IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received May 30, 2021, accepted June 3, 2021, date of publication June 7, 2021, date of current version June 16, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3087134

Business Feasibility Study for Storage-Based Customer Flexibility Platform of Load-Serving Entity

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This work was supported by the Chungnam National University.

ABSTRACT A storage-based customer flexibility (SCF) platform enables on-demand remote access to a shared pool of utility-scale energy storage resources at substantially low costs. It can provide users the ability to charge and discharge electrical energy to and from remote batteries. This study demonstrates the economic feasibility of an SCF platform business under realistic conditions. Accordingly, the load-serving entity is set as the SCF operator, and the subscriptions from various types of customers and multi-use battery energy storage systems are considered to increase profitability. An economic feasibility verification is provided based on the generating pattern of individual customers, and a robust optimization is performed for the SCF platform operations considering the market price uncertainty, aggregated requests, and customers' willingness to pay for the SCF service. The proposed study is simulated in a California environment.

INDEX TERMS Customer aggregation, multi-use energy storage, profit maximization, storage-based customer flexibility platform.

I. INTRODUCTION

The platform has been defined in different contexts by several studies, while Parker *et al.* defined it as the set of components used in common across a product family, and suggested interactions between various parties as a key concept of the platform [1]. Recently, a sharing platform, which is the combination of the sharing economy and the platform, is being spotlighted as a business model that has many advantages for both users and investors. In particular, users of a sharing platform are not required to own the product or technology to access it temporarily, as shown in representative examples such as Airbnb and Uber [2].

End users in a power grid can achieve benefits, such as saving of electricity bills, by implementing battery energy storage systems (BESSs), as revealed in several studies [3]–[8]. However, these studies have all reached a common conclusion: BESSs are beneficial to end users but are currently not viable because of the relatively high investment cost. Thus, the introduction of a sharing platform of BESSs is a possible solution to the viability problem. Hence, the storage-based customer flexibility (SCF) platform has emerged to provide virtual BESS services, allowing end users to pay a service fee and remotely access energy storage resources. Several studies have examined the feasibility of this business model. To the best of our knowledge, the same concept has been proposed with basic economic feasibility study in different papers at about the same time [9], [10]. Subsequently, studies on the economic feasibility of the business model have been conducted with different target customers and their behaviors [11]–[13] while two case studies have been conducted, each applying models with different decision-making methods on the customer side depending on the level of information usage by the target audience [13].

To verify the economic feasibility of the SCF platform business, the factors affecting profits should be considered precisely and realistically. The request pattern is different for each customer type because of the different decision-making methods. Residential end users require relatively lesser amounts of energy consumption, and the absolute amount of benefit according to the optimal operation of a BESS is small. Because it is difficult to deal with real-time information, BESS scheduling decisions would be made according to

The associate editor coordinating the review of this manuscript and approving it for publication was Hui Liu.

simple rules. On the other hand, end users at a large scale will set up BESS scheduling decisions that are close to optimal because larger benefits are gained by optimizing operations using maximum real-time information.

Combining the varying customer characteristics and the features of the platform can increase the profitability of the business. If end users having various charging and discharging needs subscribe, the capacity of the SCF platform operator's BESS equipment would be required to be less than the sum of the capacity when each individual customer owns and operates their own BESSs, owing to offsets between requests. This reduces investment costs and customer fees. This is therefore a network effect in which the benefit of one participant increases as the number of participants increase [14], which is a factor that was not addressed in relevant earlier studies [9]–[13]. Furthermore, in terms of unit price, when the SCF platform operator introduces a large-scale BESS to accommodate customer requests, the effect of reduction by the utility scale occurs.

An added option for increasing the profitability of the SCF platform business is by considering the multiple uses of BESSs. SCF platform operators can generate profits by taking part in arbitrage trading with ancillary services by using the owned real BESSs. Studies have shown that energy storage can maximize profit when supplying a set of stacked services [15]–[18]. On the other hand, the source of revenue in the business model is limited to customer service fees in the previous relevant studies. Energy-market transactions have been considered only as a limited means of maintaining supply and demand as a part of the cost function with a minimization objective, and participation in the ancillary service market has been completely neglected [9]–[13].

Uncertainty also affects the profitability of the business, and it has not been addressed in previous studies [9]–[13]. If the market price uncertainty is not considered in the feasibility study of a business model, simulation results can be overly optimistic. Robust optimization has been adopted as an approach to address various data uncertainties. Bertsimas and Sim [19] presented a robust mixed-integer linear programming (MILP) formulation methodology to address data uncertainties, and it is generally applicable to solving a planning optimization problem, including the scheduling of BESSs considering uncertainty.

In this paper, we propose a methodological framework that maximizes the profit of the SCF platform operator to verify the feasibility of the SCF platform business more precisely. Using a methodological framework, we first determine the best plan for individual customers to determine their willingness to pay for using SCF services and the operation pattern of BESSs. An individual-customer BESS operation pattern is obtained according to the basic decision-making model for residential customers, and the smart decision-making model is applied for industrial and photovoltaic (PV)-generating facility customers [13]. Based on the information obtained from the first step, we solve the problem of determining the optimal equipment capacity for maximizing the profit of an SCF platform operator. Robust optimization methodology is applied in this step to consider the uncertainty of the energy market price. The effectiveness of the proposed method is verified using simulations in California. The major contributions of this paper are as follows:

1) In the proposed strategy, the multiple use of BESSs, such as participating in arbitrage trading in the energy and ancillary service markets, is considered as a means to increase the business profitability.
2) Aggregated requests from various types of customers are considered to induce an offset between requests, which also contributes to the business profitability.
3) The SCF platform operator is set as a load-serving entity (LSE); the subject of the business has been previously neglected.
4) The proposed methodological framework considers the uncertainty of the energy market price for a conservative approach to the economic feasibility of the business.

The rest of this paper is organized as follows. Section II describes the concept of the business model in comparison to that of previous studies. Section III describes the formulation of the pattern-generation model for individual customers. Section IV describes the formulation of the decision-making model for an SCF platform operator. Section V describes the cases, and Section VI presents the results from the case studies conducted using the proposed methods. Section VII concludes the paper.

II. CONCEPT OF THE BUSINESS MODEL

An SCF platform operator who owns the central energy storage unit and customers who subscribe to the SCF service participate in the SCF platform. The customers transmit charging and discharging requests to the SCF platform operator within the allocated capacity range, and the SCF platform operator schedules the BESS operation and energy market transaction in consideration of such requests, market price, and operation cost.

By subscribing to the SCF service, without actually owning the BESS, general electricity customers can reduce their bill, and PV generating facilities who are under power purchase agreement (PPA) and receive curtailment orders according to the grid situation can prevent profit loss due to solar curtailment. The SCF platform operator generates revenue by receiving service fees from the customers and reduces cost due to offset between customer requests and economy of scale. Figure 1(a) depicts the concept of the business model proposed by relevant previous studies [9]–[13]. Figure 1(b) presents the concept of the business model proposed in this study. In addition to the service fee considered in previous studies, arbitrage trading in the energy market, participation in the ancillary service market as a flexibility resource, and subscription of various types of customers are also considered as sources of revenue. To pursue the effect of the economy of scale, the SCF platform operator recruits a utility-scale number of customers

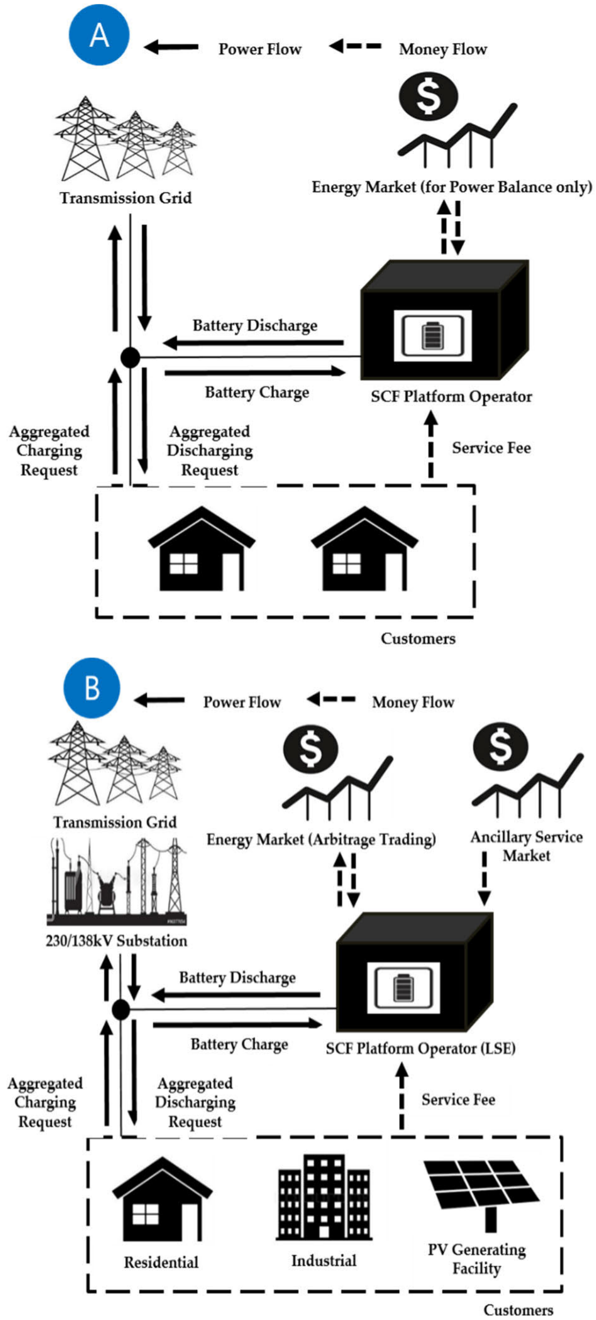

FIGURE 1. **Simplified representation of the business model proposed (a) in previous relevant studies and (b) in this present study.**

and operates a BESS equivalent to this; hence, the BESS is presented as being located at the transmission level.

Previous studies did not specify the business operator as a stakeholder in the electric power industry. Hence, it can be construed that the business operator is a new entity. However, it is reasonable that the operator of the SCF platform is an LSE rather than a new entity for the following reasons. First, the LSE must charge a fee for energy consumption, excluding the request for charging and discharging using the SCF service but not for the metered energy consumption. If the SCF platform operator and the LSE are different entities, they would face conflicts in the contents of the existing contract between the LSE and end users. This may lead to disputes between the SCF platform operator and the LSE. Second, the LSE has a customer pool, and customers will be reluctant to contract with more than one entity related to the use of electricity.

