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Optimal ESS Investment Strategies for Energy Arbitrage by Market Structures and Participants

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Abstract – Despite the advantages of energy arbitrage using energy storage systems (ESSs), the high cost of ESSs has not attracted storage owners for the arbitrage. However, as the costs of ESS have decreased and the price volatility of the electricity market has increased, many studies have been conducted on energy arbitrage using ESSs. In this study, the existing two-period model is modified in consideration of the ESS cost and risk-free contracts. Optimal investment strategies that maximize the sum of external effects caused by price changes and arbitrage profits are formulated by market participants. The optimal amounts of ESS investment for three types of investors in three different market structures are determined with game theory, and strategies in the form of the mixed-complementarity problem are solved by using the PATH solver of GAMS. Results show that when all market participants can participate in investment simultaneously, only customers invest in ESSs, which means that customers can obtain market power by operating their ESSs. Attracting other types of ESS investors, such as merchant storage owners and producers, to mitigate market power can be achieved by increasing risk-free contracts.

Keywords: Energy arbitrage, Energy storage system, Investment strategy, Nash equilibrium, Social welfare

1. Introduction

System load flattening provides system-wide benefits, which reduce operational costs in the short-term, and defer the construction of additional supply units in the long-term [1-3]. Power demand is generally inelastic in terms of price and thus not effectively responsive to price incentives. On the other hand, time-varying electricity prices encourage energy storage owners (ESOs) to use their energy storage systems (ESSs) for energy arbitrage, which is load flattening. Furthermore, demand shifting with ESS does not change the utility of customers because the amount of power actually consumed by customers does not change.

Many studies have been conducted on the use of ESSs to reduce energy costs in response to price [4-6]. Although the performance of ESS use in terms of cost saving has been technically verified in previous studies, energy arbitrage using ESSs is uneconomical because the cost of ESSs remains high [5]. Nevertheless, energy arbitrage using ESSs has become a promising option for load flattening because the volatility of electricity prices has increased and ESS costs have decreased.

Evaluation of the economic value of energy arbitrage with ESSs and the optimal ESS investment for arbitrage have been investigated and conducted in many studies [7-9]. These studies assumed that ESOs are price-takers. However, increasing ESS investment for energy arbitrage changes demand, which affects electricity prices. Changes in electricity prices affect not only the value of energy arbitrage but also the welfare of market participants [7, 10]. In other words, energy arbitrage using ESSs reduces the arbitrage value by reducing the variance of the prices. And customers lower their energy costs through the reduced price, while producers gain increased profit due to the increased price. Therefore, the investment incentives of ESS for energy arbitrage differ for each market participant.

Ref. [10] analyzed the changes in the welfare of market participants due to energy arbitrage using the two-period model and found the optimal ESS investment combination of investors to maximize social welfare. However, although the actual amount of ESS investment is determined by ESS cost, the study identified the investment level by using the upper bound condition. Moreover, the incentives to attract investors for the optimal combination can incur additional social costs, and these costs are not reflected in the proposed model.

This paper is an extension of [10]. We develop the model considering the costs of ESS and risk-free contracts to determine optimal ESS investment strategies for investors. We verify the arbitrage is impossible in the retail market under time-of-use (TOU) tariff even if ESS is economical and whether the assumption of ESOs as price-takers is appropriate in the wholesale market structure under system marginal price (SMP). Optimal ESS investment strategies

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are also presented for three types of investors in three market structures. When two or more players compete non-cooperatively, the optimal strategies are determined with game theory. The strategies for each player are formulated in the form of a mixed complementarity problem (MCP) and solved by using the PATH solver of GAMS.

2. Two-period Model of Energy Arbitrage with ESS

2.1 Energy arbitrage with ESS

Time-varying electricity price incentivizes ESOs to use ESS for energy arbitrage, which is load flattening; thus, ESOs shift the demand from high- to low-price periods to save energy costs. Energy arbitrage with ESS allows the power demand to be responsive to price without changing the utility of customers because the actual usage of electricity does not change. Despite these advantages, the use of ESS for energy arbitrage has not been commercialized because of the high cost of ESS. However, this cost will be lowered while the customer's utility will become increasingly important. Therefore, energy arbitrage using ESS is a promising option for load flattening.

