as BESS is regarded as being at the end of life when $L = 0.2$.

As suggested in [22], we determined the interval of each cycle by decoupling of consecutive cycles (Figure 3). Each cycle's impact on degradation is calculated using the linearity property, and multiplied with BESS installation costs to obtain degradation costs of one cycle.

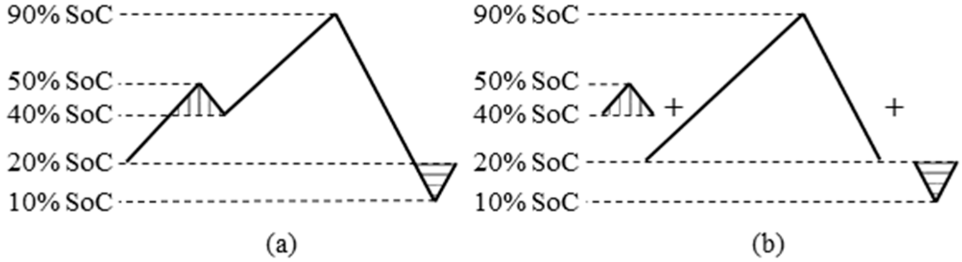

Figure 3. Decoupling of the charging and discharging cycles [22]: (**a**) original cycles, and (**b**) decoupled cycles.

3.2. BESS Operation Strategies

This paper has divided the BESS operation strategies of ESOs for electricity charge reduction into the existing method for demand charge minimization and the method for both demand and energy charge minimization. The objective functions of these strategies are expressed as Equations (8) and (9):

Demand charge minimization:

$$\min_{BESS_{m,d,t}}\left[\sum_{m=1}^{M}\rho_{base}\cdot p_m{}^{max}\right] \tag{8}$$

Demand charge and energy charge minimization:

$$\min_{BESS_{m,d,t}}\left[\sum_{m=1}^{M}\rho_{base}\cdot p_m{}^{max}+\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T}(\rho_{m,d,t}\cdot p_{m,d,t})\right] \tag{9}$$

In Korea, selling electricity by customers to the main grid is not allowed even if the customers have power charged in their own BESS. Accordingly, we have assumed that BESS is applied only for minimizing the electricity bill.

Relations among BESS output, original demand and measured power are described by Equation (10), and relations between BESS output and SoC are described by Equation (11):

$$p_{\mathrm{m,d,t}} = demand_{\mathrm{m,d,t}} + BESS_{\mathrm{m,d,t}}, \forall m, d, t \tag{10}$$

$$\mathrm{SoC}_{\mathrm{m,d,t}} = \mathrm{SoC}_{\mathrm{m,d,t-1}} + \frac{\eta}{100} \cdot \left(\frac{\mathrm{BESS}_{\mathrm{m,d,t}} \cdot \frac{24}{T}}{\mathrm{BESS}^{\mathrm{cap}}} \right), \forall m, d, t \tag{11}$$

Subject to following constraints of Equations (12)–(14):

BESS power output limits:

$$\mathrm{BESS}^{\mathrm{min}} \leq \mathrm{BESS}_{\mathrm{m,d,t}} \leq \mathrm{BESS}^{\mathrm{max}}, \forall m, d, t \tag{12}$$

BESS energy limits:

$$\mathrm{SoC}^{\mathrm{min}} \leq \mathrm{SoC}_{\mathrm{m,d,t}} \leq \mathrm{SoC}^{\mathrm{max}}, \forall m, d, t \tag{13}$$