NOMENCLATURE

ACRONYMS

BESS	Battery energy storage system
SCF	Storage-based flexibility
LSE	Load serving entity
PV	Photovoltaic
PCS	Power conversion system
NPV	Net present value
PPA	Power purchase agreement
IRR	Internal rate of return
MILP	Mixed-integer linear programming

INDICES

t	Index of time
h	Index of hour
d	Index of day
y	Index of year
k	Index of iteration for robust-based optimization

PARAMETERS IN PATTERN GENERATION FOR INDIVIDUAL CUSTOMERS

$\mu_{imp}^{h,d,y}$	Unit price of the energy for an individual customer to buy electricity from the LSE at hour h on day d in year y ($/kWh)
$\mu_{ppa}^{h,d,y}$	Unit price of the energy for an individual customer to sell self-generated electricity under the PPA contract at hour h on day d in year y ($/kWh)
$\mu_{avg}^{d,y}$	Average unit price of the energy for an individual customer to buy electricity from the LSE during day d in year y ($/kWh)
$\mu_{pcs,IC}$	Unit price of the PCS for an individual customer ($/kW)
$\mu_{b,IC}$	Unit price of the BESS battery for an individual customer ($/kWh)
$\mu_{bop,IC}$	Unit price for balance of plant for an individual customer ($/kW)
$\mu_{cc,IC}$	Unit price of construction and commissioning for an individual customer ($/kWh)
$\mu_{fom,IC}$	Unit price of the fixed operation cost of BESS for an individual customer ($/kW)
$\mu_{vom,IC}$	Unit price of the variable operation cost of BESS for an individual customer ($/kWh)
u_{pv}	Unit price of the PV system for an individual customer ($/kW)

A_{max} Maximum available area for PV generation system (m^2)
A_{pv} Required area for a 1 kW PV generation system (m^2)
$R_{pvo}^{h,d,y}$ Forecasted PV generation in the ratio of capacity of the PV generation system at hour h on day d in year y (%)
pr_{ctl} Probability of delivery of solar curtailment for PPA subjected customers (%)

VARIABLES IN PATTERN GENERATION FOR INDIVIDUAL CUSTOMERS

NPV_{IC} NPV of an individual customer during the life span of BESS ($)
EX_{IC}^{y} Operating expenditure of an individual customer in year y ($)
EX_{DC}^{y} Demand charge expenditure of an individual customer in year y ($)
$EX_{0,IC}$ Initial capital expenditure of an individual customer ($)
REV_{IC}^{y} Revenue of an individual customer in year y ($)
REV_{sub} Revenue from subsidy of an individual customer ($)
$P_{imp}^{h,d,y}$ Electrical power imported to an individual customer by the LSE at hour h on day d in year y (kW)
$P_{ch,IC}^{h,d,y}$ Charging power of the PCS of an individual customer at hour h on day d in year y (kW)
$P_{dch,IC}^{h,d,y}$ Discharging power of the PCS of an individual customer at hour h on day d in year y (kW)
$P_{load}^{h,d,y}$ Load of an individual customer at hour h on day d in year y (kW)
$P_{exp}^{h,d,y}$ Exported power to the grid from an individual customer at hour h on day d in year y (kW)
$E_{b,IC}^{h,d,y}$ Remaining energy of the BESS battery of an individual customer at hour h on day d in year y (kWh)
$C_{pcs,IC}$ Capacity of the PCS of an individual customer (kW)
$C_{b,IC}$ Capacity of the BESS of an individual customer (kWh)
C_{pv} Capacity of the PV system of an individual customer (kW)
μ_{wtp} Monthly willingness to pay for SCF service of an individual customer ($)
$a_{IC}^{h,d,y}$ Auxiliary binary variable for charging and discharging status of PCS at hour h on day d in year y
$X_{ctl}^{h,d,y}$ Random binary variable indicating the delivery probability of solar curtailment (%)

PARAMETERS IN OPTIMIZATION FOR SCF PLATFORM OPERATOR

$\mu_{rt}^{h,d,y}$ Unit price of the energy in real time energy market at hour h on day d in year y ($/kWh)
$\mu_{rtmin}^{h,d,y}$ Minimum unit price of the energy in real time energy market considering uncertainty at hour h on day d in year y ($/kWh)
$\mu_{rtmax}^{h,d,y}$ Maximum unit price of the energy in real time energy market considering uncertainty at hour h on day d in year y ($/kWh)
$\mu_{spr}^{h,d,y}$ Unit price of the capacity in spinning reserve market at hour h on day d in year y ($/kW)
R_{tax} Income tax rate for corporations (%)
R_{res}^{y} Residential customer subscription rate in year y (%)
R_{ids}^{y} Industrial customer subscription rate in year y (%)
R_{pvf}^{y} PV generating facility customer subscription rate in year y (%)
N_{res} Target subscription number of residential customers
N_{ids} Target subscription number of industrial customers
N_{pvf} Target subscription number of PV generating facility customers
μ_{res} Monthly customer fee for using SCF service paid by a residential customer ($)
μ_{ids} Monthly customer fee for using SCF service paid by an industrial customer ($)
μ_{pvf} Monthly customer fee for using SCF service paid by a PV generating facility customer ($)
$\mu_{pcs,SCF}$ Unit price of the PCS for a SCF platform operator ($/kW)
$\mu_{b,SCF}$ Unit price of the BESS battery for a SCF platform operator ($/kWh)
$\mu_{bop,SCF}$ Unit price for balance of plant for a SCF platform operator ($/kW)
$\mu_{cc,SCF}$ Unit price of construction and commissioning for a SCF platform operator ($/kWh)
$\mu_{fom,SCF}$ Unit price of the fixed operation cost of BESS for a SCF platform operator ($/kW)
$\mu_{vom,SCF}$ Unit price of the variable operation cost of BESS for a SCF platform operator ($/kWh)
pr_{spr} Probability of execution of spinning reserve (%)
G^{k} Parameter for control of the level of robustness at interval k
Γ_0 Parameter for control of the level of robustness

VARIABLES IN OPTIMIZATION FOR SCF PLATFORM OPERATOR

NPV_{SCF} NPV of a SCF platform operator during the business period ($)

EX^{y}_{SCF}	Operating expenditure of a SCF platform operator in year y (\$)
EX^{y}_{red}	Reduction in energy sales revenue of a SCF platform operator in year y (\$)
$EX_{0,SCF}$	Initial capital expenditure of a SCF platform operator (\$)
REV^{y}_{SCF}	Revenue of a SCF platform operator in year y (\$)
$P^{h,d,y}_{rtp}$	Power purchased by a SCF platform operator from the real time energy market at hour h on day d in year y (kW)
$P^{h,d,y}_{rts}$	Power sold by a SCF platform operator in the real time energy market at hour h on day d in year y (kW)
$P^{h,d,y}_{spr}$	Power participated in the spinning reserve market by a SCF platform operator at hour h on day d in year y (kW)
$P^{h,d,y}_{ch,SCF}$	Charging power of the PCS of a SCF platform operator at hour h on day d in year y (kW)
$P^{h,d,y}_{dch,SCF}$	Discharging power of the PCS of a SCF platform operator at hour h on day d in year y (kW)
$P^{h,d,y}_{aggch}$	Aggregated charging request from the customers at hour h on day d in year y (kW)
$P^{h,d,y}_{aggdch}$	Aggregated discharging request from the customers at hour h on day d in year y (kW)
$E^{h,d,y}_{b,SCF}$	Remaining energy of the BESS battery of a SCF platform operator at hour h on day d in year y (kWh)
$C_{pcs,SCF}$	Capacity of the PCS of a SCF platform operator (kW)
$C_{b,SCF}$	Capacity of the BESS of a SCF platform operator (kWh)
μ_{wtp}	Monthly willingness to pay for SCF service of a SCF platform operator (\$)
$a^{h,d,y}_{SCF}$	Auxiliary binary variable for charging and discharging status of PCS at hour h on day d in year y
$X^{h,d,y}_{spr}$	Random binary variable indicating the execution probability of spinning reserve (%)
z_0	Variable for robust-based optimization
$q^{h,d,y}_{0}$	Variable for robust-based optimization at hour h on day d in year y
$d^{h,d,y}$	Variable for robust-based optimization at hour h on day d in year y
$w^{h,d,y}$	Variable for robust-based optimization at hour h on day d in year y

PARAMETERS IN COMMON

r_{disc}	Annual discount rate (%)
η_{ch}	Charging efficiency of the PCS (%)
η_{dch}	Discharging efficiency of the PCS (%)
E_{init}	Initial state of charge of BESS battery (%)
E_{max}	Maximum state of charge of BESS battery (%)
E_{min}	Minimum state of charge of BESS battery (%)
$bigN$	Auxiliary substantial number

III. PATTERN GENERATION OF INDIVIDUAL CUSTOMERS

The SCF platform is a conceptual business model for which data do not yet exist. Before collecting real customer data from a pilot project, it is necessary to create a reasonable customer pattern for a feasibility study. The two main factors derived through the pattern generation model for individual customers are the BESS operation pattern and BESS-related cost. The sum of the BESS operation patterns by time period is the basis for determining the equipment capacity of the SCF platform operator. Additionally, the BESS-related cost corresponds to the customer's maximum willingness to pay for SCF services and is the basis for determining the SCF service fee. We assume that several types of end users, such as residential, industrial, and PV generating facilities, want to be customers of the SCF service.

