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# Shared Electrical Energy Storage Service Model and Strategy for Apartment-Type Factory Buildings

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**ABSTRACT** Electrical energy storage (EES) is a promising and convenient solution for energy efficient buildings, but the high cost of EES limits the expansion of its use. This study presents a shared EES (s-EES) service model including the architecture for implementing the service and a strategy for operating the service for apartment-type factory buildings composed of individually owned units. The proposed architecture for the s-EES service consists of physically connected energy and communication infrastructures, and logical operation of the EES virtually assigned to each participating unit. The conceptual scheme for the s-EES service is presented in the architecture. The service strategy is designed to meet the profit maximization problems of the participants and energy service provider (ESP). The optimal s-EES size and service price conditions are calculated using Lagrangian relaxation, and exchanging information between the participant and the ESP. A case study which uses data from Korea shows that more than 80% of the units in a building participate in the service because of the benefits. The benefits for both the ESP and the units grows with an increase in participating units and a decrease in EES cost. Considering 30%, 50% and 70% EES cost reduction, the ESP's profit increases linearly to about 8, 850, and 1500 dollars a month, respectively. The additional total profit of participants increases exponentially to about 300, 640, 2400 dollars a month, respectively, when compared to individual EES usage. In the s-EES service model, an ESP can provide EES service at a low price through economies of scale, and units in the building can use the EES at a lower price than if they were installed individually.

**INDEX TERMS** Demand-side management, electrical energy storage, energy storage system, energy management system, apartment-type factory, flatted factory, multi-dwelling unit, electric bill.

## I. INTRODUCTION

### A. MOTIVATION

Economic growth and increasing population drive electricity demand. Energy use in residential and commercial buildings is a major contributor to growth. In 2017, energy in the buildings sector (residential and commercial) represented approximately 39% of total U.S. energy consumption [1] and 21% of total world-wide energy consumption [2]. In particular, electricity consumption is steadily increasing compared to the stagnant consumption of primary energy sources such as

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natural gas [1]. The convenience of use and control increases the number of appliances that use electricity for heating, cooling, and lighting [3], [4]. Therefore, it is necessary to increasing energy efficiency and reducing electricity expenditure in buildings.

### B. PRIOR WORKS

There are direct and in-direct approaches to increasing energy efficiency and reducing electricity expenditure in buildings. Direct approaches include using energy efficient equipment such as light shelves [5], LEDs [6] and building-integrated photovoltaics [7]. Another direct approach is to improve building infrastructure with materials such as glass fiber

boards for building envelope insulation, which reduces thermal transmittance [8]; energy-saving glazing [9]; and materials [10] for minimizing heating and cooling loss. Energy controls are indirect approaches, and include heating ventilation and air conditioning (HVAC) control applied with a genetic algorithm [11] and machine learning-based regression techniques [12]; and cost-effective demand response in apartment-type factory buildings [13]. However, these approaches require changing conventional equipment into new ones or affecting occupants' convenience through energy control.

Electrical energy storage (EES) is used in various applications to improve stability, sustainability, and reliability of renewable energy sources [14] and power systems [15]. In the building sector, thermal energy storage is considered for thermal and cooling energy management [16], [17]. However, growing electrical demand in buildings, EES is considered a promising solution for energy-efficient buildings [18]. EES can be applied to conventional buildings without changing installed equipment or reducing occupants' convenience. A model predictive control-based energy management framework with EES was proposed to reduce electricity expenditure for residual buildings in [19]. In [20], the optimal EES size planning was investigated to minimize the total electricity cost of buildings, including EES investment. EES is also used to support energy-efficient approaches by reducing the uncertainty of renewable sources and demand. The authors in [21] presented a mathematical analysis of financial incentive policies in the U.S. for integrated photovoltaic and battery energy storage (PV-BES) systems considering four types of buildings. EES sizing and operational strategies for reducing the renewable energy uncertainty were suggested in [22]. These studies show the effectiveness of EES, but the high cost of EES systems limits the expansion of EES usage [23].

The economic evaluation of EES is based on game theory. A hybrid battery energy storage system for load shifting is modeled as a cooperative game, and the Nash equilibrium solutions are obtained from the genetic algorithm in [24]. Mondal et al. presented a distributed energy management system model with storage using the multiple-leader-multiple-follower Stackelberg game model [25]. Motalleb et al. suggested a non-cooperative game market model for selling stored energy from EES, and the optimal bidding strategies for the aggregators in the market model [26]. A cooperation game between the wind power-regenerative electric boilers and the wind power-energy storage system is presented to maximize the daily benefit of the system using the particle swarm optimization algorithm [27]. However, these studies do not cover EES sharing and building environments.

### C. CONTRIBUTION

In this work, a shared EES (s-EES) service model is proposed for application to building environments. In particular, multi-unit buildings such as apartment-type factory buildings and flatted factories are considered. In countries with a high population density and high land prices, apartment-type factory

buildings are common in urban areas [28]. In Korea, approximately 31% of all companies are located in apartment-type factories [29]. An apartment-type factory building is a complex of multiple individually owned small factories and/or offices. It has a high energy consumption density and low energy efficiency compared to conventional office buildings. Therefore, increasing the energy efficiency and reducing the electric bills are a critical problem related to capital and operational costs for occupants in apartment-type factory buildings. Furthermore, the problem can expand into multi-dwelling unit environments [30].

The basic concept of EES sharing was introduced in [30], [31]. In conventional works, cloud or clustered ESS is added for distributed customers, and the proposed models are to maximize the total social welfare. The approaches can show the existence of the economic feasibility of the ESS, but how to operate the installed ESS and how to share the profits among participants are not covered. However, this paper covers the methodology to share the limited ESS capacity considering the situation of each participant and the operation strategy for the service provider.