2.2 Definition and ESS operation strategy of market participants

We classify market participants into three groups: 1) producer/supplier, 2) customer/consumer, and 3) merchant storage owner (MSO)/stand-alone storage operator [10], [11]. MSO who are neither producers nor customers, are likely to own and operate ESSs for energy arbitrage to maximize their benefits. The scheme of ESS operation for energy arbitrage is shown in Fig. 1.

G_t and D_t are the amounts of generation and demand at time *t*, respectively. E_t^P, E_t^S, and E_t^C are the outputs of ESS (positive value for discharging) owned by producers, MSOs, and customers at time *t*, respectively. S_t and C_t are the power supplied by the generation side ($S_t = G_t + E_t^P$) and the power consumed by the demand side ($C_t = D_t - E_t^C$), respectively.

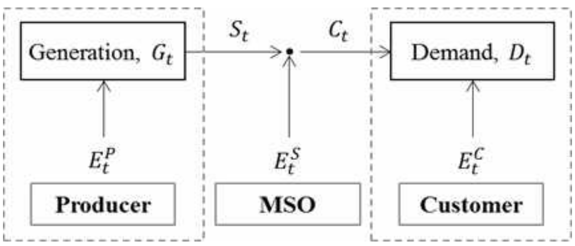

Fig. 1. Scheme of ESS ownership and operation for energy arbitrage by market participants

Table 1. Representative entities

Market participant	Wholesale market	Retail market
Producer	Genco.	Retailer
Customer	Retailer	End user
MSO	Anyone except for the producer and customer	Anyone except for the producer and customer

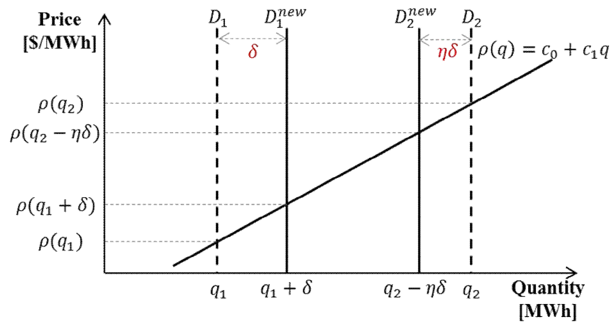

Fig. 2. Two-period model: effects of energy arbitrage using ESS on price and demand in periods 1 and 2

Table 1 shows the representative entities of each market participant in wholesale and retail markets.

Market participants are assumed to own and operate ESSs for their own benefits, and their ESS operational strategies are the same: charging ESS when the electricity price is low and discharging the charged power when the price is high.

2.3 Two-period model considering risk-free contracts and ESS costs

The two-period model for explaining energy arbitrage using ESS is used in this study, and the model is graphically shown in Fig. 2.

In the model, we assume that the supply curve, $\rho(q)$, is linear with coefficients c_0 and c_1 ($c_0 \geq 0, c_1 > 0$) [7, 10], and the demand curves (D_1, D_2) are perfectly inelastic in price [10]. ESO charges δ [MWh] ($\delta \geq 0$) when the price is low (period 1, off-peak period) and discharges $\eta\delta$ [MWh] when the price is high (period 2, on-peak period). η is the charging/discharging efficiency of ESS ($0 < \eta < 1$). Many prior studies showed that electricity price and power load are linearly related seasonally [7].

We modify the model proposed in [10] by considering ESS costs and risk-free contracts.

Investors invest in ESS when energy storage becomes profitable with energy arbitrage. Therefore, the optimal amount of ESS investment is determined by the ESS cost, which is not considered in the existing model. The coefficient of storage cost, c_{ESS}, is defined as the cost of 1 MWh ESS for a full charging and discharging cycle and can be obtained by calculating the degradation costs of ESS. We assume that the cost of ESS scales linearly [12].