A. ECONOMIC ANALYSIS

The purpose of the formulation is to minimize the net present value (NPV) of the cost of an individual customer under economic and physical constraints. The objective function of the optimization problem is formulated as

$$\begin{aligned} &MinimizeNPV_{IC} \\ &= Minimize\left[\sum\nolimits_{y\in Y}\left[\left(EX^{y}_{IC}-REV^{y}_{IC}\right)\left(\frac{1}{1+r_{disc}}\right)^{y}\right]\right. \\ &\quad \left. +EX_{0,IC}-REV_{sub}\right]. \end{aligned} \tag{1}$$

Because the revenue from subsidy and the expenditure by demand charge cannot be expressed as a generalized formula, they are expressed as single variables. However, the actual content is reflected in the simulation. The variable operating cost proportional to the power charging and discharging capacity is considered in place of the nonlinear deterioration model of the battery. The battery deterioration model is not suitable for inclusion in the optimization problem because it uses equipment specifications, such as the capacity of the battery, as an input value, which is determined by the optimization. The operating expenditure and revenue for each year are expressed as

$$\begin{aligned} EX^{y}_{IC} &= \sum\nolimits_{d\in D}\sum\nolimits_{h\in H} P^{h,d,y}_{imp}\mu^{h,d,y}_{imp} + EX^{y}_{DC} \\ &\quad +EX^{y}_{ESS,IC}, \quad \forall h \in H, d \in D, y \in Y, \end{aligned} \tag{2}$$

$$\begin{aligned} EX^{y}_{ESS,IC} &= C_{pcs,IC}\mu_{fom,IC} \\ &\quad +\sum\nolimits_{d\in D}\sum\nolimits_{h\in H}\left(P^{h,d,y}_{ch,IC}+P^{h,d,y}_{dch,IC}\right)\mu_{vom,IC}, \\ &\quad \forall h \in H, d \in D, y \in Y, \end{aligned} \tag{3}$$

$$\begin{aligned} REV^{y}_{IC} &= \sum\nolimits_{d\in D}\sum\nolimits_{h\in H} P^{h,d,y}_{exp}\mu_{ppa}, \\ &\quad \forall h \in H, d \in D, y \in Y. \end{aligned} \tag{4}$$

BESS and PV generation systems can be installed to reduce electricity bills for residential and industrial customers and to increase profitability for PV generating facility customers. The initial capital expenditure is expressed as

$$EX_{0,IC} = EX_{ESS0,IC} + C_{pv}\mu_{pv}, \tag{5}$$

$$EX_{ESS0,IC} = C_{pcs,IC}(\mu_{pcs,IC} + \mu_{bop,IC}) + C_{b,IC}(\mu_{b,IC} + \mu_{cc,IC}). \tag{6}$$

The total battery cost is the same as the maximum willingness to pay for the SCF service during the BESS lifespan, which is expressed as Equation (7). The monthly maximum willingness to pay for the SCF service is expressed as Equation (8).

$$NPV_{ESS,IC} = \sum_{y\in Y}\left[EX^{y}_{ESS,IC}\left(\frac{1}{1+r_{disc}}\right)^{y}\right] + EX_{ESS0,IC}, \tag{7}$$

$$\mu_{wtp} = \frac{NPV_{ESS,IC}}{12N_{yr}}. \tag{8}$$

B. GRID CONSTRAINTS

It is assumed that power always balances supply and demand, and surplus photovoltaic power is exported to the grid, expressed as

$$P^{h,d,y}_{load} = P^{h,d,y}_{imp} - P^{h,d,y}_{exp} + R^{h,d,y}_{pvo}C_{pv} - P^{h,d,y}_{ch,IC} + P^{h,d,y}_{dch,IC}, \quad \forall h \in H, d \in D, y \in Y. \tag{9}$$

C. PV GENERATION SYSTEM CONSTRAINTS

It is assumed that the amount of power back-transferred to the grid is limited to a specific percentage of the rated power of the PV generation system when a curtailment order is delivered. The random variable indicating whether the curtailment order is given follows the Bernoulli distribution with a probability of 1 being the result of the trial, pr_{ctl}, expressed as

$$P\left(X^{h,d,y}_{ctl} = 1\right) = pr_{ctl}, \quad \forall h \in H, d \in D, y \in Y, \tag{10}$$

$$P\left(X^{h,d,y}_{ctl} = 0\right) = 1 - pr_{ctl}, \quad \forall h \in H, d \in D, y \in Y, \tag{11}$$

$$P^{h,d,y}_{exp}X^{h,d,y}_{ctl} \leq (1 - R_{ctl})\, P^{h,d,y}_{pvo}C_{pv}, \quad \forall h \in H, d \in D, y \in Y. \tag{12}$$

According to Equation (13), it is assumed that the PV generation system installation area cannot exceed the usable area.

$$A_{max} \geq A_{pv}C_{pv}. \tag{13}$$

D. BESS CONSTRAINTS

Among BESS-related constraints, equations (14)-(17) are applied in common. However, equations (18)-(25) and equations (26)-(29) are applied respectively depending on the customer type. The hourly remaining energy is calculated by equations (14)-(16) and the upper and lower bounds are constrained by equation (17).

$$E^{h,d,y}_{b,IC} = E_{init}C_{b,IC} + P^{h,d,y}_{ch,IC}\eta_{ch} - \frac{P^{h,d,y}_{dch,IC}}{\eta_{dch}}, h = 1, \quad \forall d \in D, y \in Y, \tag{14}$$

$$E^{h,d,y}_{b,IC} = E^{h-1,d,y}_{b,IC} + P^{h,d,y}_{ch,IC}\eta_{ch} - \frac{P^{h,d,y}_{dch,IC}}{\eta_{dch}}, h > 1, \quad \forall d \in D, y \in Y, \tag{15}$$

$$E^{h,d,y}_{b,IC} = E_{init}C_{b,IC}, h = 24, \quad \forall d \in D, y \in Y, \tag{16}$$

$$E_{min}C_{b,IC} \leq E^{h,d,y}_{b,IC} \leq E_{max}C_{b,IC}, \quad \forall h \in H, d \in D, y \in Y. \tag{17}$$

The equations related to the hourly charging and discharging power of the power conversion system (PCS) described below are applied separately as a basic decision-making model for residential customers and a smart decision-making model for industrial customers or PV generating facilities according to the characteristics of individual customers. Because it is difficult for residential customers to operate BESSs in an optimal manner, it is assumed that the BESS is operated following a simple rule of charging when the rate is lower than the daily average and discharging when the rate is higher than the daily average. Industrial and PV generating facility customers that gain a large benefit from operating BESSs optimally are assumed to operate BESSs in an optimal manner, making most of the information they have.

1) BASIC DECISION-MAKING MODEL

The basic decision-making model simply compares the daily average price of power with the current price to determine whether to charge or discharge. Additionally, the amount is determined according to the simple rule shown in Equations (18)–(25):

$$P^{h,d,y}_{dch,IC} = min\left\{C_{pcs,IC}, P^{h,d,y}_{load}, E_{init}C_{b,IC} - E_{min}C_{b,IC}\right\}, \quad h = 1, d = 1, y \in Y, \tag{18}$$

$$P^{h,d,y}_{dch,IC} = min\left\{C_{pcs,IC}, P^{h,d}_{load}, E^{h+23,d-1,y}_{b,IC} - E_{min}C_{b,IC}\right\}, \quad h = 1, d > 1, y \in Y, \tag{19}$$

$$P^{h,d,y}_{dch,IC} = min\left\{C_{pcs,IC}, P^{h,d}_{load}, E^{h-1,d,y}_{b,IC} - E_{min}C_{b,IC}\right\}, \quad h > 1, \quad \forall d \in D, y \in Y, \tag{20}$$

$$P^{h,d,y}_{dch,IC} = 0, \mu^{h,d,y}_{grid} \leq \mu^{d,y}_{avg} \forall h \in H, d \in D, y \in Y, \tag{21}$$

$$P^{h,d,y}_{ch,IC} = min\left\{C_{pcs,IC}, E_{max}C_{b,IC} - E_{init}C_{b,IC}\right\}, \quad h = 1, d = 1, y \in Y, \tag{22}$$

$$P^{h,d,y}_{ch,IC} = min\left\{C_{pcs,IC}, E_{max}C_{b,IC} - E^{h+23,d-1,y}_{b,IC}\right\}, \quad h = 1, d > 1, y \in Y, \tag{23}$$

$$P^{h,d,y}_{ch,IC} = min\left\{C_{pcs,IC}, E_{max}C_{b,IC} - E^{h-1,d,y}_{b,IC}\right\}, \quad h > 1, \quad \forall d \in D, y \in Y, \tag{24}$$

$$P^{h,d,y}_{ch,IC} = 0, \mu^{h,d,y}_{grid} \geq \mu^{d,y}_{avg} \quad \forall h \in H, d \in D, y \in Y. \tag{25}$$

2) SMART DECISION-MAKING MODEL

In a smart decision-making model, an optimal value is found using all information without applying separate rules other than the physical constraints shown in Equations (26) and (27). Equations (28) and (29) use an auxiliary variable to prevent simultaneous charging and discharging operations [20].

$$P_{ch,IC}^{h,d,y} \le C_{pcs,IC}, \quad (26)$$

$$P_{dch,IC}^{h,d,y} \le C_{pcs,IC}, \quad (27)$$

$$P_{ch,IC}^{h,d,y} \le a_{IC}^{h,d,y} bigN, \quad (28)$$

$$P_{dch,IC}^{h,d,y} \le \left(1 - a_{IC}^{h,d,y}\right) bigN. \quad (29)$$

IV. OPTIMIZATION FORMULATION FOR SCF PLATFORM OPERATOR

A. ECONOMIC ANALYSIS

Optimal planning is established for the SCF platform operator based on the results obtained from individual customer optimization. The purpose of the formulation is to maximize the NPV of the profit of an SCF platform operator under economic and physical constraints. The reduction in energy sales revenue, because LSE provides SCF services to existing customers, is regarded as an expenditure. The objective function of the optimization problem is formulated as

$$\begin{aligned} &MaximizeNPV_{SCF} \\ &= Maximize \left\lfloor \sum\nolimits_{y\in Y} \left[\left(REV_{SCF}^{y} - EX_{SCF}^{y} - EX_{red}^{y}\right) \left(\frac{1}{1+r_{disc}}\right)^{y} \right] - EX_{0,SCF} \right\rfloor. \end{aligned} \quad (30)$$

The SCF platform operator profits from the fee of the SCF service, participation in arbitrage trading, and ancillary service. In this study, it is assumed that the SCF platform operator takes part in the spinning reserve market in ancillary service markets. The revenue and operating expenditures for each year are expressed as

$$\begin{aligned} REV_{SCF}^{y} = &\left(\sum\nolimits_{d\in D} \sum\nolimits_{h\in H} \left[P_{rts}^{h,d,y} \mu_{rt}^{h,d,y} + P_{spr}^{h,d,y} \mu_{spr}^{h,d,y}\right] \right. \\ &+12 \left(R_{res}^{y} N_{res} \mu_{res} + R_{ids}^{y} N_{ids} \mu_{ids} \right. \\ &\left.\left. + R_{pvf}^{y} N_{pvf} \mu_{pvf}\right)\right) (1 - R_{tax}), \\ &\forall h \in H, d \in D, y \in Y, \end{aligned} \quad (31)$$

$$\begin{aligned} EX_{SCF}^{y} = &\sum\nolimits_{d\in D} \sum\nolimits_{h\in H} \left[P_{rtp}^{h,d,y} \mu_{rt}^{h,d,y} \right. \\ &\left. + \left(P_{ch,SCF}^{h,d,y} + P_{dch,SCF}^{h,d,y}\right) \mu_{vom,SCF}\right] \\ &+ C_{pcs,SCF} \mu_{fom,SCF}, \quad \forall h \in H, d \in D, y \in Y. \end{aligned} \quad (32)$$

