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# Dynamic Virtual Energy Storage System Operation Strategy for Smart Energy Communities

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**Abstract:** The concept of a virtual energy storage system (VESS) is based on the sharing of a large energy storage system by multiple units; however, the capacity allocation for each unit limits the operation performance of the VESS. This study proposes an operation strategy of a dynamic VESS for smart energy communities. The proposed VESS operation strategy considers the usage-limited constraint rather than the capacity allocation constraint and it guarantees the usage of VESS resources of each participant for an operation period. Therefore, the degrees of freedom for VESS operation can be increased at each operation time. The dynamic VESS operation problem is formulated as a mixed-integer linear problem that could be solved optimally by applying gradient methods and dual decomposition. The dataset of a VESS in Korea is used for simulation. The simulation results demonstrate that, when the proposed operation strategy is used, the cost efficiency achieved is more than twice that achieved when the existing VESS operation strategy is used. Furthermore, the proposed strategy accurately reflects the characteristics of the participants; thus, more units can participate in the VESS operation service. The proposed VESS operation can improve the system performance of the utility grid and increase the net benefit of the participants.

**Keywords:** virtual energy storage system; energy storage system; energy sharing; energy management system; operation; smart energy community

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## 1. Introduction

As the distributed power generation is growing, owing to the advent of renewable energy generation, power system operation is becoming challenging because the frequency variation and duration of disruptions that indicate power system reliability are increasing [1]. An energy storage system (ESS) is an essential system to ensure the continuity of power or energy to the customers [2]. ESSs are used in different ways, from utility-scale applications, including black start [3], voltage regulation [4], frequency regulation [5], grid fluctuation suppression [6], and spinning reserve [7], to demand-scale applications, including demand flexibility management [8] and energy bill reduction [9]. To meet the net zero emissions objective of the International Energy Agency (IEA) by 2050, the share of energy system flexibility from ESS is expected to increase from 0.2% in 2020 to 6% in 2030 [10]. However, the high cost of ESS acts as a barrier to its usage, although the cost is reducing today due to technological developments [11].

Recently, virtual ESSs (VESSs) have been introduced, and their concept is to allow logical sharing of a physical ESS by multiple participants [12]. A VESS is an energy sharing method that is being considered in energy systems. Another representative energy sharing method is the peer-to-peer (P2P) energy transaction [13], which involves trading excess energy produced between peers to improve benefits. However, similar to the cloud data storage services [14], a VESS is a shared pool of energy storage resources that provides storage services to small participants [15]. Installation of a VESS, which offers more capacity than individual ESS installations, achieves economies of scale. It allows participants to use the ESS service at a lower price compared with that of installing and using an individual ESS.

In a study, a business model was presented based on the shared ESS considering the business cases in 2016 and 2025 [16]. The results indicate that ESS sharing leads to additional profits. VESS structures have been proposed considering different scenarios, such as heat storage capability of a building [17], flexible demand and flywheel ESS [18], residential demand with air conditioners [19], and electric vehicles combined with air conditioning load [20].

In particular, the main topic in the area of VESS research is the energy management of the VESS by applying methodologies such as optimization [21,22] and game theory [23–25]. Zhao et al. [21] proposed a pricing-based virtual storage sharing scheme formulating a two-stage optimization problem for the interaction between the aggregator and participants. They highlighted total cost reduction for the participants by using VESS. Zhong et al. [22] developed a real-time energy management system for an energy storage sharing system to minimize the time average system cost. Their method was based on the current system states, without having to predict the future uncertain system states. Zaidi et al. [23] proposed a combinatorial auction mechanism to obtain the desired ESS capacity using a VESS. To determine the solution of the auction, an algorithm that combines a genetic algorithm with particle swarm optimization was used. Tushar et al. [24] designed a modified auction-based mechanism to determine the cost of usage and allocation of VESS capacity, and they applied a non-cooperative Stackelberg game between the participants and auctioneer to determine the solution. Chakraborty et al. [25] formulated an ESS sharing problem as a cooperative game having two cases, (a) cost minimization with already procured storage elements and (b) expected cost minimization for joint storage investment. They showed that ESS sharing in a cooperative manner is an effective way to amortize storage costs and increase the system's utilization. All these studies show that VESS is an effective way to lower the cost barrier of ESS usage, and participants can achieve profits by way of savings on electricity bills. Research on VESS is summarized in Table 1.

**Table 1.** Summary of virtual energy storage system (VESS) research.

| Reference | Methodology | Objective | Main Contribution |
|---|---|---|---|
| [16] | Case study | Net profit value | Energy storage system (ESS) sharing as business cases |
| [17] | Linear program | Operation cost minimization | Building-based VESS model |
| [18] | Droop control | Frequency response | VESS model consisting of flexible demand and conventional flywheel ESS |
| [19] | Consensus-driven distributed control | Voltage regulation | Residential demand with air conditioners as the VESS |
| [20] | Linear program | Operation cost minimization | VESS based on electric vehicles combined with air conditioning load |
| [21] | Two-stage optimization | Profit maximization of aggregator and users | Price-based virtual capacity allocation |
| [22] | Lyapunov optimization | Time average system cost minimization | Online algorithm without having to predict future uncertain system states |
| [23] | Combinatorial auction | Social welfare maximization | Combinatorial auction framework for capacity allocation |
| [24] | Modified auction | Cost saving maximization | Application of a non-cooperative Stackelberg game for payment rules |
| [25] | Coalitional game | Energy cost minimization | Benefit enhancement by cooperation between players |

Most contemporary studies have only focused on profits by the economies of scale using a VESS. However, the usage of a VESS does not always generate benefits for community participants [26]. Therefore, it is necessary to increase the additional gain when using VESSs. In addition to the economics of scale, another benefit of the VESS is that it allows energy sharing based on logical operation. The logical operation means that the logical charging and discharging operations of the participants cancel each other. Using logical-operation-based energy sharing, ESS with a larger capacity can be serviced [21,27]. From the participants' point of view, energy sharing according to logical operation can increase the degrees of freedom of operation, as they can achieve additional benefits by dynamic VESS operation.