The main contributions of this paper are summarized as follows:

- *The s-EES service model and architecture:* This paper focuses on the implementation of the service in apartment-type factory buildings. The demand for a building is treated as the sum of that of all occupants [32]. In order to apply the s-EES service, individual metering of occupants is required such as net metering [33]. An s-EES service scheme is proposed, including an s-EES service provider mechanism and customer decision process. In addition, an architecture to support the s-EES service model is presented considering virtual net metering combined with a communication infrastructure.
- *The s-EES service strategy:* The s-EES service strategy is also proposed for implementing the service. To operate the service, it is required to determine the s-EES size, service price, and participant selection. The optimization problem is formulated to maximize the profit of a service provider and participants. Using Lagrangian relaxation, the solution to achieve the optimal value is proposed. It is interactively solved with the information exchange between the service provider and participants. This appears to be a unit commitment problem because the solution of the problem is a participating unit's selection, and an energy assignment to this unit. However, this paper considers the different environment of buildings and introduces a service model for a new energy service provider even if the mathematical approach is similarly formulated to conventional UC problems. A case study was performed by simulating the effects of the s-EES service for an apartment-type building in Korea. Numerical results show that both the service provider and participants can profit through the s-EES service. In addition, the performance sensitivity was analyzed

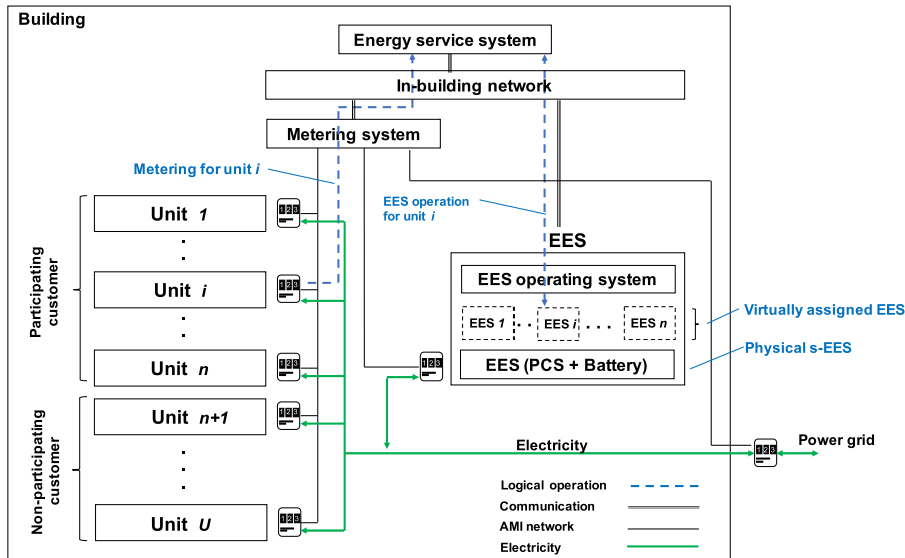


FIGURE 1. S-EES system architecture.

according to the characteristics of the service provider and participants.

II. S-EES SERVICE MODEL

Recently the various types of energy service providers (ESPs) have started to appear. Some of the models include peer to peer energy transaction models across a distribution network [34], [35]. Companies such as Sonnen Community, Vandebrom, and Piclo already have been operating prosumer energy trading services among participants located in different places. However, those new types of ESPs may have potential conflicts with utilities in the future. Contrarily, building-level problems are easier to handle than grid-level problems. A utility company generally contracts with a building customer for the entire building. Therefore, a single metering device is usually installed for the building for billing. However, it is common to have multiple units in a building. Those units are owned by financially separate entities such as individual companies. Therefore, a sub-metering solution is required for billing individual companies.

One of the common solutions involves installing an EES if an individual unit wants to manage its electricity bill. In this case, the EES is installed behind the meter, so it does not affect any other systems except for the electricity usage pattern of the unit. To do this, the unit purchases and installs its EES, and can operate the EES for peak shifting or price response to minimize the electricity bill.

An EES consists of a power conditioning system (PCS) and battery, and usually appropriate-capacity products are selected among ready-made products; this limits customer selection for optimizing the capacity. Furthermore, an individual installation increases the cost because of the limited purchasing power of a single customer. Furthermore, tenant relocations from the building are not uncommon; this reduces the value of an installed EES.

An s-EES can be an excellent solution to overcome these individual EES installation problems. An ESP can install an s-EES in the public space of a building and lease the partial capacity of the s-EES to participants. The ESP can reduce the installation costs because the ESP purchases a more substantial EES capacity than would the individual units. Participants in the s-EES program of the building can obtain the equivalent or more economical service without capital expenditures. This situation is preferable for both the ESP and participants.

A communication infrastructure is required to support the s-EES model. Figure 1 shows that the architecture of the s-EES infrastructure consists of a virtually assigned EES to each participating unit. If the sub-metering infrastructure for each unit is already set up within the building, then virtual metering for logically assigned EESs to participating units can be performed easily. The virtual metering value calculated from individual EES operation should be combined with the physical metering value of the corresponding unit. The s-EES is operated as the sum of individual EES usage physically even though virtual EESs are independently operated logically.

Figure 2 shows the conceptual scheme for the s-EES service. The left side shows the operational model of the ESP, and the right side shows the decision process of the participants. First, the ESP sets the appropriate target EES capacity and its price offer on the basis of a load analysis of the units and the EES installation and operating costs. Each unit in the building decides whether to participate in the ESP's s-EES program on the basis of the price offer. If a unit can reduce its total cost with EES, then the unit can select EES self-installation or participation in the s-EES program considering the cost comparison result. Even if it is not economical for the self-install case, the price offer can be low enough to participate in the s-EES program. If it is