To avoid the price risk in the electricity market, producers and customers trade some of their total trading volumes through bilateral and/or forward contracts. Given that the external effects of price changes on the welfare of customers and producers do not affect these contracts, the amount of power traded through these contracts influences on the strategies of investors. In this study, these types of contracts are defined as "risk-free contracts," and the ratio of risk-free contracts to total trade volume is expressed as ω. The amount of electricity traded through risk-free contracts is assumed to exert no affect on market price, and the ratios of the contracts in periods 1 and 2 are the same ($\omega_1 = \omega_2$).

From the model, we can derive the surplus changes in customer, producer, and ESO by energy arbitrage using ESS as (1)-(3), respectively.

$$\Delta CS = c_1(\eta q_2 - q_1)(1-\omega)\cdot\delta \quad (1)$$

$$\Delta PS = c_1(q_1 - \eta q_2)(1-\omega)\cdot\delta + \frac{1}{2}c_1(1+\eta^2)\cdot\delta^2 \quad (2)$$

$$\Delta ES = \{c_0(\eta-1) + c_1(\eta q_2 - q_1) - c_{ess}\}\cdot\delta - c_1(1+\eta^2)\cdot\delta^2 \quad (3)$$

For ease of interpretation, we substitute the coefficients of (1)-(3) for uppercase letters A, B, and C as (4)-(6). Subsequently, (1)-(3) can be rewritten as (7)-(9).

$$A = c_1(\eta q_2 - q_1) \quad (4)$$

$$B = \frac{1}{2}c_1(1+\eta^2) \quad (5)$$

$$C = c_0(1-\eta) \quad (6)$$

$$\Delta CS = A(1-\omega)\cdot\delta \quad (7)$$

$$\Delta PS = -A(1-\omega)\cdot\delta + B\cdot\delta^2 \quad (8)$$

$$\Delta ES = \{(A-C) - c_{ESS}\}\cdot\delta - 2B\cdot\delta^2 \quad (9)$$

All market participants can be ESS investors for energy arbitrage, and their optimal investment strategies maximize the sum of the arbitrage profit by the ESS they invested in and their surplus changes. Therefore, the strategies of MSOs, producers, and customers are shown as (10)-(12), respectively.

$$\max_{\delta}\left(\Delta ES\right) \quad (10)$$

$$\max_{\delta}\left(\Delta PS + \Delta ES\right) \quad (11)$$

$$\max_{\delta}\left(\Delta CS + \Delta ES\right) \quad (12)$$

3. Optimal ESS Investment Strategy of ESOs as Price-takers

3.1 Under time-of-use tariff

Time-of-use (TOU) tariff provides pre-set differential rates by a pre-set time interval to reflect the price variability of the wholesale market to the retail market. The rates are designed by retailers and unaffected by demand changes. Therefore, the supply curves are modified in the model (Fig. 3).

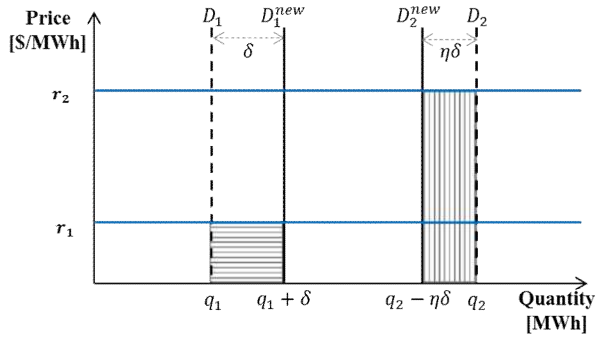

Fig. 3. Two-period model under TOU tariff

The changes in the welfare of customers and MSOs under TOU tariff are expressed as (13), (14), respectively.

$$\Delta CS = \int_{r_1}^{r_1} q_1 d\rho + \int_{r_2}^{r_2} q_2 d\rho = \mathbf{0} \quad (13)$$

$$\Delta ES = \{(\eta r_2 - r_1) - c_{ESS}\}\cdot\delta \quad (14)$$

In the retail market structure, end users and retailers are the customers and producers, respectively.

The optimal ESS investment strategy involves determining the capacity of ESS that maximizes the sum of a player's welfare change and the benefit of energy arbitrage.