This study proposes a dynamic VESS operation strategy for smart energy communities (SECs). SECs are local energy communities [28,29] which have their own energy service providers (SPs) or energy management systems (EMSs) and can operate the VESS based on SPs or EMSs. To utilize the VESS, the proposed strategy considers the benefit of increasing the number of participants and operation capacity compared with an individual ESS operation to achieve economic benefit.

The main contributions of this study are summarized as follows:

- *Dynamic VESS operation strategy*: In this study, a dynamic VESS operation strategy is proposed considering the usage-limited constraint. The existing VESS allocates the VESS capacity to each participant and operates as an individual ESS [21,27]. When the logical charging and discharging operations of the participants occur simultaneously, the operations of VESS cancel each other. However, at the existing capacity-constraint-based VESS operation, the state of allocated VESS for each participant is logically recorded as used, as in the individual ESS operation. In this case, participants receive cost benefit only without the operation benefit by the multi-participant diversity. To achieve the operational benefit, the proposed strategy considers the usage-limited constraint instead of the allocated capacity constraint of the existing VESS allocations. The usage-limited constraint satisfies the requirement of guaranteeing the usage of the VESS resource of each participant during an operation period. Therefore, the proposed strategy can improve the degrees of freedom of the operation at each decision time.
- *Experimental result and discussion using real data set:* The performance of the proposed strategy is verified using the real data set measured in Korea. The experimental results show that when applying the proposed dynamic VESS operation strategy, participants can achieve greater benefit than the existing VESS operation strategy and have a cost benefit of more than double when compared with that of using the existing VESS operation. Using the results, we carefully discuss how the proposed VESS operation strategy achieves these additional benefits with varying the VESS service price and electricity tariff. Moreover, the future research directions of the VESS for SECs are also suggested.

The rest of this paper is organized as follows: In Section 2, the VESS for the SEC model is described, and in Section 3, the design method of the proposed VESS operation strategy is discussed. In Section 4, measurement studies applied to the proposed strategy are presented. In Section 5, lessons and future research directions are discussed. Finally, the conclusions of the study are presented in Section 6.

## 2. Virtual Energy Storage Systems for Smart Energy Communities

Three prime components of the VESS for SECs are depicted in Figure 1. A VESS can be configured by either a smart energy service provider (SESP) or a third-party VESS service provider. In this study, it is considered that the VESS is configured by the SESP and thus it is operated in a non-profit manner, where the implementation cost is recovered through the service cost. The SEC consists of community members who are both residential or commercial units, and the SESP, which is the demand aggregator for the community members. The SESP manages the energy transactions between the members and energy producers, such as between the VESS and utility grid. Considering the service price of the VESS, the community members participate in the VESS service. The SESP logically decides individual ESS operation actions for each participant according to the objective and constraints of the VESS operation. The determined actions are combined into one action at each operation time and are used to operate the VESS. From the viewpoint of the SESP, a VESS is a physical ESS. However, it is logically shared among multiple participants according to the management of the SESP. For energy balance, the SEC is also connected to the utility grid.

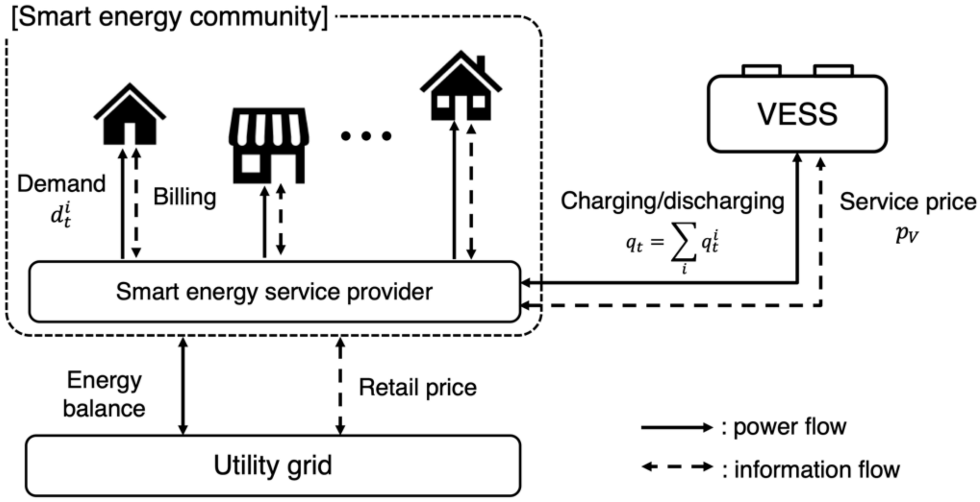



**Figure 1.** Constitution of a virtual energy storage system (VESS) for smart energy community (SEC).

Effectively serving the demand of the SEC using the resources in the VESS is the main challenge of this system. The VESS serves according to the capacity limit of the resources, which is determined by the size of the resource that the VESS has implemented and how the resource of the VESS is allocated. If the capacity is insufficient, it will not be able to provide the adequate service, and if there is too much capacity, the burden of the operating cost will increase.

The VESS cost is also related to the cost of the physical ESS capacity. By increasing the capacity, the unit cost of the VESS is reduced by the economics of scale. If $c_0$ is the VESS capacity for charging and discharging operations, the unit cost of the VESS related to the ESS is modeled as [27]

$$p_C(c_0) = \alpha_1 \exp(-\alpha_2 c_0) + \alpha_3 \text{ [USD/kWh]}, \tag{1}$$

where $\alpha_1$, $\alpha_2$, and $\alpha_3$ are the ESS cost parameters based on the ESS characteristics. $\alpha_1$ and $\alpha_2$ represent the variable costs according to the capacity, and $\alpha_3$ is the fixed cost, such as the operation and maintenance costs. $c_0$ (kWh) is the energy capacity of the VESS. Assuming a service time of 2 h, the power capacity of the VESS is determined as $c_0/2$ h (kWh) [27]. One characteristic parameter of the ESS is service time. To simplify the problem, in this study, the service time is set to 2 h. This is the value used in other studies such as [27] and in actual products such as Tesla's powerpack [30].