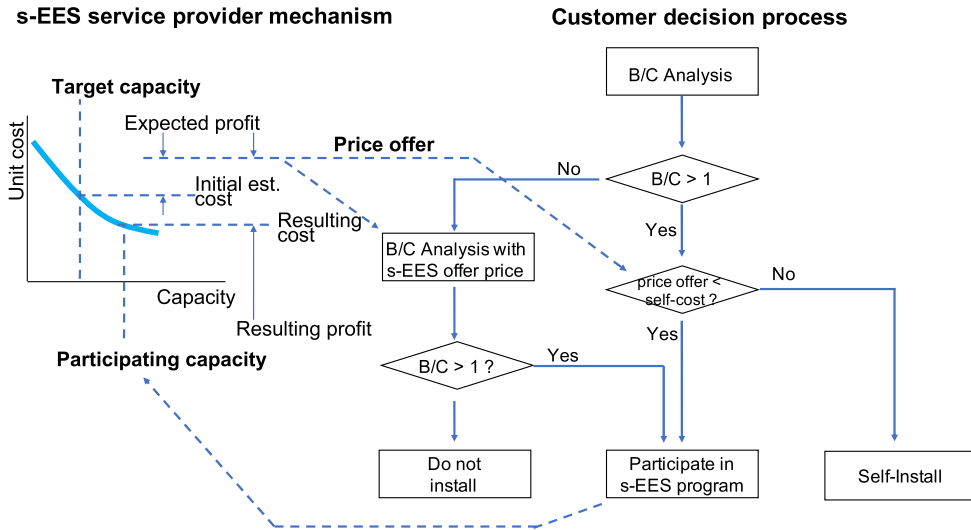


FIGURE 2. Conceptual scheme for the s-EES service.

not economical for either the self-install or s-EES program participation cases, then the unit would prefer to wait without using EES. The target capacity of the ESP can be determined to maximize the ESP’s profit. The ESP can expect higher profit with the more participating capacity than the target capacity.

III. S-EES SERVICE STRATEGY

In this section, a strategy for implementing the s-EES service is proposed. First, from the EES cost model, the profit maximization problems are formulated in terms of the participants and ESP. The service strategy and procedure to determine the s-EES size, service price, and participant selection are presented to solve the problems.

A. EES ECONOMIC COST MODEL

As mentioned previously, EES cost is the critical criterion for using the EES. The EES cost is mostly determined according to the EES type, such as Li-ion, lead-acid, or redox flow, and the EES size [36]. In the Li-ion case, the levelized cost is exponentially reduced with increasing system size as shown in Figure 3 [37]. This means that economies of scale apply to the EES cost related to its size.

Note that the levelized cost is the normalized cost by the service time, including the total EES capital expenditure, such as capacity cost, and operational expenditure, such as operational and maintenance costs and taxes. The Li-ion battery’s capacity cost, which represents most of the EES cost, has fallen approximately 36%/year in the last 5 years [37]. By 2030, the lifetime of Li-ion batteries could increase by approximately 50% and the total installed cost of a Li-ion battery could be reduced by an additional 54–61% [38]. This shows that the Li-ion levelized cost will be reduced more than 50% compared to the current cost.

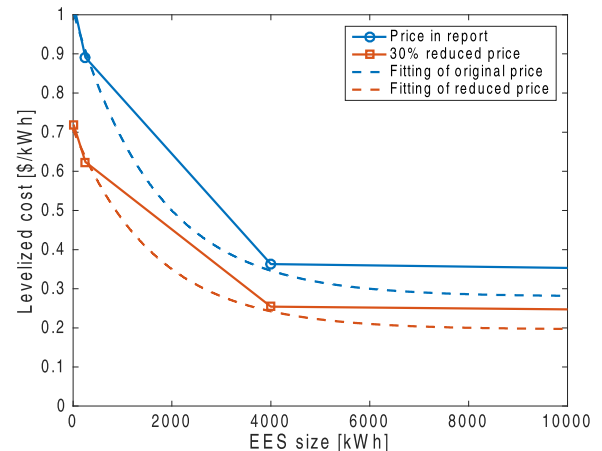


FIGURE 3. EES levelized cost varying EES size.

From these observations, the EES cost related to the size is modeled as

$$p_e(e_{ES}) = \alpha_1 \exp(-\alpha_2 e_{ES}) + \alpha_3 [$/kWh], \tag{1}$$

where  $e_{ES}$  [kWh] is the energy subsystem size of the EES. The PCS size of the EES is determined as  $e_{PS} = e_{ES}/2h$  [kW] assuming the maximum service time of the EES is 2 h [37]. The function in (1) was measured by fitting the value of Reference [37]. However, similar results are presented in studies on the EES cost analysis [39], [40]. Increasing EES size, EES equipment and maintenance cost are reduced. Thus, the unit EES cost is exponentially reduced by increasing the EES size. This is a basic advantage of economies of scale.

B. PROBLEM FORMULATION

This work focuses on the profit maximization of an ESP. However, to implement the service, participants should also profit by using the s-EES service.

1) ECONOMIC MODEL OF A PARTICIPANT

On a participant side, profit is defined as electric bill savings using the s-EES service compared to the individual EES usage. As an example, a unit (building occupant) will operate  $x$ -kWh EES individually, and an ESP services the EES with service price  $p_s$  [\$/kWh]. If the unit uses the s-EES service, then it saves the EES cost as  $x \times \{p_e(x) - p_s\}$ . In both the individual and s-EES cases, it is assumed that the unit uses the same EES size. Thus, the unit can achieve the same electric bill savings by the EES.

When a unit  $i$  uses the  $e_i$ -kWh EES, the electricity bill of unit  $i$  is measured as

$$B_i(e_i) = p_0(d_{t^*} + q_{t^*}) + \sum_{t \in T} p_t(d_t + q_t), \quad (2)$$

where  $t^* = \arg \max_{t \in T} (d_t + q_t)$ .  $p_0$  and  $p_t$  are the demand price and the energy price at time  $t$ , respectively.  $q_t$  is the energy charging/discharging to the EES at time  $t$ . The charging/discharging operation is restricted to the EES size  $e_i$  and can be determined to minimize the electricity bill using a conventional algorithm [20] because the EES operations for the proposed sharing and the conventional individual cases are logically identical.