Given that a retailer is the only electricity seller in the retail market, the profit from energy arbitrage using ESS, which is invested by the retailer, is same as the loss of sales. Therefore, retailers are not considered as ESS investors in retail markets in this study.

End users have the same ESS investment strategy as MSOs because no change occurs in the welfare of end users under the TOU tariff. The optimal ESS investment strategy for end users and MSOs is

$$\max_{\delta}\left(\Delta ES\right) = \max_{\delta}\left[\{(\eta r_2 - r_1) - c_{ESS}\}\cdot\delta\right]. \quad (15)$$

The rates of TOU tariff (r_1, r_2) do not vary with demand changes, and the charging/discharging coefficient (η) is a constant value. Thus, the optimal amount of ESS investment δ^* is determined by the storage cost factor (c_{ESS}) as follows:

$$\delta^* = \begin{cases} \infty, & if\ \eta r_2 - r_1 > c_{ESS}; \\ 0, & otherwise. \end{cases} \quad (16)$$

In other words, end users and MSOs install ESS as much as they can, when the ESS for energy arbitrage becomes profitable. Consequently, ESS investors can earn infinite

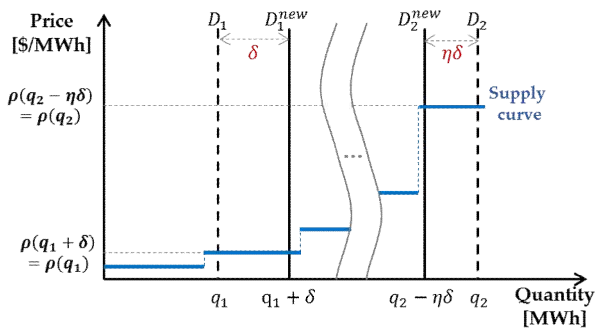

Fig. 4. Two-period model under SMP with the assumption that ESOs are price-takers

profit by energy arbitrage, whereas retailers lose infinitely.

To prevent tremendous losses, retailers design the level of rates so that the price difference between two periods does not exceed the cost of storing. Therefore, energy arbitrage trading using ESS in impossible in the retail market due to the retailers' rate design.

3.2 Under system marginal price

Many previous studies assumed that ESOs are price-takers because the changes in demand by ESS operation are considered insufficient to affect the electricity price. The modified supply curve is shown in Fig. 4.

Gencos and retailers can be customer and producer types of market participants in the wholesale market structure, respectively.

With the price-taker assumption, the welfare changes of each player can be shown as follows:

$$\Delta CS = (1-\omega)\left\{\left(\int_{\rho(q_1+\delta)}^{\rho(q_1)} q_1\, d\rho\right)+\left(\int_{\rho(q_2-\eta\delta)}^{\rho(q_2)} q_2\, d\rho\right)\right\} = \mathbf{0}\,, \quad (17)$$

$$\Delta PS = \int_{\rho(q_1)}^{\rho(q_1+\delta)} q(\rho)\, d\rho + \int_{\rho(q_2)}^{\rho(q_2-\eta\delta)} q(\rho)\, d\rho = \mathbf{0}\,, \quad (18)$$

$$\Delta ES = \left\{\left(\eta\rho(q_2)-\rho(q_1)\right)-c_{ESS}\right\}\cdot\delta\,. \quad (19)$$

The welfare of customers and producers does not change because energy arbitrage does not vary the electricity price. Therefore, all market participants have the same ESS investment strategies as the MSOs.

$$\max_{\delta}\left(\Delta ES\right) = \max_{\delta}\left[\left\{\left(\eta\rho(q_2)-\rho(q_1)\right)-c_{ESS}\right\}\cdot\delta\right]. \quad (20)$$

The optimal amount of ESS for energy arbitrage δ^* obtained from (20) is

$$\delta^* = \begin{cases} \infty, & if\ \eta\rho(q_2)-\rho(q_1) > c_{ESS}; \\ 0, & otherwise. \end{cases} \quad (21)$$

Similar to that in the TOU case, the optimal ESS investment value is determined by the price difference and parameters for ESS (η, c_{ESS}).