As mentioned above, in this study, the SESP installs and operates the VESS in a non-profit manner, and so, the VESS cost is recovered through the service price. Therefore, the service cost of the VESS is equal to its unit cost, and it is given by:

$$p_V = p_C(c_0). \tag{2}$$

A unit, which is a community member, decides to participate in the VESS service by considering its service cost. When the demand of unit $i$ at time $t$ is $d_t^i$, the electricity bill of unit $i$ is measured as:

$$B_i(\cdot) = p_0 \max_{t\in\mathcal{T}}\left(d_t^i\right) + \sum_{t\in\mathcal{T}} p_t d_t^i, \tag{3}$$

where $p_0$ is the demand price for the billing period, $p_t$ is the energy price at time $t$, and $\mathcal{T}$ is the billing period, for example, one month.

If unit $i$ participates in the VESS service with the capacity $c_i$, the electricity bill is modified as:

$$B_i(c_i) = p_0 \max_{t\in\mathcal{T}}\left(d_t^i + q_t^i\right) + \sum_{t\in\mathcal{T}} p_t\left(d_t^i + q_t^i\right), \tag{4}$$

where $q_t^i$ is the charging and discharging quantity of the unit $i$. The quantity from or to the VESS is determined by the VESS operation action $a_t^i$ and VESS round-trip efficiency $\eta$ and is given by:

$$q_t^i = \begin{cases} a_t^i \times \sqrt{\eta}, & \text{when } a_t^i \geq 0, \\ a_t^i / \sqrt{\eta}, & \text{when } a_t^i < 0. \end{cases} \tag{5}$$

where the positive value, i.e., $a_t^i \geq 0$, expresses the discharging to the utility grid, and vice versa. The operation quantity is limited by the capacity $c_i$ of the unit $i$ and it is discussed in the next section.

Considering the service cost, the net benefit of the unit $i$ is calculated as:

$$N_i(c_i) = B_i(\cdot) - B_i(c_i) - p_V c_i. \tag{6}$$

## 3. Dynamic VESS Operation Strategy

The main objective of the VESS operation for SECs is to maximize social welfare, which is the total net benefit. The objective function is expressed as follows:

$$O_B(\mathbf{c}) = \sum_{i\in\mathcal{I}} N_i(c_i), \tag{7}$$

where $\mathcal{I}$ is the participant set and $\mathbf{c}$ is the allocated capacity set for the participants.

The conventional VESS only considers cost reduction according to the economics of scale, and the VESS operation is performed in a same manner as that of the individual ESS [27]. Therefore, the VESS operation in the existing study is formulated as:

$$\begin{aligned} \text{P0}: \quad & \max_{\mathbf{c},\mathbf{a}} && O_B(\mathbf{c}) \\ & \text{subject to} && \sum_{i\in\mathcal{I}} c_i \leq c_0, \\ &&& -c_i/2 \leq a_t^i \leq c_i/2, \ \ \forall i \in \mathcal{I}, t \in \mathcal{T}, \\ &&& 0 \leq a_0^i + \sum_{j=1}^{t} a_j^i \leq c_i, \ \ \forall i \in \mathcal{I}, t \in \mathcal{T}, \end{aligned} \tag{8}$$

where $\mathbf{a}$ is the VESS operation set of the participants and $a_0^i$ is the initial state of the VESS for the unit $i$. In the problem **P0**, the first constraint implies that the allocated VESS capacity to the participant is less than the implemented VESS capacity. The second and third constraints are the ESS operation constraints of the power and energy subsystems, respectively, according to the allocated VESS capacity. The second constraint of the power subsystem states that the action at each decision time should be operated within the maximum charging and discharging range. The actual quantity is charged or discharged considering the efficiency in Equation (5). The third constraint of the energy subsystem indicates that the accumulated charge/discharge action that is the state of charge (SoC) is limited by the allocated VESS capacity. In this study, a case of 100% depth of discharge (DoD) is considered. However, additional capacity restrictions could be considered depending on the DoD.

Units participating in the VESS service operated in the form of Equation (8) can benefit from cost reduction only. However, the allocated capacity is fixed during the service period, and thus, it is difficult to obtain operational benefit from the VESS service compared with the individual ESS operation.

To achieve operational benefit, the proposed dynamic VESS operation relaxes the restrictions on the fixed allocation of the VESS capacity and a method of guaranteeing usage is incorporated instead of guaranteeing the allocated capacity method as follows:

$$\frac{24}{2T}\sum_{t\in\mathcal{T}}\left|a_t^i\right| \leq \beta\, c_i, \quad \forall i \in \mathcal{I}, \tag{9}$$

where $\beta$ is the usage factor that ensures the VESS usage of the participant. For example, $\beta = 1$ means that the participant can use one charge and discharge quantity for the allocated capacity for an average of 24 h.

Because there is no limit on the individually allocated capacity, the VESS operates in an aggregated form for all the participants. The VESS operation at time $t$ is expressed as:

$$a_t^{Total} = \sum_{i\in\mathcal{I}} a_t^i. \tag{10}$$

Using Equations (9) and (10), the proposed VESS operation can be expressed as follows:

$$\begin{aligned} \text{P1}: \quad & \max_{\mathbf{c},\mathbf{a}} && O_B(\mathbf{c}) \\ & \text{subject to} && \sum_{i\in\mathcal{I}} c_i \leq c_0, \\ & && -c_0/2 \leq a_t^{Total} \leq c_0/2, \quad \forall t \in \mathcal{T}, \\ & && 0 \leq a_0^{Total} + \sum_{j=1}^{t} a_j^{Total} \leq c_0, \quad \forall t \in \mathcal{T}, \\ & && \tfrac{24}{2T}\sum_{t\in\mathcal{T}}\left|a_t^i\right| \leq \beta\, c_i, \quad \forall i \in \mathcal{I}. \end{aligned} \tag{11}$$

In **P1**, similar to **P0**, the allocated VESS capacity to the participants should be less than the implemented VESS capacity. However, the individual operation in **P0** is reconstructed as an aggregated operation, as shown by the second and third constraints in Equation (11). The fourth constraint is considered to guarantee the VESS usage of each participant. **P1** is a mixed-integer linear programming problem that satisfies convexity [31], and it can be effectively solved by applying gradient methods and dual decomposition [32].