Boundary constraints:

$$\mathrm{SoC}_{\mathrm{m,d,t=0}} = \mathrm{SoC}_{\mathrm{m,d,t=96}} = \frac{1}{5}(\mathrm{SoC}^{\mathrm{max}} - \mathrm{SoC}^{\mathrm{min}}), \forall m, d \tag{14}$$

where m, d, and t are the sets of months, days, and time steps, respectively; ϱ_{base} is the demand charge rate; $p_{\mathrm{m}}{}^{\mathrm{max}}$ is the m-th month peak demand for applying to demand charge; $\varrho_{\mathrm{m,d,t}}$ is the energy charge rate at time (m, d, t); $p_{\mathrm{m,d,t}}$ is the measured power by the power supplier at time (m, d, t); $demand_{\mathrm{m,d,t}}$ is the original demand at time (m, d, t); $\mathrm{SoC}_{\mathrm{m,d,t}}$ is the state of charge of the BESS at time (m, d, t); η is the efficiency of charging/discharging; $\mathrm{BESS}_{\mathrm{m,d,t}}$ is the amount of BESS charging/discharging energy at time (m, d, t) (positive value for charging); $\mathrm{BESS}^{\mathrm{cap}}$ is the maximum capacity of PCS; $\mathrm{BESS}^{\mathrm{min}}$ and $\mathrm{BESS}^{\mathrm{max}}$ are the minimum and maximum constraints of BESS charging/discharging, respectively; $\mathrm{SoC}^{\mathrm{min}}$ and $\mathrm{SoC}^{\mathrm{max}}$ are the minimum and maximum constraints of SoC, respectively; and $\mathrm{SoC}_{\mathrm{m,d,t=0}}$ is the initial SoC of BESS.

The first terms of Equations (8) and (9) represent demand charges, whereas the second term of Equation (9) indicates energy charges. The demand charge is a multiple of the demand charge rate and the demand for applying to demand charges, and energy charge is a multiple of the energy charge rate and power usage at the time of use. Through optimization, an operation schedule that minimizes the charges by ESS is deducted. In Equation (10), power usage measured by the supplier at time t is the sum of charging and discharging amounts of the BESS and the original demand, of which a value over zero means charging, otherwise it means discharging. Charging and discharging efficiency, which includes self-discharging, is expressed in Equation (11). Equations (12) and (13) represent the operation range of PCS and SoC of the BESS, respectively. Equation (14) shows boundary constraints, aiming at retaining 20% of SoC at the beginning and end of the BESS' daily operation. This value was set to be favorable in consideration of the small load at the operation beginning time (early hours) and the relatively large load at the operation end time (late night) based on experiences.

To compare the total costs of each operation strategy, this paper evaluates electricity charges and degradation costs levied by operation strategies. The degradation cost model, Equation (7), enables us to calculate each degradation cost by the operation strategy and evaluate the economic viability of the strategies.

4. Simulation

4.1. Data and Assumptions

Load data put into the simulation came from Korean Namgwangju Substation recorded from July 2014 to April 2015. Each data includes 96 time steps in a day in 15 min intervals.

In order to decide the maximum demand for applying to the demand charges requires the peak load of 12 months before a month to pay the charges. For this simulation, we assumed the peak demand of the simulation period was the maximum demand for demand charges for each month. We also hypothesized that the BESS was installed on the urban railway load and operated for electricity bill reduction, and the relevant BESS is a lithium ion battery with the specifications shown in Table 2 below.

Table 2. BESS's specifications and relevant parameters.

BESS Parameters	Value	Unit	Relevant Parameter
PCS Capacity	1000	(kW)	$BESS^{min} = -1000$ $BESS^{max} = 1000$
Battery Capacity	2000	(kWh)	$BESS^{cap} = 2000$
SoC Operation Scope	10~90	(%)	$SoC^{min} = 200$ * $SoC^{max} = 1800$
Charging/Discharging Efficiency	90	(%)	$\eta = 90$
C-rate	0.5	(c)	-

* 2000 (kWh) × 10(%)/100(%) = 200 (kWh).

Evaluating ESO's economic benefits in each BESS operation strategy to find the optimal strategy is one of the main purposes of the simulation. If the size of the BESS is optimized, operation results will be more cost-effective. However, the optimal sizes of BESSs are all different in each strategy. Therefore, when comparing the economic benefits between strategies, the BESS size should be constant as a control variable to solely evaluate the performance of each strategy. The optimal size of the BESS can be calculated after the optimal operation strategy is determined.