The electricity bill savings of unit  $i$  with the EES is calculated as

$$\tilde{G}_i(e_i) = B_i(0) - B_i(e_i). \quad (3)$$

In addition, the net profit of unit  $i$  considering the EES cost becomes

$$G_i(e_i) = \{B_i(0) - B_i(e_i)\} - p_e(e_i)e_i. \quad (4)$$

When unit  $i$  participates in the s-EES service, the EES cost  $p_e(e_i)$  is changed to the s-EES service price  $p_s$ ,

$$G_i(e_i, p_s) = \{B_i(0) - B_i(e_i)\} - p_s e_i. \quad (5)$$

The service price  $p_s$  is a given value from the ESP. Therefore, the profit maximization problem on the participant side is formulated as the EES size determination,

$$\begin{aligned} \text{P1: } & \max_{e_i} G_i(e_i, p_s) \\ & \text{s.t. } G_i(e_i, p_s) \geq 0, \\ & p_e(e_i) \geq p_s, \\ & e_i \geq 0. \end{aligned} \quad (6)$$

The first constraint is a basis constraint to achieve the positive profit by the EES usage. For applying the EES, the EES cost is less than the electricity bill savings by the EES usage. The second constraint expresses that the s-EES service price should be lower than the cost of the individual EES case to participate in the s-EES service.

Note that the problem in (6) is a convex problem, so it can be solved by simple algorithms based on the

Newton–Raphson or gradient descent method [41]. When the unit receives the service price  $p_s$  from the ESP, the unit decides whether to participate in the service considering the optimal EES usage size obtained by solving the problem **P1** in (6).

2) ECONOMIC MODEL OF THE ENERGY SERVICE PROVIDER

On the ESP side, profit is determined as a cost margin between the EES service price and the operational cost. Assuming that the s-EES size is  $e_T$ , the profit of the ESP becomes

$$G_{ESP}(e_T, p_s, \mathcal{A}) = \sum_{i \in \mathcal{A}} p_s e_{i^*} - p_e(e_T) e_T, \quad (7)$$

where  $e_{i^*}$  is the optimum EES size of unit  $i$ . The size is determined by solving the problem **P1** of (6).

The profit maximization problem on the ESP side is formulated as

$$\begin{aligned} \text{P2: } & \max_{e_T, p_s, \mathcal{A}} G_{ESP}(e_T, p_s, \mathcal{A}) \\ & \text{s.t. } G_{ESP}(e_T, p_s, \mathcal{A}) \geq 0, \\ & \sum_{i \in \mathcal{A}} e_{i^*} \leq e_T, \\ & e_T, p_s \geq 0, \end{aligned} \quad (8)$$

where the profit of the ESP is determined by the s-EES size  $e_T$ , the service price  $p_s$ , and the participant set  $\mathcal{A}$ . The first constraint is a mandatory constraint for the positive profit of the ESP. The second constraint is the constraint to guarantee service to each participant. In the next section, an s-EES service strategy is proposed to maximize the ESP’s profit by solving the problem in (8).

3) S-EES SERVICE STRATEGYS

The participant set is selected among the units choosing to participate in the service. A unit’s decision to participate is measured by the service price. The service price is limited by the EES size. This means that the decision variables of the ESP’s profit in (8) are determined as the result of interactions among variables.

To solve the problem **P2**, the optimization problem in (8) is relaxed using the Lagrangian multipliers  $\lambda$  and  $\nu$  as shown in (9), as shown at the bottom of this page.

The optimal values  $e_T^*, p_s^*, \mathcal{A}^*$  and the Lagrangian multipliers  $\lambda^*$  and  $\nu^*$  should satisfy the Karush–Kuhn–Tucker (KKT) conditions [41], as follows:

$$G_{ESP}(e_T^*, p_s^*, \mathcal{A}^*) \geq 0, \quad \sum_{i \in \mathcal{A}^*} e_{i^*} \leq e_T^*, \quad (10a)$$

$$e_T^*, p_s^*, \lambda^*, \nu^* \geq 0, \quad (10b)$$

$$\lambda^* \cdot G_{ESP}(e_T^*, p_s^*, \mathcal{A}^*) = 0, \quad (10c)$$

$$\nu^* \cdot \left( e_T^* - \sum_{i \in \mathcal{A}^*} e_{i^*} \right) = 0, \quad (10d)$$

$$f(e_T, p_s, \mathcal{A}, \lambda, \nu) = G_{ESP}(e_T, p_s, \mathcal{A}) + \lambda \cdot G_{ESP}(e_T, p_s, \mathcal{A}) + \nu \cdot \left( e_T - \sum_{i \in \mathcal{A}} e_{i^*} \right). \quad (9)$$



$$\frac{\partial f}{\partial e_T} = \frac{\partial G_{SP}}{\partial e_T} + \lambda^* \cdot \frac{\partial G_{SP}}{\partial e_T} + v^* = 0, \quad (10e)$$

$$\frac{\partial f}{\partial p_s} = \frac{\partial G_{SP}}{\partial p_s} + \lambda^* \cdot \frac{\partial G_{SP}}{\partial p_s} = 0. \quad (10f)$$

In (10c),  $\lambda^* = 0$  or  $G_{ESP}(e_T^*, p_s^*, \mathcal{A}^*) = 0$ . If  $G_{ESP}(e_T^*, p_s^*, \mathcal{A}^*) = 0$ , then the ESP achieves no profit. This means that it does not make sense for the ESP to provide the s-EES service. Therefore, the optimal value of  $\lambda^*$  becomes zero.

Applying  $\lambda^* = 0$  to (10e),  $v^*$  is calculated as

$$v^* = -\frac{\partial G_{ESP}}{\partial e_T} = p_e(e_T) + e_T \frac{\partial p_e(e_T)}{\partial e_T} > 0, \quad (11)$$

and, by using (10d), the optimal s-EES size  $e_T^*$  is measured as

$$e_T^* = \sum_{i \in \mathcal{A}^*} e_i^*. \quad (12)$$

From (10f), the service price  $p_s^*$  is unbounded. This is because the problem **P2** is an unbounded problem on the service price side. To find the optimal service price, the ESP's profit is rewritten by substituting (12) into (7):

$$G_{ESP}(e_T, p_s, \mathcal{A}) = \underbrace{\{p_s - p_e(e_T)\}}_{\text{Profit by price}} \cdot \underbrace{\sum_{i \in \mathcal{A}} e_i^*}_{\text{Profit by size}}. \quad (13)$$