The VESS operations of **P0** and **P1** can be compared schematically, as shown in Figure 2. In the cases of Figure 2a,b, the participants used the same amount of charging and discharging quantities. The VESS for participant 2 performs the same operation. However, the VESS for participant 1 operates differently based on **P0** and **P1** in Section A. In Figure 2a, the VESS operation for participant 1 is limited by the maximum capacity allocated to the participant. However, the VESS for the same participant in Figure 2b operates over the allocated capacity. This is because the VESS by **P1** is operated by the usage limit rather than the capacity limit. Therefore, the VESS by **P1** can operate more dynamically to maximize the net benefit to the participants compared to the VESS operation by **P0**.

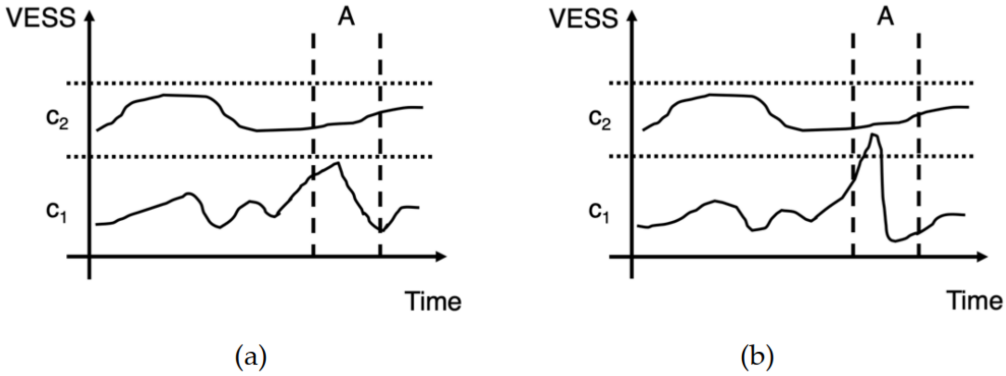



**Figure 2.** Comparison of the virtual energy storage system (VESS) operation according to **P0** and **P1**: (**a**) VESS operation for participants 1 and 2 by **P0**; (**b**) VESS operation for participants 1 and 2 by **P1**.

## 4. Results

### *4.1. Experimental Environment*

To perform the simulations, the ESS cost parameters are set as $\alpha_1 = 0.17$, $\alpha_2 = 0.00040$, and $\alpha_3 = 0.043$ by fitting the value used in Reference [33]. Even after applying the economies of scale, the ESS cost is still higher; therefore, it is discounted by 50% from the value available in [33]. The SEC having 127 units is considered, and its demand data are recorded at one-hour resolution as a part of the Korea Micro Grid Energy Project (K-MEG) [34]. The time-of-use tariff for general customers of the Korea Electric Power Company is used to calculate the electricity bill, as shown in Table 2.

**Table 2.** Time-of-use tariff of Korea electric power company [35].

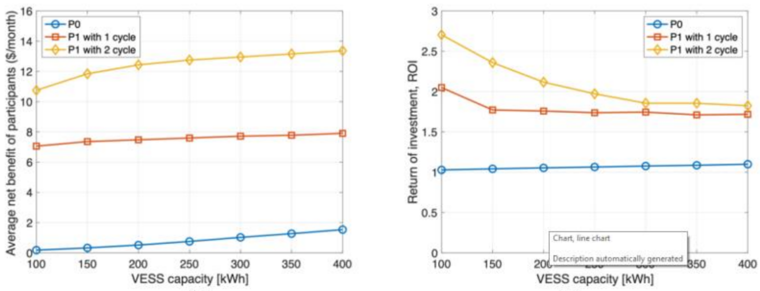
| Demand Price (USD/kW) | Energy Price (USD/kWh) Off-Peak | Mid-Peak | On-Peak |
|---|---|---|---|
| 7.4818 | 0.0476 | 0.0942 | 0.1146 |

To verify the performance of the proposed dynamic VESS operation strategy, the net benefits to the participants in Equation (6) are measured, and the effects of the system parameters are determined. Moreover, to measure financial profitability, the ROI is calculated by dividing the profit earned from an investment by the cost of that investment [36], as follows:

$$ROI = \frac{1}{I} \sum_{i \in \mathcal{I}} \frac{B_i(\cdot) - B_i(c_i)}{p_V c_i}. \quad (12)$$

### *4.2. Performance Analysis*

Figure 3 shows the average net benefit and return of investment (ROI) of the participants by the VESS operation with varying VESS capacity. The average net benefit is measured as the average value of the net benefit of the participants in Equation (6) with the billing period of 1 month. The ROI shows that the economic efficiency of service participation is calculated using Equation (12). Moreover, changes in VESS capacity show the effect of changes in service cost of the VESS. In Figure 3a,b the line with circles represents the results of the VESS operation using **P0**, and the lines with squares and diamonds present the results of applying the VESS operation of **P1** considering the usage factors as $\beta = 1$ and $\beta = 2$, respectively. As shown in Figure 3a, the net benefit of the participants increases as the VESS capacity increases. This is because the unit cost of the VESS reduces with the increment in the VESS capacity using Equation (1). Therefore, the capacity of the VESS allocated to the participants increases. In the case of the VESS operation by **P0**, in which the operation is limited according to the allocated capacity, the net benefit increases significantly as the VESS capacity increases. The results of the VESS operations by **P1** with one cycle and two cycles achieve much higher net benefit than by **P0**. This verifies that the proposed VESS operation of managing the usage is more effective than the VESS operation, which limits the allocated capacity. In the case of the VESS operation by **P1** with one cycle, the increment of the net benefit exhibits marginal change when the implemented VESS capacity is varied. In this case, the usage factor restricts the VESS operation, and the participants achieve the benefit by reducing the unit VESS only.