The first capital expenditure of the SCF platform operator is expressed as

$$\begin{aligned} EX_{0,SCF} = &C_{pcs,SCF}(\mu_{pcs,SCF} + \mu_{bop,SCF}) \\ &+ C_{b,SCF}(\mu_{b,SCF} + \mu_{cc,SCF}). \end{aligned} \quad (33)$$

B. GRID CONSTRAINTS

It is assumed that power always balances supply and demand, which is expressed as

$$\begin{aligned} &P_{ch,SCF}^{h,d,y} - P_{dch,SCF}^{h,d,y} \\ &= P_{aggch}^{h,d,y} - P_{aggdch}^{h,d,y} + P_{rtp}^{h,d,y} - P_{rts}^{h,d,y} \\ &\quad - P_{spr}^{h,d,y} X_{spr}^{h,d,y}, \quad \forall h \in H, d \in D, y \in Y. \end{aligned} \quad (34)$$

Power supplied to the grid via the execution of spinning reserve cannot be delivered from the energy market during the same period, which is expressed as

$$\begin{aligned} &X_{spr}^{h,d,y} P_{rtp}^{h,d,y} \\ &\le X_{spr}^{h,d,y} \left(P_{ch,SCF}^{h,d,y} - P_{dch,SCF}^{h,d,y} - P_{aggch}^{h,d,y} + P_{aggdch}^{h,d,y} + P_{rts}^{h,d,y}\right), \\ &\forall h \in H, d \in D, y \in Y. \end{aligned} \quad (35)$$

C. MARKET CONSTRAINTS

The random variable indicating whether the real-time spinning reserve is executed follows the Bernoulli distribution with a probability of 1 as a result of the trial, pr_{spr}, expressed as

$$P\left(X_{spr}^{h,d,y} = 1\right) = pr_{spr}, \quad \forall h \in H, d \in D, y \in Y, \quad (36)$$

$$P\left(X_{spr}^{h,d,y} = 0\right) = 1 - pr_{spr}, \quad \forall h \in H, d \in D, y \in Y, \quad (37)$$

$$0 \le pr_{spr} \le 1, \quad \forall h \in H, d \in D, y \in Y. \quad (38)$$

D. BESS CONSTRAINTS

Equations (39)–(42) describe the constraints for the hourly remaining energy of the BESS:

$$\begin{aligned} E_{b,SCF}^{h,d,y} &= E_{init} C_{b,SCF} + P_{ch,SCF}^{h,d,y} \eta_{ch} - \frac{P_{dch,SCF}^{h,d,y}}{\eta_{dch}}, \\ &\quad h = 1, \quad \forall d \in D, y \in Y, \end{aligned} \quad (39)$$

$$\begin{aligned} E_{b,SCF}^{h,d,y} &= E_{b,SCF}^{h-1,d,y} + P_{ch,SCF}^{h,d,y} \eta_{ch} - \frac{P_{dch,SCF}^{h,d,y}}{\eta_{dch}}, \\ &\quad h > 1, d = 1, y \in Y, \end{aligned} \quad (40)$$

$$E_{b,SCF}^{h,d,y} = E_{init} C_{b,SCF}, h = 24, \quad \forall d \in D, y \in Y, \quad (41)$$

$$E_{min} C_{b,SCF} \le E_{b,SCF}^{h,d,y} \le E_{max} C_{b,SCF}, \quad \forall h \in H, d \in D, y \in Y. \quad (42)$$

The operation of the PCS is possible within the range, excluding the capacity participating in the spinning reserve market. Equations (43) and (44) describe the constraints for the hourly charging and discharging power of the PCS:

$$C_{pcs,SCF} \ge P_{ch,SCF}^{h,d,y}, \quad (43)$$

$$C_{pcs,SCF} \ge P_{dch,SCF}^{h,d,y} + P_{spr}^{h,d,y}. \quad (44)$$

Equations (45) and (46) utilize an auxiliary variable to prevent simultaneous charging and discharging operations [20].

$$P_{ch,SCF}^{h,d,y} \le a_{SCF}^{h,d,y} bigN, \quad (45)$$

$$P_{dch,SCF}^{h,d,y} \le \left(1 - a_{SCF}^{h,d,y}\right) bigN. \quad (46)$$

E. ROBUST-BASED APPROACH

To manage the uncertainty of the energy market price, a robust-based approach is applied. Equations (47) and (48)-(52) describe the objective function and constraints of the counterpart of a standard robust MILP model obtained by using linearization method and duality theorem [19], respectively.

$$Minimize \sum_{t=1}^{T} e^t x^t + z_0\Gamma_0 + \sum_{t=1}^{T} q^t \tag{47}$$

$$\text{Subject to } z_0 + q^t \geq d^t w^t, \quad \forall t \in T \tag{48}$$

$$q^t \geq 0, \quad \forall t \in T \tag{49}$$

$$w^t \geq 0, \quad \forall t \in T \tag{50}$$

$$z_0 \geq 0 \tag{51}$$

$$x^t \leq w^t, \quad \forall t \in T. \tag{52}$$

The counterpart of the standard model is applied to the optimization of the SCF platform operator proposed in this paper. The robust-based optimization of the SCF platform operator is expressed as

$$\begin{aligned} &Minimize\,(-NPV_{SCF}) \\ &= Minimize\Bigg(-\Bigg\lfloor \sum\nolimits_{y\in Y}\Big[\left(REV_{SCF}^{y} - EX_{SCF}^{y} - EX_{red}^{y}\right) \\ &\left(\frac{1}{1+r_{disc}}\right)^{y}\Big] - EX_{0,SCF}\Bigg\rfloor\Bigg) \\ &+z_0\Gamma_0 + \sum\nolimits_{y\in Y}\sum\nolimits_{d\in D}\sum\nolimits_{h\in H} q_0^{h,d,y} \end{aligned} \tag{53}$$

$$\text{Subject to Constraints } (31)-(46) \tag{54}$$

$$z_0 + q_0^{h,d,y} \geq d^{h,d,y} w^{h,d,y}, \quad \forall h \in H, d \in D, y \in Y. \tag{55}$$

$$q_0^{h,d,y} \geq 0, \quad \forall h \in H, d \in D, y \in Y. \tag{56}$$

$$w^{h,d,y} \geq 0, \forall h \in H, d \in D, y \in Y. \tag{57}$$

$$z_0 \geq 0 \tag{58}$$

$$P_{rts}^{h,d,y} + P_{rtp}^{h,d,y} \leq w^{h,d,y}, \quad \forall h \in H, d \in D, y \in Y. \tag{59}$$

The algorithm for the robust-based optimization of the SCF platform operator is described as follows:

1) Set prices $\mu_{rt}^{h,d,y} = \mu_{rtmin}^{h,d,y}$; $\forall h \in H, d \in D, y \in Y$.
2) Set $d^{h,d,y} = G^k\left(\mu_{rtmax}^{h,d,y} - \mu_{rtmin}^{h,d,y}\right)$; $\forall h \in H, d \in D, y \in Y$, where G^k is a coefficient with a value of 0 to 1 in increments of 5% per iteration step.
3) Robust-based optimization of the SCF platform operator (54)-(61) is performed and results are obtained.
4) Steps 2 and 3 are performed iteratively until $G^k > 1$.
5) Exit the loop if $G^k > 1$; the maximum and minimum robust plans of the SCF platform operator are achieved from the obtained results in step 3.

V. CASE DESCRIPTIONS

A. PATTERN GENERATION FOR INDIVIDUAL CUSTOMERS

The MILP model is solved in a Python environment using the solver GUROBI. It is assumed that 10,000 residential, 100 industrial, and 100 PV generating facility customers subscribe to the service in California. It is assumed that residential and industrial customers use SCF services to reduce electricity bills from the Californian LSE Pacific Gas & Electric (PGE) through tariff E-6 for residential customers and tariff B-20 for industrial customers [21], [22]. Tariff B-20, a large-scale customer plan offered by PGE, is subject to a demand rate that is affected by the peak demand for a month [22]. PV generating facility customers are not served by an LSE and supply power to the grid under the PPA contract, using BESS to reduce financial loss caused by limited supply due to a curtailment order. At least one annual hourly load pattern was collected for each customer type served by the LSE and set as a reference pattern [23], and random noises were applied to the reference pattern to create a different load pattern for each customer. Figures 3–5 show the reference pattern of the annual load for residential and industrial customers.

Individual customers save money by incentives such as investment tax credits (ITC) and the self-generation incentive program (SGIP). ITCs allow a certain percentage of the total cost paid to install solar panels from the federal tax burden for the year if the battery is charged by the solar energy system on-site. In 2021, a rate of 26 % was applied. SGIP provides incentives when certain conditions are satisfied with renewable energy resources and storage. According to Step 3, it is assumed that residential customers receive an incentive of \$0.35/Wh and industrial or PV generating facility customers receive an incentive of \$0.25/Wh [24]. For the PV generating facility customers subject to PPA contracts, it is assumed that curtailment orders that limit the generated power to 80% of the rated capacity are delivered at 33.33 % probability every hour from 9 am to 4 pm when solar power generation is high. The price of the PPA contract reflects recent market conditions [25].

The usable area for installing the PV generation system is assumed to be 100 m^2 for residential customers, 3,000m^2 for industrial customers, and 50,000 m^2 for PV generating facility customers. The hourly PV generation ratio to the maximum output data during a year was calculated as a function of weather conditions [26] using weather data for 2016 in New York City, USA, located at a latitude like that of northern California, as input to the function [27]. Figure 6 shows statistical information on the annual PV generation ratio to maximum output.