All market participants invest in ESS as much as they can when the ESS for energy arbitrage becomes profitable. However, infinite ESS investment is contrary to our assumption that ESOs are price-takers. In fact, the more energy arbitrage with ESS, the lower the arbitrage value because of price smoothing. ESS is invested until the value of energy arbitrage equals the cost of storing. Therefore, ESOs cannot be price-takers for energy arbitrage using ESS in the wholesale market structure.

4. Optimal ESS Investment Strategy Considering the Impacts of Energy Arbitrage on Market Price

4.1 Welfare impacts for market participants

The increase in ESS for energy arbitrage affects the prices of the electricity market. The price-smoothing effect not only reduces the value of energy arbitrage but also influence the welfare of market participants. The increase in electricity prices (due to increased demand) by ESS charging at low prices increases producer profits and decreases customer profits. ESS discharging at high prices exerts the opposite effect. Therefore, ESS investors determine the optimal amount of ESS by considering the benefits of energy arbitrage with their own ESS and their welfare changes by total ESS.

4.2 Optimal strategies by market structures

CASE 1: Vertically integrated market structure

The aim is to determine the optimal amount of ESS for a vertically integrated utility. The utility is both the producer and customer in the wholesale electricity market. Therefore, the optimal strategy for the utility is

$$\begin{aligned} &\max_{\delta}\left(\Delta CS+\Delta PS+\Delta ES\right) \\ &= \max_{\delta}\left[\left\{\left(A-C\right)-c_{ESS}\right\}\cdot\delta - B\cdot\delta^2\right], \end{aligned} \quad (22)$$

which yields the following optimum value

$$\delta^W = \begin{cases} \dfrac{(A-C)-c_{ESS}}{2B}, & if\ A-C > c_{ESS}; \\ 0, & otherwise. \end{cases} \quad (23)$$

Compared with that in [10], the costs of storing determine the optimal value. In addition, the optimal value is unaffected by risk-free contracts because the welfare gains from risk-free contracts for the customer are transferred from the producer's welfare losses.

Eq. (22) is also the strategy for maximizing social welfare which is the goal of policy makers and governors.

CASE 2: Competitive wholesale market: single-agent type n-player non-cooperative game

The optimal amount of ESS installation by sectors in the competitive wholesale market structure is determined.

When more than one player is present in each sector, the incentive for a player is affected by the other players' ESS investment in the same sector. We assume that in each sector, the players symmetrically own ESS and compete non-cooperatively. It is similar to the Cournot model, and we obtain the Nash equilibrium with game theory.

The different agents have their own investment strategies when the players in only one sector are allowed to invest in ESSs, and the rest of the players in the other sectors are not allowed to do so. We assume the presence of N MSOs, M producers, and Z customers. The strategies for MSO *i*, producer *j*, and customer *k* are expressed as (24)-(26), respectively.

$$\max_{\delta_i} \pi_S(\delta_i, \delta_{-i}) = \max_{\delta_i} \left\langle \begin{bmatrix} \eta\{c_0 + c_1(q_2 - \eta\delta_i - \eta\delta_{-i})\} \\ -\{c_0 + c_1(q_1 + \delta_i + \delta_{-i})\} - c_{ESS} \end{bmatrix} \cdot \delta_i \right\rangle \tag{24}$$

$$\begin{aligned} \max_{\delta_j} \pi_P(\delta_j, \delta_{-j}) &= \max_{\delta_j} \left\{ \pi_S(\delta_j, \delta_{-j}) + \frac{1}{M} \Delta PS(\delta_j, \delta_{-j}) \right\} \\ &= \max_{\delta_j} \begin{bmatrix} \begin{bmatrix} \eta\{c_0 + c_1(q_2 - \eta\delta_j - \eta\delta_{-j})\} \\ -\{c_0 + c_1(q_1 + \delta_j + \delta_{-j})\} - c_{ESS} \end{bmatrix} \cdot \delta_j \\ + \dfrac{1}{M} \begin{Bmatrix} c_1(q_1 - \eta q_2)(1-\omega)\cdot(\delta_j + \delta_{-j}) \\ + \dfrac{1}{2} c_1(1+\eta^2)\cdot(\delta_j + \delta_{-j})^2 \end{Bmatrix} \end{bmatrix} \end{aligned} \tag{25}$$