(a) (b)

**Figure 3.** Performance comparison of the VESS operation according to **P0** and **P1** with varying VESS capacity: (**a**) average net benefit of participants; (**b**) return of investment of participants.

The result obtained by **P0** has the ROI of slightly greater than 1. However, when the VESS capacity is 100 kWh, the ROIs of 2.0 and 2.7 are achieved according to the results of the proposed VESS operations with one and two cycles, respectively. This means that the proposed VESS operations using **P1** are more than twice as cost-effective as the existing operation using **P0**. Increasing the implemented VESS capacity reduces the ROIs of the proposed VESS operations. This is because the participants use more VESS capacity to achieve benefits by increasing the implemented VESS capacity as depicted in Figure 3a, but the increase in benefit is less than the increase in cost.

Figure 4 shows how savings on the electricity bill are achieved by applying the VESS operation. The electricity bill consists of a demand bill and energy bill as shown in Equation (3). In Figure 4, the blue bar, red bar, and yellow bar represent savings on the demand bill, energy bill, and total electricity bill, respectively, compared with the electricity bill without the VESS operation in Equation (3). The proposed VESS operation achieves more total savings on the electricity bill compared with that of the VESS operation by **P0**. Particularly, the VESS operation for reducing the demand bill is to lower the peak demand by charging operation. The savings on the demand bill are highly related to the maximum allocated VESS capacity. Therefore, the proposed VESS operation provides more savings on the demand bill in comparison to VESS operation by **P0**. The VESS is charged and discharged to shift the demand from high price times to other times for reducing the energy bill. In the case of the energy bill, the VESS operation by **P0** saves more in comparison to the proposed VESS operation. This means that the proposed VESS operation uses more resources to achieve savings on the demand bill, so the savings on the energy bill is limited.

Figure 5 shows the peak demand reduction ratio obtained with varying implemented VESS capacity. The peak demand not only relates to the demand bill from the participants' point of view but also to the system operation from the aspect of the utility grid. The peak demand reduction reduces the necessity of the regulation capacity and new power plant construction in the utility grid [37]. The higher peak demand reduction provides the utility grid with more opportunities to reduce the system cost. As shown in Figure 5, the proposed VESS operation can provide more system cost reduction than the VESS operation by **P0**, owing to the reduction in the peak demand. When the usage factor is limited, as shown by the result of **P1** with one cycle, the peak demand reduction converges, even if the implemented VESS capacity increases. However, the peak demand reduction is higher than that of **P0** in all the cases. This result shows that the proposed VESS operation exhibits higher performance than the VESS operation by **P0**, not only from the participants' point of view but also from the utility point of view.

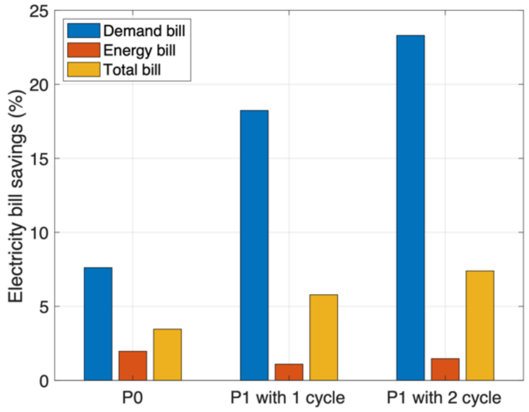



**Figure 4.** Savings on electricity bills of the participants when the implemented VESS capacity is 150 kWh.

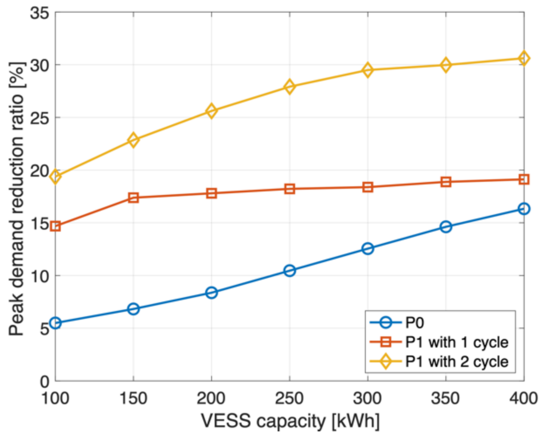



**Figure 5.** Peak demand reduction ratio with varying implemented VESS capacity.

*4.3. Characteristic Analysis*

Figures 6 and 7 showcase the units that have benefitted from the VESS operation. Figure 6 displays the percentage of the participants that are using the VESS service among all SEC units. As the implemented VESS capacity increases, the participation ratio also increases. This is because the VESS service cost is reduced with increase in the implemented VESS capacity due to the economics of scale. In the case of VESS operation by **P0**, where the economics of scale is the main driver of the benefit, this trend appears more clearly. When the proposed VESS operation of **P1** is applied, most units participate in the VESS service because participants achieve higher savings on the demand bill due to the dynamic operation, as shown in Figure 4.

Figure 7 shows the Pearson's linear correlation coefficient (PLCC) between the characteristics of the participants and allocated VESS capacity to the participants [38]. The results indicate that the allocated VESS capacity, which is the usage of VESS, has a higher correlation with the peak demand in Figure 7b than with the electricity bill in Figure 7a. This means that the demand bill according to the peak demand acts as a dominant factor in the decision to use the VESS, as shown in the results in Figure 4, as well. Moreover, as the implemented VESS capacity increases, the PLCC of the results by applying **P0** also increases, but it is lower than that obtained by the proposed VESS operation. This means that the proposed VESS operation using **P1** better reflects the characteristics of the participants than the VESS operation using **P0**.