The tariff system applied to Namgwangju Substation followed the rates in Table 1.

4.2. Results

The BESS operation results of Case 2 and Case 3 are shown in Figures 4 and 5, respectively. Each (a) in the figures indicates the original demand and the demand led by BESS operation of 23 July 2014. For easier interpretation, we marked the energy charge rates. Each (b) shows the BESS output and SoC on the corresponding date.

In Case 2, the original peak demand, 4927.5 kW, decreased to 3927.5 kW by BESS operation. The demand in the closing hour also declined for the changed peak demand to become a new peak demand within the BESS operation period. We can see BESS does not react for charge reduction in the section with a high energy charge rate as it operates for demand charge minimization only (Figure 4a). It declines the customers' peak load only, so its charging and discharging cycle proportionally operates to peak scale once or twice a day (Figure 4b).

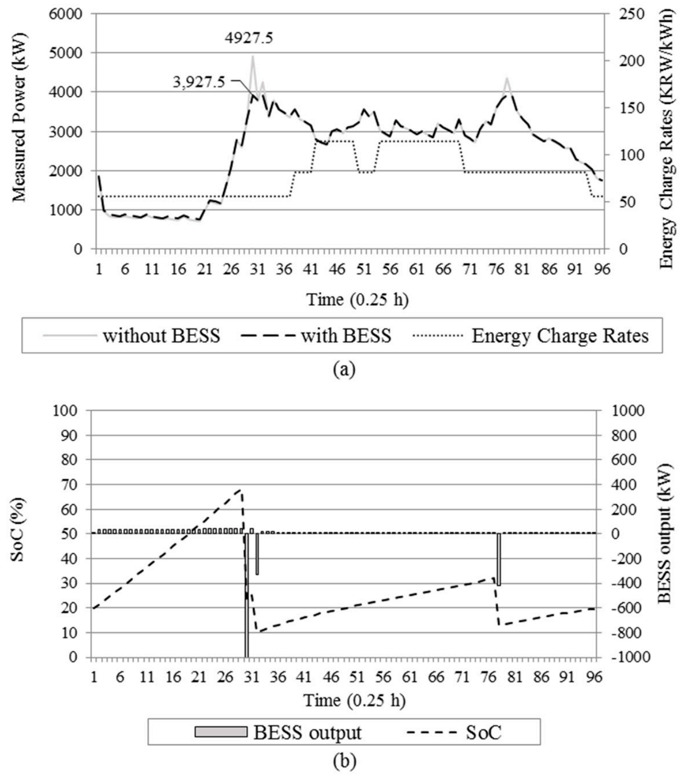

Figure 4. Result of Case 2 (**a**) Measured power, and (**b**) BESS output and SoC.