$$\begin{aligned} \max_{\delta_k} \pi_C(\delta_k, \delta_{-k}) &= \max_{\delta_k} \left\{ \pi_S(\delta_k, \delta_{-k}) + \frac{1}{Z} \Delta CS(\delta_k, \delta_{-k}) \right\} \\ &= \max_{\delta_k} \begin{bmatrix} \begin{bmatrix} \eta\{c_0 + c_1(q_2 - \eta\delta_k - \eta\delta_{-k})\} \\ -\{c_0 + c_1(q_1 + \delta_k + \delta_{-k})\} - c_{ESS} \end{bmatrix} \cdot \delta_k \\ + \dfrac{1}{Z} \{c_1(\eta q_2 - q_1)(1-\omega)\cdot(\delta_k + \delta_{-k})\} \end{bmatrix} \end{aligned} \tag{26}$$

where δ_i, δ_j, and δ_k are the capacity of storage owned by MSO *i*, producer *j*, and customer *k*, respectively; δ_{-i}, δ_{-j} and δ_{-k} are the capacity of storage owned by the rival firms of MSO *i*, producer *j*, and customer *k* in each sector, respectively.

The optimal values (Nash equilibria) of MSOs, producers, and customers are obtained as (27)-(29), respectively, by using the method used in [10] or by solving the problems formulated in the MCP form.

$$\delta^S = \begin{cases} \dfrac{N}{N+1} \dfrac{(A-C) - c_{ESS}}{2B}, & if\ A - C > c_{ESS}; \\ 0, & otherwise, \end{cases} \tag{27}$$

$$\delta^P = \begin{cases} \dfrac{\left(\dfrac{M+\omega-1}{M} A - C\right) - c_{ESS}}{2B}, & if\ \dfrac{M+\omega-1}{M} A - C > c_{ESS}; \\ 0, & otherwise, \end{cases} \tag{28}$$

$$\delta^C = \begin{cases} \dfrac{\left(\dfrac{Z-\omega+1}{Z} A - C\right) - c_{ESS}}{\dfrac{Z+1}{Z}\cdot 2B}, & if\ \dfrac{Z-\omega+1}{Z} A - C > c_{ESS}; \\ 0, & otherwise. \end{cases} \tag{29}$$

CASE 3: Competitive wholesale market: multi-agent type n-player non-cooperative game

We determine the optimal amount of ESS installation for players when all player can invest in ESS simultaneously in the competitive wholesale market structure.

Similar to that in CASE 2, the investment incentives are influenced not only by investors in the same sector but also by investors in other sectors. The strategies for MSO *i*, producer *j*, and customer *k* are expressed as (30)-(32), respectively.

$$\max_{\delta_i^S} \pi_S(\delta_i^S, \delta_{-i}^S) = \max_{\delta_i^S} \left\langle \begin{bmatrix} \eta\{c_0 + c_1(q_2 - \eta\delta_i^S - \eta\delta_{-i}^S)\} \\ -\{c_0 + c_1(q_1 + \delta_i^S + \delta_{-i}^S)\} - c_{ESS} \end{bmatrix} \cdot \delta_i^S \right\rangle \tag{30}$$

$$\begin{aligned} \max_{\delta_j^P} \pi_P(\delta_j^P, \delta_{-j}^P) &= \max_{\delta_j^P} \left\{ \pi_S(\delta_j^P, \delta_{-j}^P) + \frac{1}{M} \Delta PS(\delta_j^P, \delta_{-j}^P) \right\} \\ &= \max_{\delta_j^P} \begin{bmatrix} \begin{bmatrix} \eta\{c_0 + c_1(q_2 - \eta\delta_j^P - \eta\delta_{-j}^P)\} \\ -\{c_0 + c_1(q_1 + \delta_j^P + \delta_{-j}^P)\} - c_{ESS} \end{bmatrix} \cdot \delta_j^P \\ + \dfrac{1}{M} \begin{Bmatrix} c_1(q_1 - \eta q_2)(1-\omega)\cdot(\delta_j^P + \delta_{-j}^P) \\ + \dfrac{1}{2} c_1(1+\eta^2)\cdot(\delta_j^P + \delta_{-j}^P)^2 \end{Bmatrix} \end{bmatrix} \end{aligned} \tag{31}$$