The simulation period was assumed to be 20 years, considering the cycle life of Li-Ion batteries [28]. The unit price of individual customers' BESS equipment and PV generation system is set differently by the scale of customers according to the 2018 Li-Ion BESS price range suggested by the report provided by the U.S. Department of Energy [29] and those reflecting recent solar market

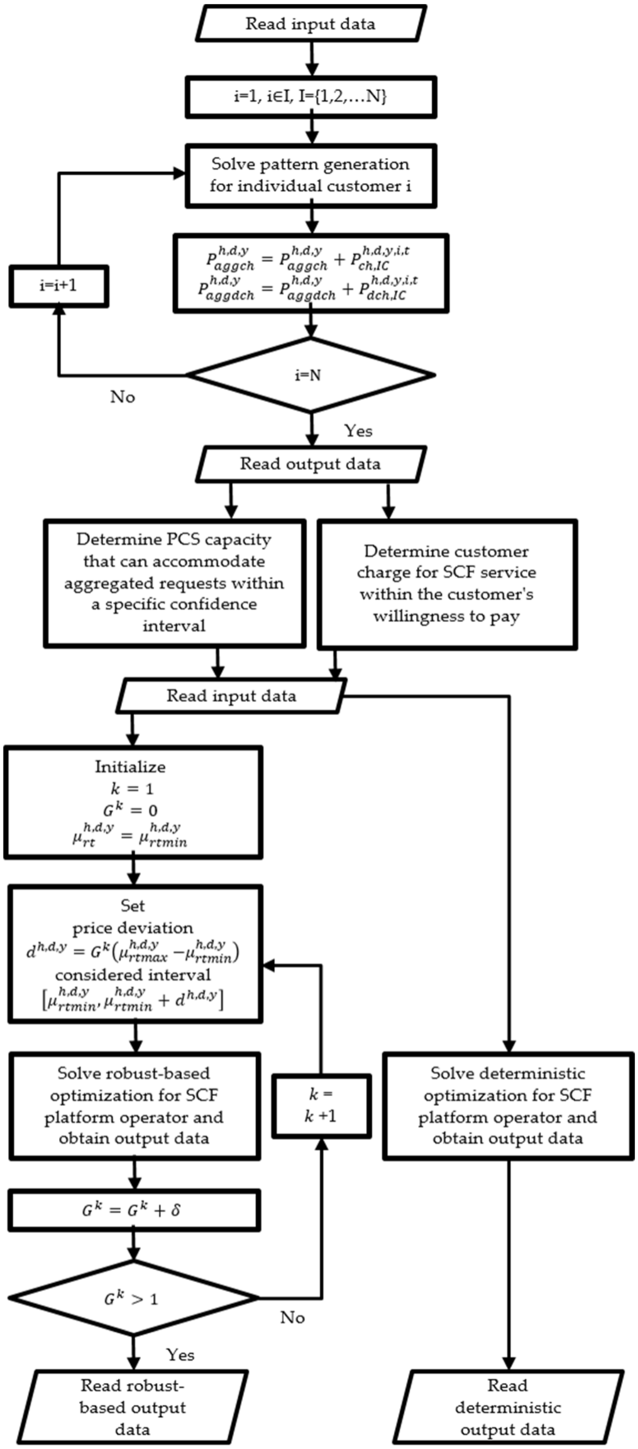

FIGURE 2. Scheme of the working procedure.

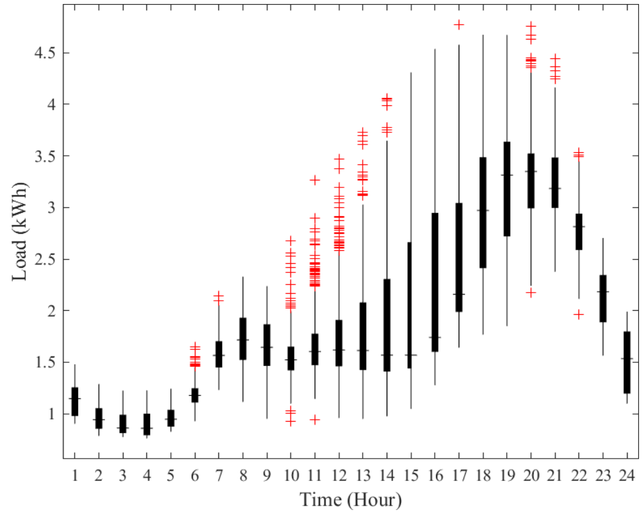

FIGURE 3. Reference pattern of annual residential customer load.

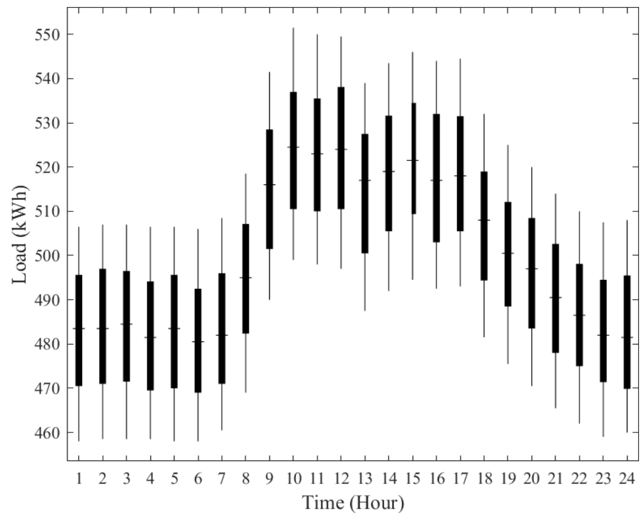

FIGURE 4. First reference pattern of annual industrial customer load.

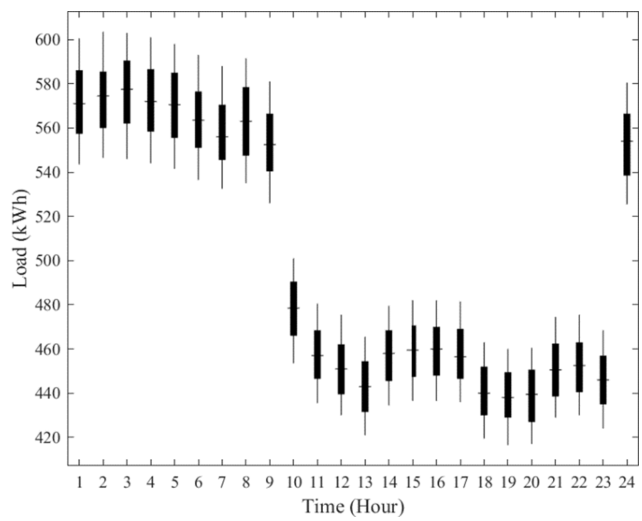

FIGURE 5. Second reference pattern of annual industrial customer load.

conditions [26], [30]. The simulation settings for the pattern generation of individual customers are shown in Table 1.

B. OPTIMIZATION FOR SCF PLATFORM OPERATOR

The MILP model is solved in a Python environment using the solver GUROBI. It is assumed that the SCF platform operator purchases scarce power and sells surplus power through the real-time energy market and that it participates in the day-ahead spinning reserve market. The price data of the energy market and spinning reserve market refer to historical

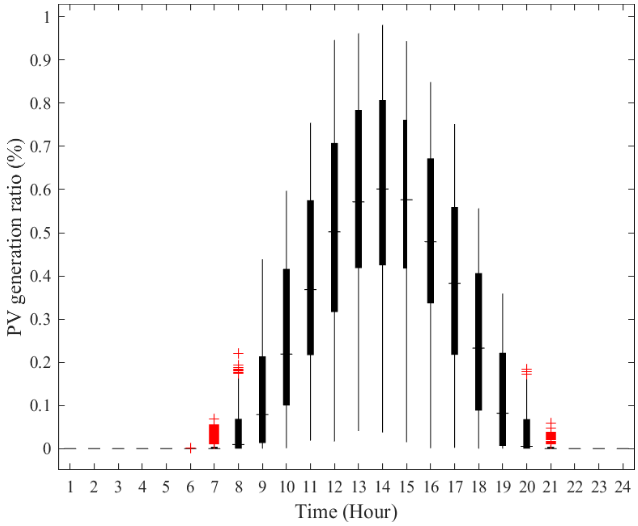

FIGURE 6. Pattern of annual PV generation ratio.

TABLE 1. Simulation settings for pattern generation of individual customers.

Parameters	Value		
	Residential	Industrial	PV generating facility
r_{disc}	5 (%)	5 (%)	5 (%)
E_{init}	50 (%)	50 (%)	50 (%)
E_{max}	90 (%)	90 (%)	90 (%)
E_{min}	10 (%)	10 (%)	10 (%)
$\mu_{b,IC}$	271 (\$/kWh)	271 (\$/kWh)	220 (\$/kW)
$\mu_{pcs,IC}$	288 (\$/kW)	288 (\$/kW)	230 (\$/kW)
$\mu_{bop,IC}$	100 (\$/kW)	100 (\$/kW)	80 (\$/kW)
$\mu_{cc,IC}$	101 (\$/kWh)	101 (\$/kWh)	92 (\$/kWh)
$\mu_{fom,IC}$	10 (\$/kW)	10 (\$/kW)	10 (\$/kW)
$\mu_{vom,IC}$	0.03 (\$/kWh)	0.03 (\$/kWh)	0.03 (\$/kWh)
μ_{pv}	1650 (\$/kW)	1650 (\$/kW)	700 (\$/kW)
μ_{ppa}	0 (\$/kWh)	0 (\$/kWh)	0.03 (\$/kWh)
η_{ch}	95 (%)	95 (%)	95 (%)
η_{dch}	95 (%)	95 (%)	95 (%)
$bigN$	1,000,000	1,000,000	1,000,000
A_{pv}	13 (m^2)	13 (m^2)	13 (m^2)
R_{ctl}	0 (%)	0 (%)	20 (%)
pr_{ctl}	0 (%)	0 (%)	33.33 (%)

data [31] provided by CAISO. The probability of real-time execution of the spinning reserve is assumed to be 5 % [32]. The business period is set at 20 years, which is the same as the simulation period of pattern generation for individual customers. The aggregated request is obtained by summing the hourly charging energy minus the discharging energy of each customer for all customers. Costs of financing, human resources, and land-use are not considered in this simulation.

The capacity of the PCS was set to accommodate the aggregated request within a 95 % confidence interval. Thus, requests outside the general range are assumed to be handled by the energy market. From the pattern generation of individual customers, the willingness to pay by customer type is determined as \$45.77 for residential customers, \$2,658.24 for industrial customers, and \$4,453.58 for PV generating facility customers, respectively. Considering that

TABLE 2. Simulation settings for optimization of SCF platform operator.

Parameters	Value	Parameters	Value
r_{disc}	5 (%)	$\mu_{b,SCF}$	220 (\$/kW)
$C_{pcs,SCF}$	3,796 (kW)	$\mu_{pcs,SCF}$	230 (\$/kW)
N_{res}	10,000	$\mu_{bop,SCF}$	80 (\$/kW)
N_{ids}	100	$\mu_{cc,SCF}$	92 (\$/kWh)
N_{pvf}	100	$\mu_{fom,SCF}$	10 (\$/kW)
E_{init}	50 (%)	$\mu_{vom,SCF}$	0.03 (\$/kWh)
E_{max}	90 (%)	η_{ch}	95 (%)
E_{min}	10 (%)	η_{dch}	95 (%)
μ_{res}	9.15 (\$/month)	$bigN$	1,000,000
μ_{ids}	531.65 (\$/month)	pr_{spr}	5 (%)
μ_{pvf}	890.72 (\$/month)	R_{tax}	8.84 (%)

TABLE 3. Case descriptions.