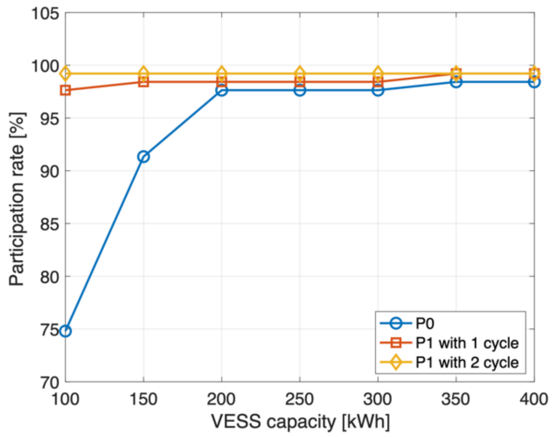



**Figure 6.** Percentage of participants using the VESS service. The participant rate is measured as the number of units who participant the VESS service among all SEC units, i.e., 127 units.

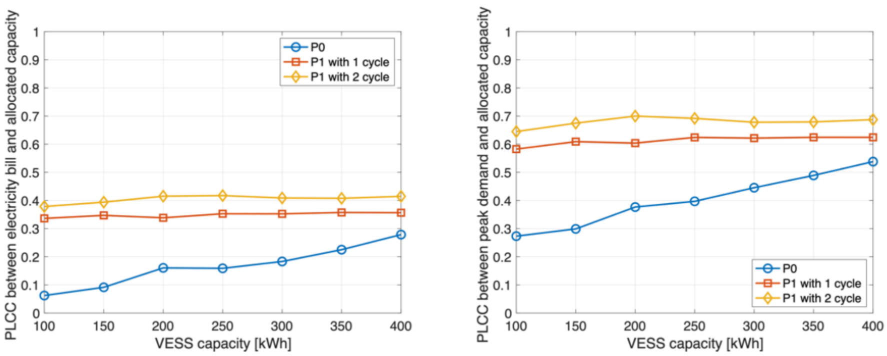



**Figure 7.** Pearson's linear correlation coefficient (PLCC) between the characteristics of the participants and the allocated VESS capacity with varying implemented VESS capacity: (**a**) PLCC between the original electricity bill and the allocated VESS capacity; (**b**) PLCC between the peak demand and the allocated VESS capacity.

### *4.4. Sensitivity Analysis*

As shown in Equation (6), the net benefit of participants is determined by the service price and electricity tariff. The service price is decided by the implemented VESS capacity. The results according to the VESS capacity change show the effect of the service price.

To show the effect of the electricity tariff, the ROI is measured while varying the energy price. Using the energy price in Table 2 as the baseline, the variance of the energy price is changed, as shown in Table 3. The price factor is defined as the ratio of the standard deviation of the baseline to the changed energy price during the billing period.

As shown in Figure 8, when the price factor increases, i.e., the variance of the energy price increases, the ROI improves. This is because the VESS operational availability is enhanced by increasing the variance of the electricity tariff. This shows that VESS is a more economically efficient method when the electricity tariff volatility is large. Moreover, in all cases of price factor, the proposed VESS operation method using **P1** outperforms the VESS operation using **P0**. When the price factor is less than 1, the ROI by applying the VESS operation using **P0** is 1. This means that the participants cannot achieve additional benefits using the VESS by **P0** in this range.

**Table 3.** Energy price with varying price factor.

| Price Factor | Energy Price (USD/kWh) Off-Peak | Mid-Peak | On-Peak |
|---|---|---|---|
| $0.0 = \left(\frac{0}{0.0290}\right)$ | 0.0799 | 0.0799 | 0.0799 |
| $0.5 = \left(\frac{0.0145}{0.0290}\right)$ | 0.0638 | 0.0870 | 0.0973 |
| $1.0 = \left(\frac{0.0290}{0.0290}\right)$ | 0.0476 | 0.0942 | 0.1146 |
| $1.5 = \left(\frac{0.0434}{0.0290}\right)$ | 0.0315 | 0.1013 | 0.1320 |
| $2.0 = \left(\frac{0.0579}{0.0290}\right)$ | 0.0154 | 0.1085 | 0.1494 |
| $2.5 = \left(\frac{0.0724}{0.0290}\right)$ | 0.0000 | 0.1156 | 0.1667 |

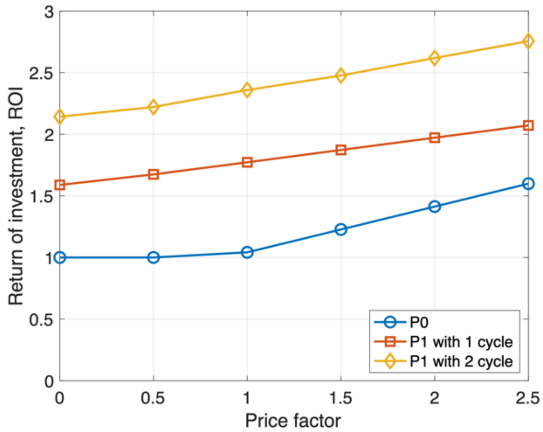



**Figure 8.** Return of investment of participants with varying the price factor.

## 5. Discussion

From the results in Section 4, it is clear that the proposed dynamic VESS operation by **P1** provides more benefits to the VESS service participants and utility grid than the existing VESS operation using **P0**. Based on the results, the following recommendations can be made for VESS operation in SECs:

- The proposed dynamic VESS operation considering the usage-limited constraint is more cost-effective than the existing VESS operation with a capacity constraint, as shown in Figure 3. The effective peak demand reduction in the proposed VESS operation represents significant savings on the demand bill, as shown in Figure 4. This shows that the peak demand dominates the VESS operation and the proposed VESS operation more adaptively operates the VESS to maximize social welfare compared to the existing VESS operation.
- When the proposed VESS operation is applied, more units can participate in the VESS service, as shown in Figure 6. The reason is that it is possible to obtain not only the benefit from the reduction in the service cost according to the existing economics of scale but also the benefit of savings on the demand bill according to the additional decrease in the peak demand.
- The PLCC results of the proposed VESS operation have a higher correlation with the characteristics of the participants, as shown in Figure 7. This means that the proposed VESS operation accurately reflects the characteristics of the participants compared with the existing VESS operation.
- In all the cases where the implemented VESS capacity is changed, the peak demand is considerably reduced by the proposed VESS operation compared with the existing VESS operation, as shown in Figure 5. Peak demand affects the system operation

performance of the utility grid as well as the electricity bill of the units. The peak demand reduction increases the benefits for both the units and utility grid.
- With increasing the variance of the electricity tariff, the economic benefit, i.e., ROI, is improved, as shown in Figure 8. This means that the VESS is dynamically operated according to the electricity tariff.

This study presents a dynamic VESS operation strategy for SECs, and the following future research directions can be suggested:

- This study has considered passive units to be the energy consumers. However, with demand-side management programs such as the demand response and peer-to-peer energy transactions, a unit can be operated as an energy prosumer that acts as both the consumer and producer. A VESS operation problem can be formulated by considering an active unit with demand-side management programs.
- By using the proposed VESS operation, more units can participate in the VESS service. However, the benefits of the VESS service vary from participant to participant. The fairness problem can be considered to ensure fairness in the VESS operation.
- Flexible resources, such as electric vehicles, can be considered as resources. An increase in the implemented VESS capacity increases the benefits of the VESS operation. However, increasing the fixed VESS capacity reduces the ROI. Therefore, a problem considering fixed and flexible ESS resources can be formulated for dynamic VESS operation.
- This study has not included the costs of energy distribution and transmission to the ESS. This is because the energy community exists within close distance, usually at the same distribution line. The system can be extended to large-scale grid connection cases with the cost.

## 6. Conclusions

This study proposed a dynamic VESS operation strategy for the SEC to maximize the social welfare of the participants. The VESS for the SEC model, including the VESS, SEC, and utility grid as the main components, was described. The dynamic VESS operation problem considering the usage-limited constraint for each participant was formulated as a mixed-integer linear problem that can be solved optimally by applying gradient methods and dual decomposition. The proposed operation used the VESS resource more dynamically than the fixed VESS capacity-allocation-based operation. The simulation results using the real dataset in Korea demonstrated that the participants serving by the proposed VESS operation achieved greater net benefit with a maximum cost efficiency of 2.7 times greater than that of the existing VESS operation. The simulation also showed that the proposed VESS operation accurately reflects the characteristics of the participants, and thus, more units can participate in the VESS operation service. In addition, the peak demand reduction provides the possibility of improving the system performance of the utility grid and increasing the net benefit to the participants.

In this study, the basic environments for the VESS, SEC, and utility grid were considered. This study can be extended to more complex environments. For the SEC model, this study considered only passive units as energy consumers. This can be extended to the environment of active units, such as prosumers who participate in demand-side management programs. For the VESS model, it can be considered that the VESS capacity is installed in a flexible size, such as an electric vehicle, in addition to the fixed size. Finally, by including the power system requirements, the utility grid model can be extended to a more realistic environment.