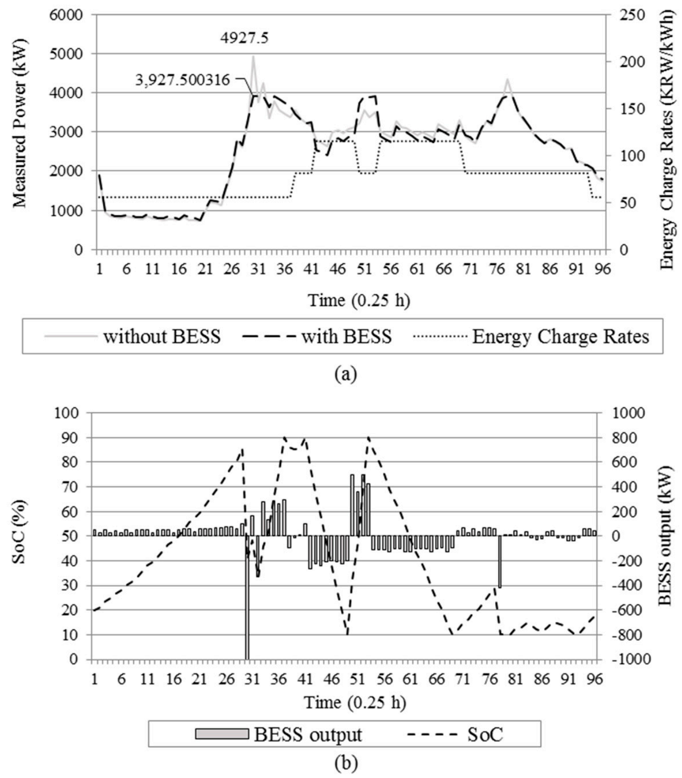

Figure 5. Result of Case 3 (**a**) measured power, and (**b**) BESS output and SoC.

Differently from Case 2, Case 3 shows the BESS operation shifts the demand at high rate times to low in response to energy charge rates, as well as the peak demand decrease in commuting hours

(Figure 5a). The peak of Case 3 appears slightly higher than the new peak of Case 2, 3927.5 kW with a small difference of 0.316 W. This is because the operation assessed operating in response to energy charge rates to be more cost efficient rather than using up all of the charged electricity in the BESS for peak shaving, considering the peak time in commuting hours is close to the first peak section of energy charge rates. It demonstrates that each operation for demand and energy charge minimization, respectively, can influence each other due to constraints on BESS capacity and continuity of operation. Additionally, the BESS capacity limit restrains shifting demand in response to the rates. Time slots between 41 and 48, and 53 and 68 (peak rate time) show it discharging at an output around 200 kW and 100 kW, respectively, not at the maximum output of the PCS battery capacity limits (1 MW) (Figure 5b). Additionally, Case 3 appears to operate BESS more frequently than Case 2, which will incur more degradation costs.

We have investigated the impact the operations of each case on BESS degradation and calculated the costs. When calculating, we supposed the BESS cost to be 0.5 billion won (KRW). Figure 6a displays the change of SoC in BESS operation and Figure 6b indicates the accumulated degradation level caused by BESS operation as percentages. We connected the four weeks of data from four seasons into 2688 time steps to show the frequency of charging and discharging of the BESS and degradation of the BESS, thereof, by the seasons as shown below.

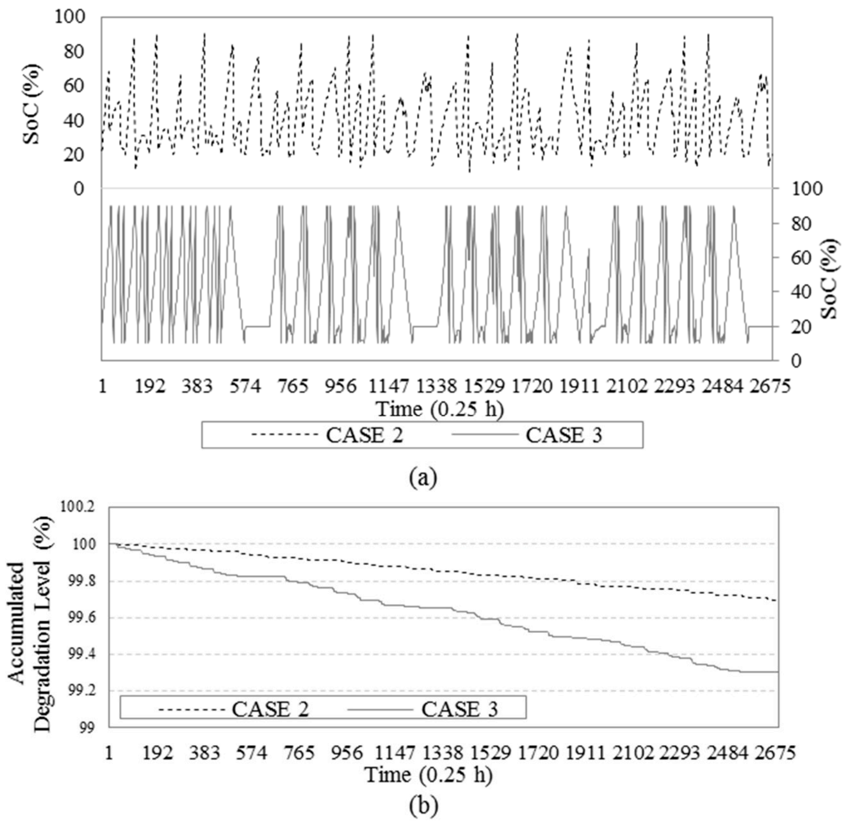

Figure 6. Impact of operation strategies on degradation by case: (**a**) SoC, and (**b**) accumulated degradation level.