Case	Provide SCF service	Participate in Arbitrage Trading	Participate in Ancillary Service
1	O	O	O
2	O	X	O
3	O	O	X
4	O	X	X

SCF services are not generally familiar, monthly fees are set at 20% of the maximum willingness-to-pay for each customer type. The SCF platform operator is subject to a fixed income tax rate of 8.84 %, applied by the state of California, on all income it generates. Because SCF platform operators introduce equipment on a utility scale, relatively low equipment costs are applied compared to small-scale customers. The unit price of BESS equipment for the SCF platform operator is the low value of the 2018 Li-Ion BESS price range suggested by the report provided by the U.S. Department of Energy [29]. Considering that it takes time to recruit customers, it is assumed that the number of customers increases by 10 % of the target number each year for the first 10 years. The simulation settings for the optimization of the SCF platform operator are shown in Table 2.

The simulation was conducted for four cases according to the method of multi-using BESSs to verify the effectiveness of multi-use of BESSs, as described in Table 3. The SCF platform operator receives profits by providing SCF services in common in all cases: in case 1, it participates in both arbitrage trading and ancillary service; in case 2, only ancillary service; in case 3, only arbitrage trading; in case 4, it does not participate in either. In the case of not participating in arbitrage trading, trading in the energy market is carried out at a minimum level to maintain the supply-demand balance. A robust-based approach is applied for each case according to the consideration of uncertainty in a range of G^k from 0 to 1, respectively. The minimum and maximum energy market prices are set as 90% and 110% of historical data, respectively, and Γ_0 is set as 114,627 to consider all possible deviations of the energy market price during the entire business period and annual discount rate.

TABLE 4. Simulation results.

Case	BESS Capacity (kWh)	Annual Revenue ($)	Annual Reduction in Energy Sales Revenue ($)	NPV of Profit ($)	IRR (%)
1	7,592	3,409,283	981,034	10,496,738	30.5
2	4,218	3,310,030	981,034	9,921,038	35
3	0	3,162,375	981,034	9,039,158	46.5
4	0	3,162,375	981,034	9,039,158	46.5

VI. RESULT AND DISCUSSION

A. SIMULATION RESULTS

1) EFFECT FROM MULTI-USE OF BESS

Table 4 presents the deterministic optimal results of BESS capacity planning and variables related to profits determined according to whether the BESS is multi-use for the SCF platform operator. The annual revenue represents the value when the level of service subscription reaches the target of 100 %. The NPV of profit and internal rate of return (IRR) show positive values in all cases, despite the decline in annual revenue of $981,034 from the existing energy sales business, as LSE provides SCF services to existing customers. Among all cases, the NPV of profit is the highest in case 1 when both participating in arbitrage trading and ancillary services, in addition to providing SCF services. Although the NPV of profit is the highest in case 1, IRR is the lowest. This is caused by the fewer BESS equipment investments in the other cases. Meanwhile, through the comparison of cases 2 and 3, it is shown that the NPV of profit appears to decrease more when the SCF platform operator does not participate in ancillary services than when it does not participate in arbitrage trading. Whether participating in arbitrage trading, in addition to providing SCF services, it makes no difference according to the comparison between cases 3 and 4. The capacity of BESS is determined to be zero in cases 3 and 4, in which the SCF platform operator does not participate in ancillary services. This is because in cases 3 and 4, it is economical to operate the business only by procuring energy from the energy market without a BESS. As shown in Figure 8, compared with when the deterministic approach is applied, the NPV of profit from the robust-based approach decreases by about 3% in case 1. In all cases, the consideration of uncertainty does not cause a decrease of over 7% in the NPV of profit; hence, the value of the NPV of profit still remains positive. The detailed composition of the annual revenue by case and scenario is presented in Figure 9, which shows the value obtained from a deterministic approach when customer subscription reached the target number.

Among the details of annual revenue, the proportion of revenue from the SCF service is the largest, and revenue from the ancillary service accounts for the lowest proportion. The revenue from the SCF service is the same for all cases because it is not related to the multi-use of the BESS, and revenue from the ancillary service is slightly larger in case 1 than in case 2.

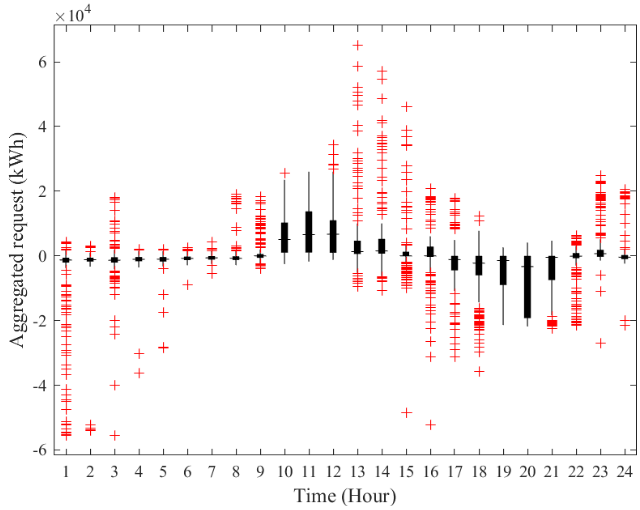

FIGURE 7. Aggregated request from all customers.

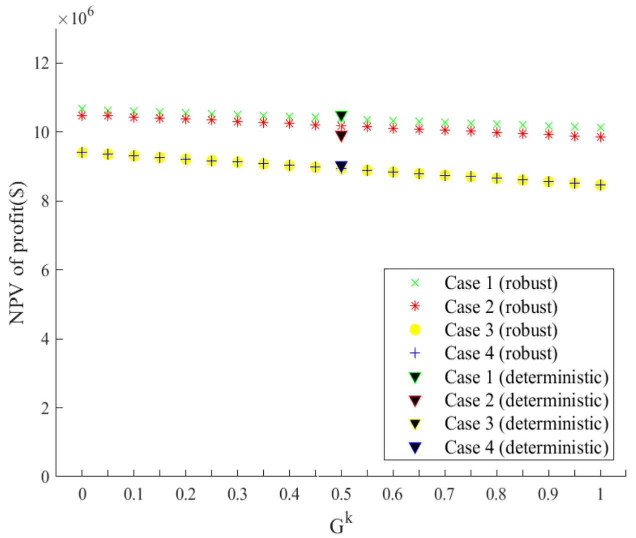

FIGURE 8. NPV of profit from deterministic and robust approach for different values of the parameter G^k.

The revenue from the energy market is the largest in case 1, and the level is similar in the other cases but slightly smaller in case 2, which does not participate in arbitrage trading.

Figure 10 shows the aggregated request on a typical day in February, and Figures 11–13 show the operation schedule of the SCF platform operator on the same day obtained from a deterministic approach. The positive and negative values on the y-axis represent the aggregated amount of charging and discharging requests from customers in Figure 10, the amount of energy purchased and sold in the energy market in Figure 11, and the amount of charging and discharging energy of the BESS in Figure 12, respectively. As shown in Figures 11 and 12, the amount of aggregated charging and discharging requests exactly matches the energy sold and purchased in the energy market over all time periods in cases 3 and 4. In cases 1 and 2, as shown in Figure 12, the BESS is active in responding to customer requests. However, the BESS operation of charging and discharging is

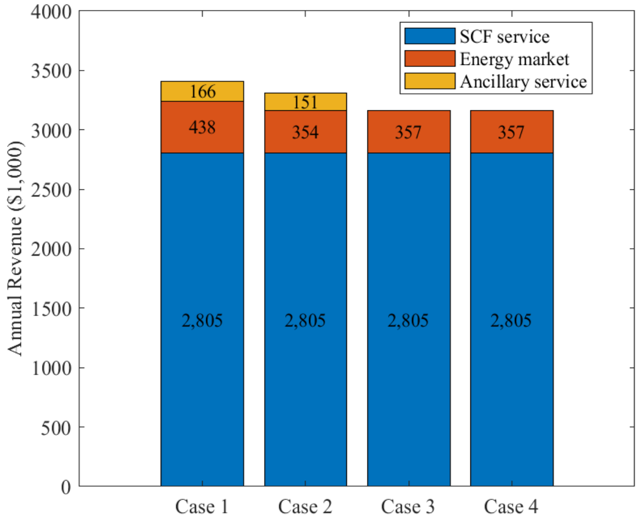

FIGURE 9. Comparison of annual revenue by cases when customer subscription reached the target number.

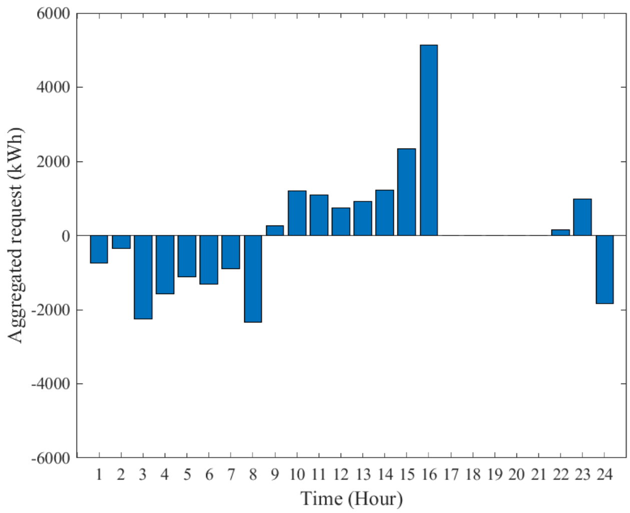

FIGURE 10. Aggregated request from all customers on a typical day.

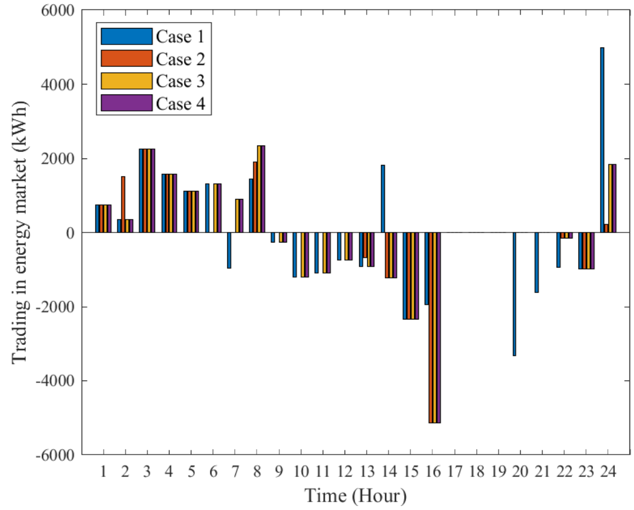

FIGURE 11. Energy traded in energy market on a typical day.