In (13), with increasing service price  $p_s$ , the profit by price grows. However, the profit by size is reduced because the optimum EES size of each unit  $e_i^*$  is decreased from the problem **P1**. This means that the service price is interactively calculated considering both problem **P1** and problem **P2**. Using the gradient method based on the iteration [41], the optimal service price is calculated as

$$p_s^{(i+1)} = p_s^{(i)} + \varepsilon_i \nabla_{p_s} G_{ESP}(e_T, p_s, \mathcal{A}), \quad (14)$$

where  $\varepsilon_i$  is the step size at the  $i$ -th iteration and  $\nabla_x$  is the gradient operation about  $x$ . With the approximation of the gradient as a slope between iteration points, the service price is determined as

$$p_s^{(i+1)} = p_s^{(i)} + \varepsilon_i \frac{G_{ESP}(e_T^{(i)}, p_s^{(i)}, \mathcal{A}^{(i)}) - G_{ESP}(e_T^{(i-1)}, p_s^{(i-1)}, \mathcal{A}^{(i-1)})}{p_s^{(i)} - p_s^{(i-1)}}. \quad (15)$$

The participant set  $\mathcal{A}$  is determined from the problem **P1** as the set of units who have a positive profit. The ESP always enrolls the units who will use the service. As shown in (13), by expanding the participant set, the ESP's profit can be enhanced with an increased s-EES size.

The procedure to implement the s-EES service strategy is presented in Figure 4 as a flowchart. As shown in the flowchart, the proposed strategy is divided into the participant part and the ESP part. Each player (participants and ESP) of each part tries to maximize its own profit. Moreover, these two parts are associated with each other. The results from

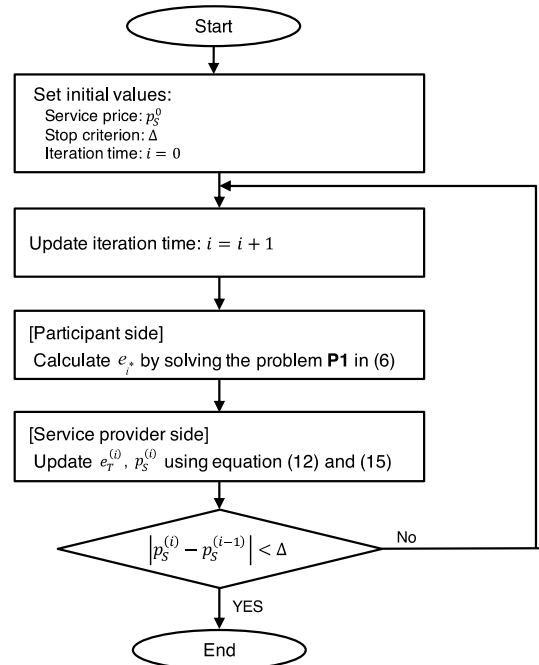


FIGURE 4. Flowchart of the proposed process.

each part are iteratively updated to converge on the optimum value.

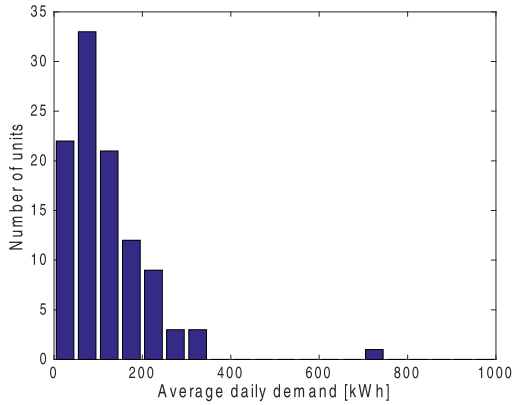
Through the s-EES service, an ESP can provide an EES service at a low price through economies of scale. The ESP profits from the difference between the EES installation cost and the service price paid by the units, and the participating units achieve the profit from using the EES at a lower service price than if they were installed individually.

## IV. CASE STUDY

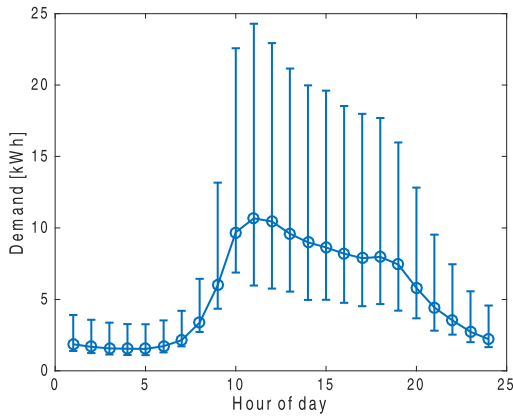
### A. EXPERIMENTAL ENVIRONMENT

An apartment-type building demand set for January 2014 was used for this study because the load demand is highest throughout a year for the building. The data was recorded at one-hour resolution as a part of the Korea Micro Grid Energy Project (K-MEG) [13], [42]. The building consists of 116 units. Figure 5 presents the demand profile of each unit. Approximately 70% of the units consume less than 150 kWh per day, but two units use more than 700 kWh per day, as shown in Figure 5(a). In Figure 5(b), the demands of the units are observed versus time. The line shows the average demand of units, and the bar presents the value range from 25% to 75% of the units' demand. Figure 5(b) shows that the demand is maximized at approximately 11:00 and the variance of demand by each unit is higher from 10:00 to 19:00 than the usage amount in the other times of the day. This is because the demand consumption is high during working hours. It also means that each unit similarly consumes the demand on average, but the demand pattern of each unit is different. The demand pattern difference among units can reduce the EES capacity requirement, increasing the availability of the s-EES service.

For the electricity bill calculation, the electricity rate table of Korea Electric Power Company was used, shown



(a) Average daily demand histogram



(b) Hourly demand

**FIGURE 5.** Demand profile of each unit. In Figure 5(b), the line shows the average demand of units, and the bar presents the value range from 25% to 75% of each unit’s demand.

in Table 1. The electricity rate is the Time-of-Use (TOU) tariff for general customers [43]. The EES cost factors,  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  were assumed as 0.22, 0.006, and 0.08, respectively. The values were measured by fitting the reported EES cost [36]–[38]. The EES cost is the hard constraint for operating the EES service, so the results were analyzed by varying the EES cost. In addition, the s-EES service price is presented as the relative value to the EES cost per installed 1 kWh:

$$\text{Relative service price} = \frac{P_s}{p_e(1)}$$

**B. PROFIT**

Table 2 shows the simulation result summary with varying EES cost. The current EES cost is high, so it is difficult to gain the benefits of the EES service simply by the electricity bill savings. Therefore, many countries are encouraging EES through subsidies and rate cuts [44]. The EES cost reduction has the equivalent meaning of both cost decrease effect over time and cost reduction due to subsidies.