We tabulated the economic evaluation (electricity charges, annual investment costs), degradation level, life expectancy, and impact on power systems per the strategies in Table 3. Among the four cases, the minimum "Total Electricity Charges" and "Total Costs" values are highlighted in bold.

Table 3. Results by BESS operation strategy.

Results	Case 1	Case 2	Case 3	Case 4
Demand Charges (KRW)	441,701,100.0	352,061,100.0	352,061,128.3	441,698,535.6
Energy Charges (KRW)	1,335,480,505.9	1,335,539,732.3	1,327,068,753.9	1,326,965,217.0
Total Electricity Charges (KRW)	1,777,181,605.9	1,687,600,832.3	**1,679,129,882.2**	1,768,663,752.6
Annual Investment Costs (KRW)	0.0	19,981,904.9	72,418,567.2	49,875,431.1
Total Costs (KRW)	1,777,181,605.9	**1,707,582,737.3**	1,751,548,449.4	1,818,539,183.8
Annual Degradation Level (%)	-	4.00	14.48	9.98
Life Expectancy (year)	-	25.02	6.90	10.02
Reduction of Customer's Peak Load	-	O	O	X
Reduction of Power System Peak Load	-	X	O	O

We have seen that Case 3 saved more electricity charges than Case 2, and also lowered the customer's, and the entire peak, loads. Considering the annual investment costs derived from the degradation model, however, Case 2 is in a more favorable position than Case 3 in terms of total costs (Figure 7). This signifies BESS operations used for additional energy charge reduction bring more loss than the savings due to degradation. We can confirm this in Case 4, which demonstrates BESS operations for only energy charge minimization incur more costs in degradation compared to the reduced amount in charges in Case 2.

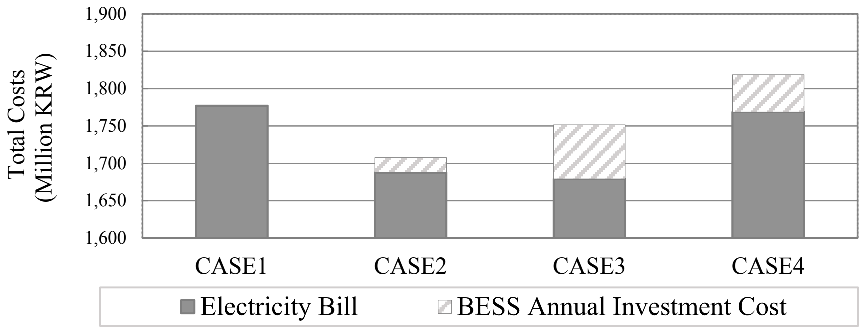

Figure 7. Comparison of total costs by BESS operation strategy.

Consequently, ESOs are predicted to operate BESSs with Case 2, driven by their own economic inducement, regardless of whether it has an undermining effect on the power system. With this wisdom, it implies that a high BESS installation cost and its short life will motivate ESOs to operate the BESS without being attracted to a market inducement (e.g., differential energy charge rates by time period). However, annual investment cost reduction, by BESS installation cost decreases or BESS life increases, is anticipated to gradually resolve this problem. From this simulation, when the current contrast value of BESS installation costs is about 17%, Case 4 will have economic viability, and when that of BESS installation costs are about 16.15%, Case 3 will settle as a more economic operation strategy than Case 2 without giving a negative impact on social benefits. In light of the rate of return (ROR) of BESS investors, it is obvious that BESS installation costs should fall further.