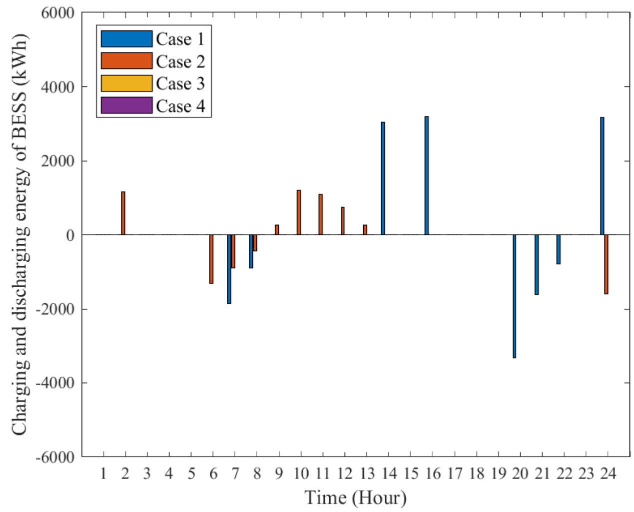

FIGURE 12. Charging and discharging energy of BESS on a typical day.

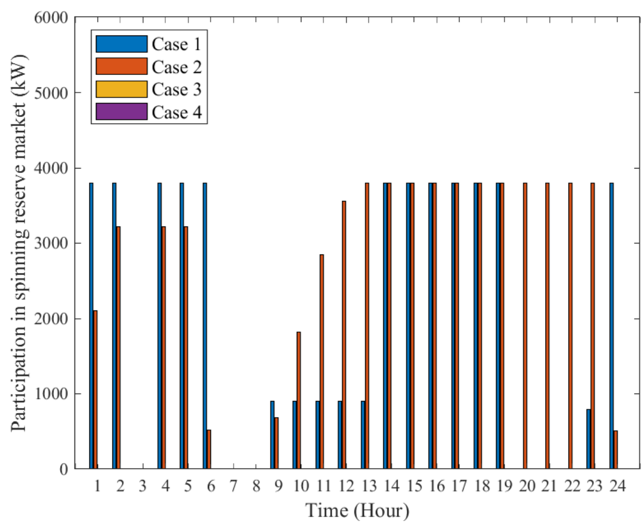

FIGURE 13. Participation in spinning reserve market on a typical day.

performed at a necessary level at a low frequency compared to trading in the energy market. As shown in Figure 13, the strategy of participation in the spinning reserve market is performed frequently and often at the highest level under the capacity constraints of the PCS.

2) EFFECT FROM SUBSCRIPTION OF VARIOUS TYPES OF CUSTOMERS

Because the types of customers subscribed are factors that affect the profitability of the SCF platform operator, a sensitivity analysis was performed from a deterministic approach accordingly. Figures 14 and 15 show the changes in the NPV of the profit and capacity of the BESS battery for cases with diverse types of customers subscribed to the service, respectively. It is shown that the NPV of profit is larger when all types of customers are subscribed than the sum of the NPV of profits when each single type of customer is subscribed for all the cases. In case 1, the NPV of profit for when all types of customers are subscribed is more than $60,000 larger than the sum of the NPV of profits when each

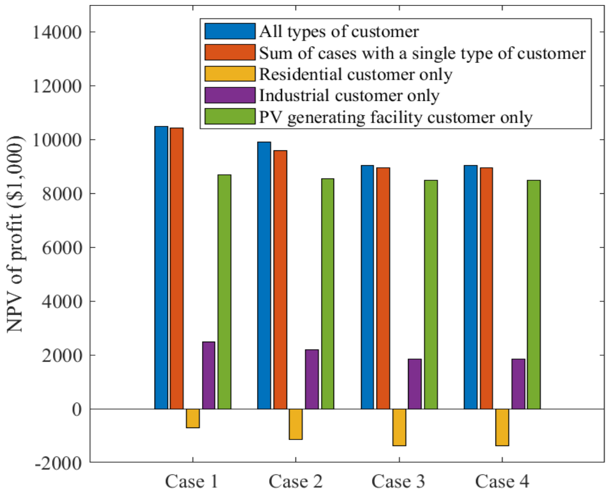

FIGURE 14. Change in the NPV of profit according to types of customers recruited.

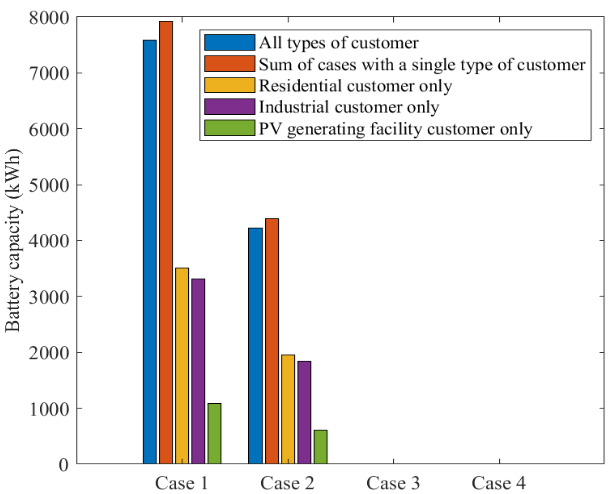

FIGURE 15. Change in the capacity of BESS battery according to types of customers recruited.

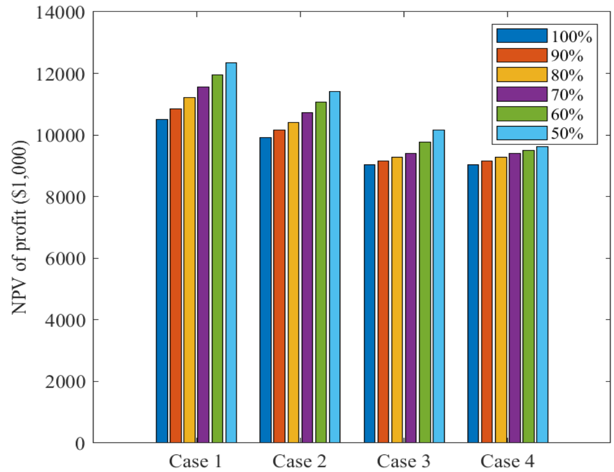

FIGURE 16. Change in the NPV of profit according to the unit price of BESS from the deterministic approach.

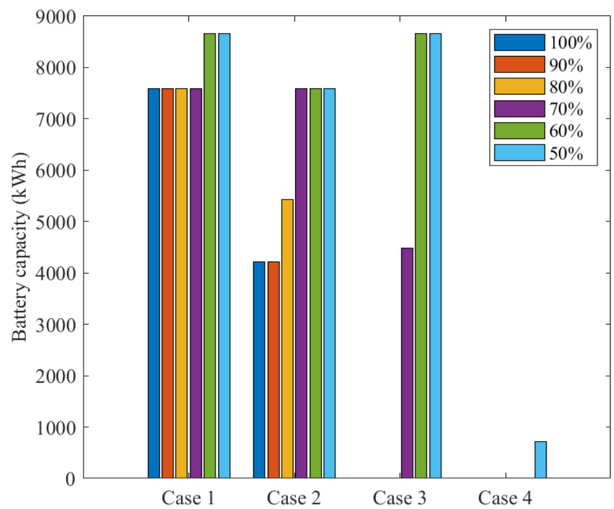

FIGURE 17. Change in the capacity of BESS battery according to the unit price of BESS from the deterministic approach.

single type of customer is subscribed. The NPV of profit mostly stays positive, except for cases where only residential customers are subscribed. The capacity of the BESS battery is smaller when all types of customers are subscribed than the sum of the capacity of the BESS battery when each single type of customer is subscribed in cases 1 and 2. The capacity of the BESS battery is determined to be zero in cases 3 and 4.

3) EFFECT FROM UNIT PRICE OF BESS

The unit price of the BESS equipment applied in this simulation was that of 2018. Because the price reduction is expected according to the forecast based on historical data, which also affects the profitability of the SCF platform operator, a sensitivity analysis was performed for each case from a deterministic approach according to the reduction in the unit price of BESS equipment. Figures 16 and 17 show the changes in the NPV of the profit and capacity of the BESS battery by cases as the unit price of BESS decreases. When the unit price of BESS reaches 70 % of the standard value in case 3 or 50 % of the standard value in case 4, the capacity of the BESS battery has a non-zero value, whereas the capacity of the BESS battery is determined to be zero when the unit price of BESS is over 70 % of the standard value in case 3 or over 50 % of the standard value in case 4. At the same level that the BESS battery value becomes non-zero, the increase in profit by a one-step decrease in the unit price of BESS increases.

B. DISCUSSION

As shown in Table 4, despite the reduction in revenue in the energy-sales business and conservative assumptions, such as the customer fee being set as low as 20% of the willingness to pay for the service, robust-based approach considering the uncertainty of the energy market price, and the number of customers being increased by 10 % of the target number each year for the first 10 years, the SCF platform business of the LSE is economically feasible under the given conditions considering that the service is unfamiliar to the public. As shown in Figure 8, when the uncertainty range of the energy market price is set at 10%, the profit of the SCF platform operator changes at a maximum of approximately 6% among all cases. Accordingly, the profitability of the SCF business is guaranteed even under a conservative approach. However, if the SCF platform business is operated by a third party other than the LSE, the LSE suffers economic losses due to a decrease in revenue from the energy-sales business without any profits generated from the SCF platform business. In this study, it is considered reasonable for the LSE to conduct the SCF platform business. However, since the possibility of a third party conducting the business cannot be excluded, the LSE requires efforts to preempt the business.

As shown in Figure 9, the proportion of revenue from participating in arbitrage trading and ancillary services is approximately 18 % in case 1, which leads to the highest NPV of profit in case 1 among all cases. The comparison of the NPV of profit between cases 1 to 4 presents the direction of strategy for SCF platform operators to expect the highest returns when participating in both arbitrage trading and ancillary services. It is also shown that the share of the revenue from the energy market is larger than that of the revenue from the ancillary market despite the uncertainty of the energy market price. However, owing to the small benefit of arbitrage trading, its contribution to a change in the NPV of profit is less than choosing to participate in ancillary service. However, because this simulation result was derived on the premise of accurate prediction of the market situation, it is necessary for the SCF platform operator to establish an appropriate facility investment strategy in consideration of the risks arising from the uncertainty of the market situation prediction.

The results in cases 3 and 4 are the same as those in Table 1, and the capacity of the BESS battery is determined to be zero, meaning that participation in arbitrage trading does not create enough benefits beyond BESS investment costs under the given conditions. In these cases, the energy to respond to the aggregated request from customers is provided only through transactions in the energy market without the BESS, which is shown through the patterns of cases 3 and 4, which match Figures 10 and 11. As shown in Figures 11–13, compared with participation in the energy and ancillary service market, BESS charging and discharging are less frequently performed at an essential level. This shows that minimizing the variable operating cost of BESS is an advantageous strategy from the economic point of view for the SCF platform operator.