**TABLE 1.** Korea electric power company general tariff (A)II – I (\$1 ≈ KRW 1,000) [43].

Demand charge [KRW/kW]	Energy charge [KRW/kWh]		
	Off-peak	Mid-peak	On-peak
7,170	71.4	101.8	116.6

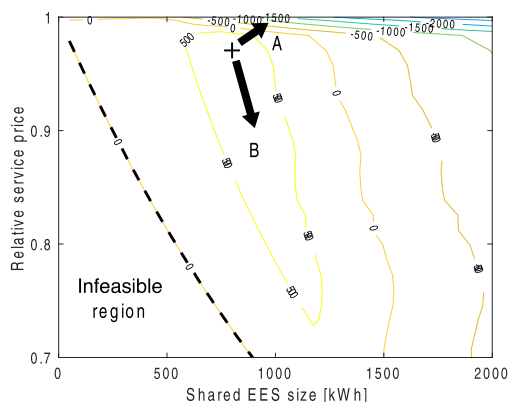
**TABLE 2.** Result summary with varying EES cost. The participant profit is measured as overall participant gain.

	EES cost reduction		
	30%	50%	70%
Monthly profit			
ESP [\$ /month]	7.9	854.1	1534.8
Participant [\$ /month]	297.9	641.4	2647.2
ESP characteristics			
S-EES size [kWh]	650	800	1475
Relative service price [%]	76.9	97.1	95.8
Participant characteristics			
Participant ratio [%]	84.8	85.7	89.5
Served EES per unit [kWh]	7.3	8.8	15.7

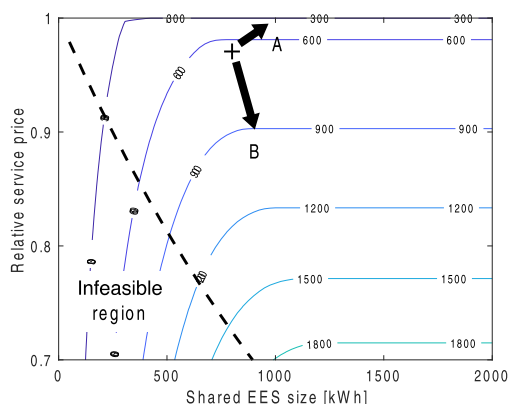
The profits in this section are additional profits from conventional individual operation on the participant side in (5), and net service profit on the ESP side in (13).

On the participant side, with decreased EES cost, the values of participant characteristics are monotonically increased in Table 2. From (5), the participants’ profit is linearly related to the EES cost. Therefore, more units participate in the s-EES service when less EES cost is applied. The profit of the overall participants is also enhanced with the increasing number of participating units. On the ESP side, when reducing the EES cost, the ESP profit is monotonically increased similarly to the participant profit, but the trend of the ESP characteristic such as relative service price does not change monotonically, as shown in Table 2.

The s-EES size has a positive relationship to the EES cost reduction. In (12), the optimal s-EES size is determined as the sum of the EES assigned to individual units. Therefore, by increasing the participation of units, the s-EES size is also increased. As the EES cost is reduced by 30%, 50%, and 70%, the service prices  $p_s$  are also reduced to 4.9, 4.4, and 2.6 \$/kWh per month, respectively. However, the relative service price has a higher value with 50% EES cost reduction rather than the cases with 30% and 70% EES cost reduction. In (15), the service price is related to the participant set as well as the EES size by the EES cost. Therefore, the ESP provides



(a) Energy service provider



(b) Participants

**FIGURE 6.** Monthly profit according to s-EES size and relative service price when the EES cost is reduced by 50% from the current EES cost. The plus signs in the figure are the optimum points on the ESP side.

low relative service prices in order to benefit from economies of scale by encouraging the participation of additional units.

Figure 6 presents the monthly profit according to s-EES size and relative service price for the 50% EES cost reduction case. Figure 6(a) shows how the s-EES service strategy is operated. The region under the dashed line is where the relative service cost is less than the s-EES cost; thus, the region is the infeasible region for the s-EES service. Except for the infeasible region, the operational region is constructed as a convex cone by the s-EES size and the relative service price. When the operational region becomes a convex cone, the gradient method-based s-EES strategy in Figure 4 is always converged to the optimum point (marked by the plus sign in the figure) from any initial points [41]. It presents the convergence and the optimality of the s-EES strategy.

Figure 6(a) also shows how the s-EES service provider achieves the profit. The profit of the ESP is reduced when the set of the s-EES size and relative service price are changed from the optimal set at the plus sign. In particular, the profit is rapidly decreased when the set is changed to the direction A. The direction A presents the case when the ESP increases the s-EES size and the service price. With increasing the s-EES

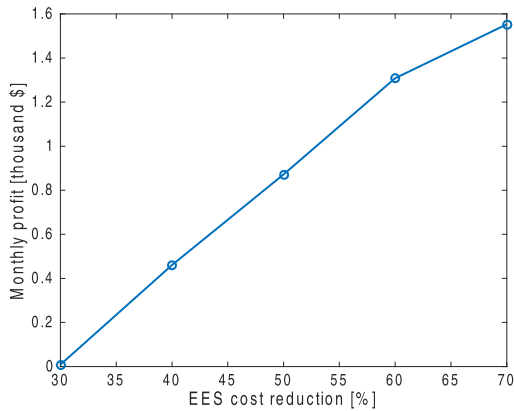
size, the EES cost burden is growing, but the s-EES service participation of the units is decreased caused by the higher service price. It reduces the ESP’s profit. When the set of the s-EES size and the service price is changed to the direction B, the EES cost burden of the ESP is increased same as the change to the direction A. However, the participation of the units is also increased by decreasing the service price. According to that, the ESP’s profit reduction is marginal. The results present that the proposed s-EES service strategy determines the s-EES size and the service price by the balance of the EES cost burden and the service participation.