$$\begin{aligned} \max_{\delta_k^C} \pi_C(\delta_k^C, \delta_{-k}^C) &= \max_{\delta_k^C} \left\{ \pi_S(\delta_k^C, \delta_{-k}^C) + \frac{1}{Z} \Delta CS(\delta_k^C, \delta_{-k}^C) \right\} \\ &= \max_{\delta_k^C} \begin{bmatrix} \begin{bmatrix} \eta\{c_0 + c_1(q_2 - \eta\delta_k^C - \eta\delta_{-k}^C)\} \\ -\{c_0 + c_1(q_1 + \delta_k^C + \delta_{-k}^C)\} - c_{ESS} \end{bmatrix} \cdot \delta_k^C \\ + \dfrac{1}{Z} \{c_1(\eta q_2 - q_1)(1-\omega)\cdot(\delta_k^C + \delta_{-k}^C)\} \end{bmatrix} \end{aligned} \tag{32}$$

where δ_i^S, δ_j^P, and δ_k^C are the capacity of storage owned by MSO *i*, producer *j*, and customer *k*, respectively;

$\delta_{-i}^{S}, \delta_{-j}^{P}$ and δ_{-k}^{C} are the total capacity of storage owned by the firms except for MSO i, producer j, and customer k, respectively.

To determine the Nash equilibrium of each player's ESS investment game, we formulate the models as MCP, which consists of first-order necessary conditions (FONC) and complementarity conditions. The FONCs and complementary conditions of MSO, producer, and customer are expressed as (33)-(35), respectively.

$$(A-C)-2B\cdot\left(\frac{Z+1}{Z}\delta^{S}+\delta^{P}+\delta^{C}\right)-c_{ESS}+\lambda^{S}=0 \quad \lambda^{S}\geq 0 \perp \delta^{S}\geq 0, \tag{33}$$

$$\left(\frac{M+\omega-1}{M}\cdot A-C\right)-2B\cdot\left(\frac{M-1}{M}\delta^{S}+\delta^{P}+\frac{M-1}{M}\delta^{C}\right)-c_{ESS}+\lambda^{P}=0 \quad \lambda^{P}\geq 0 \perp \delta^{P}\geq 0, \tag{34}$$

$$\left(\frac{N-\omega+1}{N}\cdot A-C\right)-2B\cdot\left(\delta^{S}+\delta^{P}+\frac{N+1}{N}\delta^{C}\right)-c_{ESS}+\lambda^{C}=0 \quad \lambda^{C}\geq 0 \perp \delta^{C}\geq 0, \tag{35}$$

where λ^{S}, λ^{P}, and λ^{C} are the Lagrangian multipliers associated with MSOs, producers, and customers' lower bound constraints, respectively; δ^{S}, δ^{P}, and δ^{C} are the total amount of ESS owned by MSOs, producers, and customers, respectively.

5. Numerical Studies

Numerical studies are conducted to determine the optimal amount of ESS for energy arbitrage by market participants in various market structures. The impact of market parameters (supply and demand curve) and ESS parameters (efficiency and cost) on the optimal values is analyzed. The reference values of each parameter are shown in Table 2.

In the market parameters, c_0 and c_1 are obtained by using the relationship between SMP and hourly demand data measured in Korea in the winter of 2011; q_1 and q_2 are values based on daily on-/off-peak demands in the same period. The ESS parameter, η, is conservatively applied with reference to the value from 0.90 to 0.98 for Li-ion battery systems in [12]. Given that the current cost of ESS is high, the cost of storing, c_{ESS}, is assumed for the numerical studies.

Table 2. Value of market and ESS parameters.