As shown in Figure 14, the NPV of profit for all types of customers subscribed appears to be approximately $60,000 larger than the sum of the NPV of profit for each single type of customer subscribed in case 1. This is caused by the offset effect from the subscription of various types of customers, which leads to a reduction in the required capacity of the BESS battery and investment cost, as shown in Figure 15. The difference is about 1 % of the total NPV of profit, which may seem small. However, considering that the ratio of capital expenditure to the NPV of profit is about 34 %, and the proportion will even increase if revenue decreases, due to price competition in the SCF platform business, the strategy of recruiting various customer types is certainly an important factor in improving the profitability of the SCF platform operator.

Decreasing the unit price of the BESS increases the profit of the SCF platform operator by reducing capital expenditure. As shown in cases 3 and 4 of Figure 17, when the unit price of the BESS is reached at 70 % and 50 % of the current level, respectively, the capacity of the BESS battery has a value greater than zero. This shows that if the price of BESS reaches a certain level, the benefit generated by arbitrage trading using the BESS will exceed the cost of investing in it. However, at the current level of the unit price of the BESS, if its role is limited to maintaining a minimum balance of supply and demand without participation in the arbitrage trading and ancillary service, it is not worth investing in the BESS. Compared with 2018, the unit price of the BESS is expected to decrease by about 23 % by 2025 [29], and assuming a larger business scale than that in this study, the cost reduction effect caused by the increase in the facility scale may also occur. Thus, the profitability of the SCF platform operator is expected to increase compared with the results based on basic assumptions.

VII. CONCLUSION

The SCF platform provides innovative services that end users benefit from using a BESS at a low cost, without the burden of owning and operating the BESS. The goal of this study was to verify the economic feasibility of an LSE-operating SCF platform by considering the uncertainty of the energy market price and additional measures to increase profitability in addition to collecting customer fees. This paper proposed a novel methodological framework for an SCF platform operator to maximize profit by using a BESS and aggregating various types of customers. First, optimization was performed to minimize the cost of using electricity from the perspective of individual customers with different BESS operation methods by type to derive the upper limit of customers' willingness to pay for the SCF service and the pattern of using the BESS. Subsequently, a robust-based optimization was performed to maximize the profit from the perspective of an SCF platform operator using the customer fee determined at a specific ratio of the willingness to pay and the aggregated request from individual customers as input data. From case studies conducted based on the California environment, we reached the following conclusions:

1) Despite the reduction in revenue in the energy-sales business and conservative approach considering uncertainty of the energy market price, the SCF platform business of the LSE is economically feasible in California.

2) The multi-use of BESS increases the profitability of SCF platform operators, and participation in ancillary services contributes to profits more than participation in arbitrage trading.
3) The profit from the SCF platform business with various types of customers subscribed is higher than the sum of profits from separate businesses that are conducted with a single type of customer.
4) In current price situation, without participation in the ancillary service, a strategy is adopted in which the SCF platform operator handles the aggregated requests through the energy market without an actual BESS. The benefit created from participation in arbitrage trading becomes sufficient if the price of BESS reaches approximately 70 % of its current level.

This study presents an improved direction of business strategy to increase the profitability of LSE (i.e., an SCF platform operator), which consequently leads to an increase in social welfare by ensuring the LSE in the rewards from the business and providing end users an opportunity to reduce electricity costs by having access to remote energy-storage systems.

REFERENCES

[1] G. Parker and M. Van Alstyne, "A digital postal platform: Definitions and a roadmap," MIT Center Digit. Bus., Cambridge, MA, USA, Working Paper, Jan. 2012. [Online]. Available: https://www.crunchbase.com/organization/mit-center-for-digital-business

[2] J. Wirtz, K. K. F. So, M. A. Mody, S. Q. Liu, and H. H. Chun, "Platforms in the peer-to-peer sharing economy," *J. Service Manage.*, vol. 30, no. 4, pp. 452–483, Oct. 2019.

[3] G. Graditi, M. G. Ippolito, R. Rizzo, G. Zizzo, and E. Telaretti, "Technical-economical evaluations for distributed storage applications: An italian case study for a medium-scale public facility," in *Proc. 3rd Renew. Power Gener. Conf. (RPG)*, Naples, Italy, 2014, pp. 1–7.

[4] M. C. Falvo, U. Grasselli, M. Manganelli, and A. Modesto, "Small scale ESS for LV prosumers: An economic feasibility and sensitivity analysis," in *Proc. IEEE 15th Int. Conf. Environ. Electr. Eng. (EEEIC)*, Jun. 2015, pp. 950–955.

[5] D. Metz and J. T. Saraiva, "Simultaneous co-integration of multiple electrical storage applications in a consumer setting," *Energy*, vol. 143, pp. 202–211, Jan. 2018.

[6] G. Carpinelli, S. Khormali, F. Mottola, and D. Proto, "Battery energy storage sizing when time of use pricing is applied," *Sci. World J.*, vol. 2014, pp. 1–8, Jan. 2014.

[7] G. Carpinelli, A. di Fazio, S. Khormali, and F. Mottola, "Optimal sizing of battery storage systems for industrial applications when uncertainties exist," *Energies*, vol. 7, no. 1, pp. 130–149, Jan. 2014.

[8] R. Dufo-López and J. L. Bernal-Agustín, "Techno-economic analysis of grid-connected battery storage," *Energy Convers. Manage.*, vol. 91, pp. 394–404, Feb. 2015.

[9] J. Liu, N. Zhang, C. Kang, D. Kirschen, and Q. Xia, "Cloud energy storage for residential and small commercial consumers: A business case study," *Appl. Energy*, vol. 188, pp. 226–236, Feb. 2017.

[10] D. Zhao, H. Wang, J. Huang, and X. Lin, "Pricing-based energy storage sharing and virtual capacity allocation," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[11] H. Chen, H. Cheng, G. Xu, W. Zhou, X. Zhang, and D. Sang, "Research on consumer side energy storage optimization configuration based on cloud energy storage," in *Proc. 3rd Int. Conf. Smart City Syst. Eng. (ICSCSE)*, Dec. 2018, pp. 476–481.

[12] Z. Liu, J. Yang, W. Song, N. Xue, S. Li, and M. Fang, "Research on cloud energy storage service in residential microgrids," *IET Renew. Power Gener.*, vol. 13, no. 16, pp. 3097–3105, Dec. 2019.

[13] J. Liu, N. Zhang, C. Kang, D. S. Kirschen, and Q. Xia, "Decision-making models for the participants in cloud energy storage," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 5512–5521, Nov. 2018.

[14] C. Shapiro and H. R. Varian, *Information Rules: A Strategic Guide to the Network Economy*. Boston, MA, USA: Harvard Business School Press, 1999.

[15] A. S. Tsagkou, E. D. Kerasidis, D. I. Doukas, D. P. Labridis, A. G. Marinopoulos, and T. Tengner, "Stacking grid services with energy storage techno-economic analysis," in *Proc. IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6.

[16] D. Wu, C. Jin, P. Balducci, and M. Kintner-Meyer, "An energy storage assessment: Using optimal control strategies to capture multiple services," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2015, pp. 1–5.

[17] R. Moreno, R. Moreira, and G. Strbac, "A MILP model for optimising multi-service portfolios of distributed energy storage," *Appl. Energy*, vol. 137, pp. 554–566, Jan. 2015.

[18] R. D. Rappaport and J. Miles, "Cloud energy storage for grid scale applications in the UK," *Energy Policy*, vol. 109, pp. 609–622, Oct. 2017.

[19] D. Bertsimas and M. Sim, "Robust discrete optimization and network flows," *Math. Program.*, vol. 98, pp. 48–71, Sep. 2003.

[20] R. Khalilpour and A. Vassallo, "Planning and operation scheduling of PV-battery systems: A novel methodology," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 194–208, Jan. 2016.

[21] Pacific Gas and Electric Company. (2021). *Electric Schedule E-6*. Accessed: Mar. 16, 2021. [Online]. Available: https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_SCHEDS_E-6.pdf

[22] Pacific Gas and Electric Company. (2021). *Electric Schedule B-20*. Accessed: Mar. 16, 2021. [Online]. Available: https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_SCHEDS_B-20.pdf

[23] U.S. Department of Energy. *Commercial and Residential Hourly Load Profiles for All TMY3 Locations in the United States*. Accessed: Mar. 16, 2021. [Online]. Available: https://openei.org/doe-opendata/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states

[24] Self-Generation Incentive Program. (2021). *SGIP Handbook*. Accessed: Mar. 16, 2021. [Online]. Available: https://www.selfgenca.com/documents/handbook/2021

[25] National Renewable Energy Laboratory. (2020). *Q2/Q3 2020 Solar Industry Update*. Accessed: Mar. 16, 2021. [Online]. Available: https://www.nrel.gov/docs/fy21osti/78625.pdf

[26] V. J. Fesharaki, M. Dehghani, J. J. Fesharaki, and H. Tavasoli, "The effect of temperature on photovoltaic cell efficiency," in *Proc. 1st Int. Conf. Emerg. Trends Energ. Conserv. (ETEC)*, Tehran, Iran, 2011, pp. 21–22.

[27] NOAA. *Quality Controlled Datasets*. Accessed: Feb. 9, 2021. [Online]. Available: https://www.ncdc.noaa.gov/crn/qcdatasets.html

[28] P. Haidl, A. Buchroithner, B. Schweighofer, M. Bader, and H. Wegleiter, "Systems for sustainable transportation," *Sustainability*, vol. 11, no. 23, p. 6731, Nov. 2019.

[29] U.S. Department of Energy. (2019). *Storage Cost and Performance Characterization Report*. Accessed: Mar. 16, 2021. [Online]. Available: https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf

[30] M. Bolinger, J. Seel, D. Robson, and C. Wwarner, *Utility-Scale Solar Data Update: 2020 Edition*. Berkeley, CA, USA, Lawrence Berkeley National Laboratory, 2020, p. 11.

[31] California ISO. *Open Access Same-Time Information System*. Accessed: Mar. 16, 2021. [Online]. Available: http://oasis.caiso.com/mrioasis/logon.do

[32] A. K. Varkani, A. Daraeepour, and H. Monsef, "A new self-scheduling strategy for integrated operation of wind and pumped-storage power plants in power markets," *Appl. Energy*, vol. 88, no. 12, pp. 5002–5012, Dec. 2011.

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