Figure 6(b) shows the total participant profit by s-EES size and the relative service price. Note that the point marked by the plus sign is not the profit-maximized point on the participant side because the business model is designed to maximize the profit of the s-EES service provider while guaranteeing appropriate profits to participants. Obviously, for participants, the lower the relative service price, the higher the benefit. As discussed above, when the set of the s-EES size and the service price is changed to the direction A (or direction B), the benefit of the participant is reduced (or increased). It is related to the participant ratio of the units to the s-EES service as shown in Table 2. It means that the service price limits the service participation. The participation is determined the total participant profit. However, when the s-EES size is low, such as less 200 kWh, the participant profit is more correlated to the s-EES size than to the relative service price. At this point, the total required EES size of units,  $\sum_{i \in A} e_{i^*}$ , is larger than the s-EES size. Therefore, the s-EES size constrains the participant profit in this region.

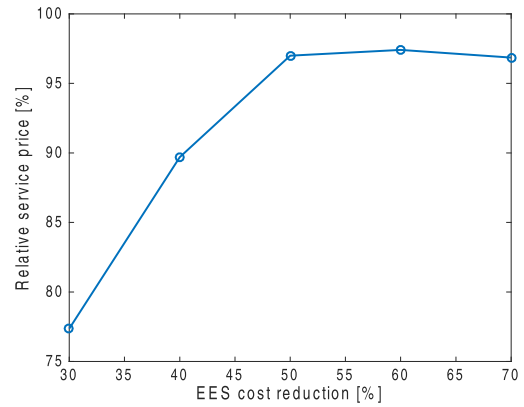
Figure 7 shows the monthly profit according to EES cost reduction. In Figure 7(b), the participant profit is exponentially enhanced by reducing the EES cost. This is because as the EES cost decreases, both the units who participate in the service and the required EES size increase, as shown in Table 2. When the EES cost is reduced, the s-EES size is increased with the increasing required EES size of the participants, but the service price is not as shown in Table 2. Therefore, the ESP’s profit is linearly increased according to the EES cost reduction in Figure 7(a). The profit increment rate is also reduced when the EES cost reduction is larger than 60% from the current price. In Table 2, approximately 90% of the total unit uses the s-EES service, so the ESP should reduce the service price to encourage the service in this region.

Figure 8 shows the total profit of the ESP and the participants in the cases of cooperative and non-cooperative operation as a blue line with circles and a red line with squares, respectively. In the non-cooperative operation considered by the proposed model, the ESP and participants maximize their own profits, and cooperative operation maximizes the overall profit of the ESP and participants. The cooperative operation achieves greater total profits than the non-cooperative operation because the cooperative operation has a larger operational region. Therefore, if the operational region is tight, such as when the EES cost reduction is very high (70%) or very low (30%), the profit gained through cooperative and

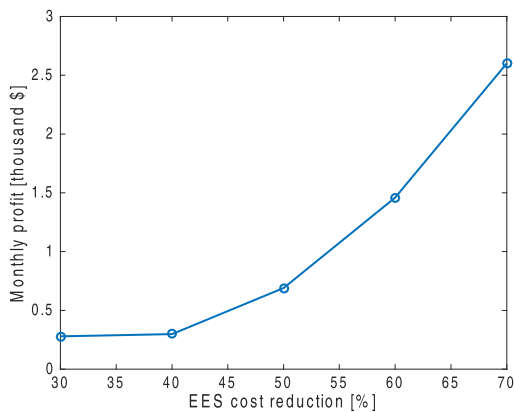




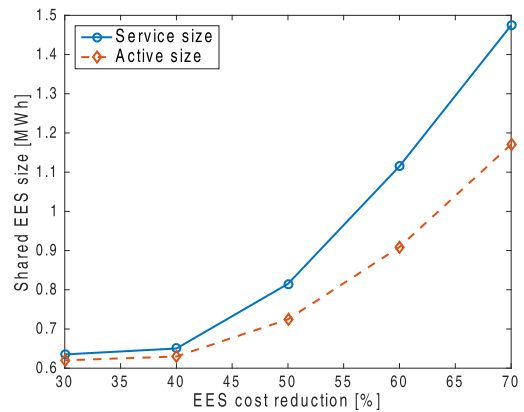
(a) Energy service provider



(a) Service price



(b) Participants



(b) S-EES size

FIGURE 7. Monthly profit according to EES cost reduction.

FIGURE 9. Change in service price and s-EES size by the EES cost reduction.

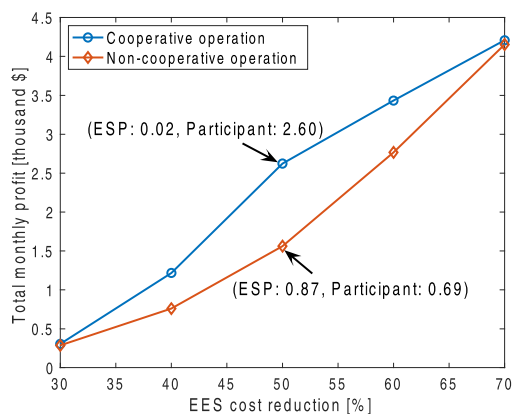


FIGURE 8. Total profit comparison between cooperative and non-cooperative operation in the proposed model.

non-cooperative operations is almost the same. Moreover, the ESP's profit is reduced by the cooperative operation from 870 dollars per month to 20 dollars per month at 50% ESS cost reduction. This is because the increase in the rate of the participant profit is greater than that of the ESP profit beyond this point, as shown in Figure 7. The model states that even if the cooperative operation generates more total profit than

the non-cooperative operation, additional problems, such as the profit balancing between ESP and participants, should be considered. That is discussed as future work.

C. CHARACTERISTICS

Figure 9 shows the change in service price and s-EES size by the EES cost reduction. In Figure 9(a), the relative service price is maximized at the 60% EES cost reduction point, and the value is reduced over that point. It is a trend similar to the profit increment ratio shown in Figure 7(a). In (13), the profit by the price is affected as a scale factor of the ESP's profit. Therefore, the decrease in the relative service price appears to reduce the profit increment ratio.