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## References


1. Steele, A.J.H.; Burnett, J.W.; Bergstrom, J.C. The impact of variable renewable energy resources on power system reliability. *Energy Policy* **2021**, *151*, 111947. [CrossRef]
2. Khan, N.; Dilshad, S.; Khalid, R.; Kalair, A.R.; Abas, N. Review of energy storage and transportation of energy. *Energy Storage* **2019**, *1*, e49. [CrossRef]
3. Li, C.; Zhang, S.; Li, J.; Zhang, H.; You, H.; Qi, J.; Li, J. Coordinated control strategy of multiple energy storage power stations supporting black-start based on dynamic allocation. *J. Energy Storage* **2020**, *31*, 101683. [CrossRef]
4. Wang, S.; Du, L.; Fan, X.; Huang, Q. Deep reinforcement scheduling of energy storage systems for real-time voltage regulation in unbalanced LV networks with high PV penetration. *IEEE Trans. Sustain. Energy* **2021**, *12*, 2342–2352. [CrossRef]
5. Zhao, T.; Parisio, A.; Milanović, J.V. Distributed control of battery energy storage systems for improved frequency regulation. *IEEE Trans. Power Syst.* **2020**, *35*, 3729–3738. [CrossRef]
6. Oh, E.; Son, S.Y. Theoretical energy storage system sizing method and performance analysis for wind power forecast uncertainty management. *Renew. Energy* **2020**, *155*, 1060–1069. [CrossRef]
7. Kim, W.J.; Lee, Y.S.; Chun, Y.H. Assessment of primary control reserve requirement from generator considering a battery energy storage system. *J. Electr. Eng. Technol.* **2020**, *15*, 315–324. [CrossRef]
8. Groppi, D.; Pfeifer, A.; Garcia, D.A.; Krajačić, G.; Duić, N. A review on energy storage and demand side management solutions in smart energy islands. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110183. [CrossRef]
9. Zakeri, B.; Gissey, G.C.; Dodds, P.E.; Subkhankulova, D. Centralized vs. distributed energy storage–Benefits for residential users. *Energy* **2021**, *236*, 121443. [CrossRef]
10. Kamiya, G.; Hassid, S.; Gonzalez, P. *Energy Storage*; International Energy Agency (IEA): Paris, France, 2021.
11. Gissey, G.C.; Dodds, P.E.; Radcliffe, J. Market and regulatory barriers to electrical energy storage innovation. *Renew. Sustain. Energy Rev.* **2018**, *82*, 781–790. [CrossRef]
12. Kalathil, D.; Wu, C.; Poolla, K.; Varaiya, P. The sharing economy for the electricity storage. *IEEE Trans. Smart Grid* **2019**, *10*, 556–567. [CrossRef]
13. Soto, E.A.; Bosman, L.B.; Wollega, E.; Leon-Salas, W.D. Peer-to-peer energy trading: A review of the literature. *Appl. Energy* **2021**, *283*, 116268. [CrossRef]
14. Wang, C.; Ren, K.; Lou, W.; Li, J. Toward publicly auditable secure cloud data storage services. *IEEE Netw.* **2010**, *24*, 19–24. [CrossRef]
15. Liu, J.; Zhang, N.; Kang, C.; Kirschen, D.S.; Xia, Q. Decision-making models for the participants in cloud energy storage. *IEEE Trans. Smart Grid* **2018**, *9*, 5512–5521. [CrossRef]
16. Lombardi, P.; Schwabe, F. Sharing economy as a new business model for energy storage systems. *Appl. Energy* **2017**, *188*, 485–496. [CrossRef]
17. Jin, X.; Mu, Y.; Jia, H.; Wu, J.; Jiang, T.; Yu, X. Dynamic economic dispatch of a hybrid energy microgrid considering building based virtual energy storage system. *Appl. Energy* **2017**, *194*, 386–398. [CrossRef]
18. Cheng, M.; Sami, S.S.; Wu, J. Benefits of using virtual energy storage system for power system frequency response. *Appl. Energy* **2017**, *194*, 376–385. [CrossRef]
19. Wang, D.; Meng, K.; Gao, X.; Qiu, J.; Lai, L.L.; Dong, Z.Y. Coordinated dispatch of virtual energy storage systems in LV grids for voltage regulation. *IEEE Trans. Ind. Inform.* **2017**, *14*, 2452–2462. [CrossRef]
20. Zhu, X.; Yang, J.; Liu, Y.; Liu, C.; Miao, B.; Chen, L. Optimal scheduling method for a regional integrated energy system considering joint virtual energy storage. *IEEE Access* **2019**, *7*, 138260–138272. [CrossRef]
21. Zhao, D.; Wang, H.; Huang, J.; Lin, X. Virtual energy storage sharing and capacity allocation. *IEEE Trans. Smart Grid* **2020**, *11*, 1112–1123. [CrossRef]
22. Zhong, W.; Xie, K.; Liu, Y.; Yang, C.; Xie, S.; Zhang, Y. Online control and near-optimal algorithm for distributed energy storage sharing in smart grid. *IEEE Trans. Smart Grid* **2019**, *11*, 2552–2562. [CrossRef]
23. Zaidi, B.H.; Bhatti, D.M.S.; Ullah, I. Combinatorial auctions for energy storage sharing amongst the households. *J. Energy Storage* **2018**, *19*, 291–301. [CrossRef]
24. Tushar, W.; Chai, B.; Yuen, C.; Huang, S.; Smith, D.B.; Poor, H.V.; Yang, Z. Energy storage sharing in smart grid: A modified auction-based approach. *IEEE Trans. Smart Grid* **2016**, *7*, 1462–1475. [CrossRef]
25. Chakraborty, P.; Baeyens, E.; Poolla, K.; Khargonekar, P.P.; Varaiya, P. Sharing storage in a smart grid: A coalitional game approach. *IEEE Trans. Smart Grid* **2019**, *10*, 4379–4390. [CrossRef]

26. Jasinski, J.; Kozakiewicz, M.; Soltysik, M. The effectiveness of energy cooperatives operating on the capacity Market. *Energies* **2021**, *14*, 3226. [CrossRef]
27. Oh, E. Risk-Based Virtual Energy Storage System Service Strategy for Prosumers. *Appl. Sci.* **2021**, *11*, 3020. [CrossRef]
28. Bukovszki, V.; Magyari, Á.; Braun, M.K.; Párdi, K.; Reith, A. Energy modelling as a trigger for energy communities: A joint socio-technical perspective. *Energies* **2020**, *13*, 2274. [CrossRef]
29. Oh, E. Risk-Based Virtual Power Plant Implementation Strategy for Smart Energy Communities. *Appl. Sci.* **2021**, *11*, 8248. [CrossRef]
30. Powerpack—Utility and Business Energy Storage, Tesla. Available online: https://www.tesla.com/powerpack (accessed on 15 February 2022).
31. Boyd, S.; Vandenberghe, L. *Convex Optimization*; Cambridge University Press: Cambridge, UK, 2004.
32. Giselsson, P.; Doan, M.D.; Keviczky, T.; De Schutter, B.; Rantzer, A. Accelerated gradient methods and dual decomposition in distributed model predictive control. *Automatica* **2013**, *49*, 829–833. [CrossRef]
33. Lazard's Levelized Cost of Storage Analysis. Lazard, Oct. 2021. Available online: https://www.lazard.com/media/451882/lazards-levelized-cost-of-storage-version-70-vf.pdf (accessed on 15 February 2022).
34. Yang, W.; Kang, H.; Kwon, Y.; Yoon, Y. *Energy Moving the World: Micro Energy Grid*; K-MEG R&D Center: Seoul, Korea, 2014; ISBN 978-89-94792-95-815320.
35. Electric Rates Table, Korea Electric Power Corporation. January 2021. Available online: https://home.kepco.co.kr/kepco/EN/F/htmlView/ENFBHP00102.do?menuCd=EN060201 (accessed on 15 February 2022).
36. Friedlob, G.T.; Plewa, F.J., Jr. *Understanding Return on Investment*; John Wiley & Sons: Hoboken, NJ, USA, 1996.
37. Roberts, B.P.; Sandberg, C. The role of energy storage in development of smart grids. *Proc. IEEE* **2011**, *99*, 1139–1144. [CrossRef]
38. Lee Rodgers, J.; Nicewander, W.A. Thirteen ways to look at the correlation coefficient. *Am. Stat.* **1988**, *42*, 59–66. [CrossRef]