5. Discussion

The BESS installed in urban railway loads is anticipated to operate for peak shaving (Case 2) so as to maximize economic profit of the ESOs. In comparison with Case 2, despite the reduction in annual electricity charges of 8.5 million KRW made by Case 3, the total costs ended up giving a rise of 43.9 million KRW owing to the increase of 52.4 million KRW in annual investment costs. Thus, ESOs are likely to operate BESSs with Case 2 for their own benefit, which will intensify the entire peak power load and SMP increase, hampering economic operations in the power system. These negative influences will grow in accordance with increases of customers' BESSs for electricity bill reduction, against which we should establish countermeasures.

The reason a BESS does not respond to differential energy charge rates is a lack of inducement to energy charge rates and high BESS installation costs. We have demonstrated that BESS installation cost ought to be reduced to about 17% compared to the current costs in order to raise a benefit from energy charge reduction under the current tariff system more than degradation costs. However, such a level of cost reduction will be hardly achieved in a short period of time. Ref. [23] proposes that utility subsidies be supported to BESS investors who are not guaranteed with a ROR from operations for arbitrage due to a high BESS cost, which many countries have been offering institutionally to promote ESS investment. Yet, this imprudent subsidization is probable to expand such BESSs, like the ones installed in urban railway loads, aggravating the negative impact on power systems. Therefore, a fundamental solution is required to attract BESSs without diminution of any positive impact on the power system while securing BESS investors' ROR. Re-composition of demand charges and energy charges in electricity bills and/or larger disparity of level of energy charge rates by section will be able to entice ESOs with energy charge rates. However, the objectives of demand and energy charges are not only demand inducement, but also withdrawal of fixed costs and variable costs. Hence, re-composition of the tariff system to offer a proper attraction for ESOs should be carefully examined in future studies.

This paper analyzed the properties of urban railway loads of which patterns differ from general loads to investigate the attractions of ESOs. We also checked the impact of BESS operation over power systems, thereby proposing measures to minimize negative influences. However, this study has the following limitations that have to be examined in future research: first, we did not reflect aggravation and offset effects that arise when various forms of loads integrate one another. Despite this, we examined a sole case of urban railway loads in this study, however, it demonstrated that the current environment could not induce distributed customer-owned BESSs in the way to give a positive impact on power systems; second, research on optimization of operation strategies to minimize total costs incorporating annual investment costs is required. In this paper, we presented a solution of electricity bill minimization. Additionally, we computed the total costs by adding degradation costs incurred from operation strategies suggested as the solution to electricity charges. If we can find an optimal operation strategy that can minimize the costs including annual investment costs, we can expect it to find the optimal strategy which results in lower total costs.

6. Conclusions

This paper determined the optimal BESS operation strategy for an urban railway load under a TOU, and analyzed the impact of the operation throughout the power system. Our attention focused on an optimal strategy for electricity bill minimization that is directly related to the applied tariff system and features of customer loads, and quantitated indirect effects of BESS operation strategies over BESS life into degradation costs. As a result, we demonstrated that the operations for a sole purpose of customer peak load shaving (Case 2) was the most economic operation strategy for ESOs, not the one that enabled additional reduction of energy charges (Case 3). The grounds were explained by Case 4, which showed BESS operation for energy charge reduction incurred more degradation costs than the amount of reduced charges due to the frequent BESS charging and discharging. Despite Case 2 being the optimal strategy for ESOs, it causes an increase of the entire peak of the power system, aggravating the burden on facilities, while Case 3 positively influences power systems, as well as ESOs. These operation strategies will continue to be utilized until Case 3 can offer a greater economic benefit to ESOs by diminution of BESS degradation costs or life extension. It implies the current TOU environment does not provide an adequate inducement for customer-owned BESSs. As BESSs that operate in response to a tariff system, such as electric vehicles, are expected to increase, establishing countermeasures is required to ensure positive implications over power systems.

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