Figure 9(b) shows the change in the s-EES size related to the EES cost reduction. The blue line with circles and the dashed red line with diamonds presents the service EES size and the active EES size, respectively. The service EES size means the physical s-EES size  $e_T$ ; the active EES size is measured as the quantity used in actual s-EES service operation. The s-EES service is operated considering the aggregated demand of participants. At the time of operation, the charge (or discharge) status of the participant is not all the same. That means some units can discharge or do not operate

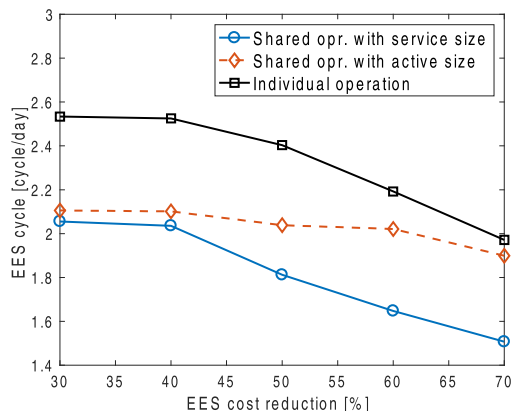


FIGURE 10. Change in EES cycle per day by the EES cost reduction.

while other units are charging. Charging and discharging can be offset to produce the same effect as virtually operating. Therefore, the active EES size in operation is less than the physically serviced EES size. This means that, considering these virtual operations, the ESP can achieve additional profits by preparing a smaller EES size than would otherwise be served.

Figure 10 presents the change in EES cycle per day by the EES cost reduction. In Figure 10, the blue line with circles and red dashed line with diamonds are the EES cycle when shared operations are applied considering the service EES size and the active EES size, respectively, and the black line with squares is the value when the EES is individually operated. The EES cycle determines the lifetime of EES systems that is the equipment replacement time, which is the costliest in maintenance. The results show that the EES cycle with shared operations is reduced compared to the individual operation. In particular, the case of the shared operation with service EES size is 20% less than the individual operation case due to the effects of superimposed charging and discharging. It means that the shared operation with service EES size is achieved additional mechanical profit increasing the EES lifetime as well as operational profit. The EES cycle of the shared operation with active EES size is also less than that of the individual operation, but the EES cycle gap between two cases is decreased with reducing EES cost. Related to the discussion in Figure 9(b), while the ESP can achieve additional profits by installing a small active EES size on the installation side, it is economically advantageous to install the service EES size in terms of system maintenance.

Figure 11 presents the participant ratio related to its daily average demand at 30%, 50%, and 70% EES cost reduction. When the EES cost is high, such as the 30% EES cost reduction case, the units who consume higher demand first use the s-EES service. With decreased EES cost, low-demand units participate in the s-EES service. This means that higher-demand units can save more on their electricity bills by EES usage. Therefore, it is possible to consider a simplified

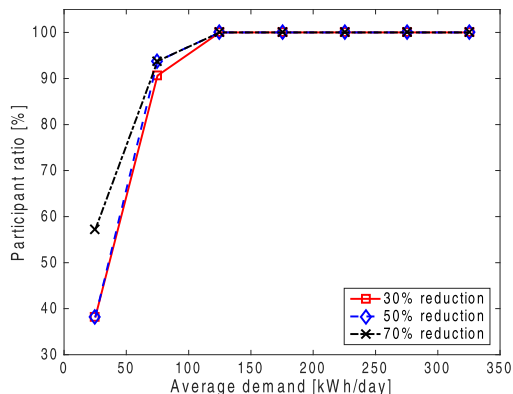


FIGURE 11. Participant ratio related to its daily average demand at 30%, 50%, and 70% EES cost reduction.

service model in the form of giving priority to high-demand units in the problem of determining the participant set.

### V. CONCLUSION

In this paper, an s-EES service model and strategy are proposed for multi-unit apartment-type factory buildings. First, the s-EES service model is presented, including an architecture for implementation. The s-EES service architecture consists of physically connected energy and communication infrastructures, and logical operation of the EES virtually assigned to each participating unit. Through the service, units in a building can use the EES at a lower price than if they were installed individually. The ESP profits from the difference between the EES installation cost and the service price to units. The s-EES service strategy to operate the service is also proposed. The strategy is proposed by focusing on the selection of the s-EES size and the service price in terms of the ESP, but it is determined interactively with the decisions on the participant side. The problem satisfies the convexity, therefore the gradient method-based s-EES strategy can obtain the optimal solution. The results using data in Korea show that more than 80% of units will participate in the service because they achieve more profit than that by the individual EES usage. In addition, the results highlight the change of the service parameters such as the s-EES size and the service price and the effect of unit demand through the EES cost reduction. Considering 30%, 50% and 70% EES cost reduction, the ESP's profit increases linearly to about 8, 850, and 1500 dollars a month, respectively. The additional total profit of the participants increases exponentially to about 300, 640, 2400 dollars a month, respectively, compared to the conventional EES usage. It offers guidance for implementing an s-EES service and participating in the service.

As future works, this work will be extended considering a more complex model from various perspectives. The detailed service models can be changed depending on the regulations

and locations. In a service aspect, this work focused on the maximization of the ESP profit. Considering the profit both ESP and participants, the service could be redesigned. In particular, a profit-sharing problem requires redressing the cooperative operation between the ESP and participants. In a system aspect, the model uses inter-grid in a building. However, when the model is extended to multi-unit cases connected to the grid such as multiple houses, the model including the grid operator could be considered. Moreover, the model has limitations in considering risks, such as a failure and the cost related to the risks, such as a penalty due to the failure, maintenance costs, and repair costs. For real-world use, many additional factors should be considered in the operating model. In a technical aspect, EES operation parameters are only constrained in the model. As shown in the result, the EES lifetime will be increased by reducing the operational EES cycle in the model. The EES lifetime is one of the major factors in the economic analysis. Considering EES lifetime due to the complex interaction between cyclic aging and calendar aging of EES, the economic profit model could be extended more practically.

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