Parameters		Value	Unit
Market parameters	c_0	19000	[KRW/MWh]
	c_1	2.2	[KRW/MWh^2]
	q_1	50,000	[MWh]
	q_2	70,000	[MWh]
ESS parameters	η	0.9	[pu]
	c_{ESS}	10,000	[KRW/MWh]

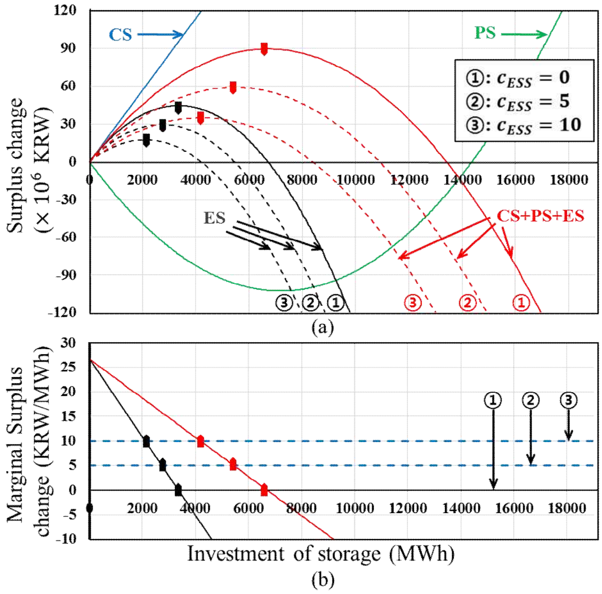

Fig. 5. Welfare changes in CASE 1 according to the amount of ESS for energy arbitrage by the costs of storing: (a) welfare changes, and (b) marginal welfare changes

CASE 1: Vertically integrated market structure

From (22) and (23), the optimal ESS investment for vertically integrated utility, δ^{W}, is around 4.19 [GWh], and the total profit is 35,018,834.76 [KRW] with the parameters from Table 2. This is the optimal value for maximizing the social welfare, as described in Section 4.2.

Fig. 5(a) shows the changes in the welfare of market participants according to the amount of ESS investment. The curves for the utility company are represented by red lines, which are the sum of the surplus of customers, producers, and storage owners. The changes in the costs of storing, c_{ESS}, affect the welfare of storage owners and thereby affect the utility strategies as shown in the figure. Fig. 5(b) shows the marginal welfare changes of the utility company (red line) and storage owners (black line), and the optimal values are determined when the marginal values and the storing costs are equal. Because the marginal surplus change of the utility company at the beginning of the investment is 26.7 [KRW] from (23), which is the price difference considering ESS efficiency, the utility company starts to invest in ESS when the storing costs start to fall below 26.7 [KRW].

CASE 2: Competitive wholesale market: single-agent type n-player non-cooperative game

We obtain the optimal ESS investment by market participants when the players in only one sector are allowed to invest in ESS, and the rest of the players in the other sectors are not allowed to do so.

When each sector is monopolistic (N=1, M=1, and Z=1), the optimal investments of the MSO, producer, and customer are around 5.69 [GWh], -2.99 [GWh], and 2.10

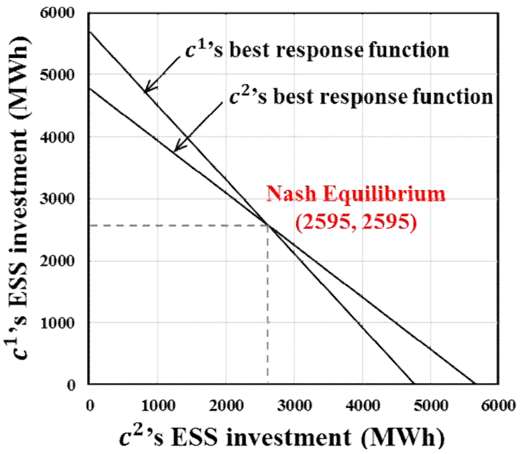

Fig. 6. Best response functions and Nash equilibrium of two customers' non-cooperative game for CASE 2

Table 3. Total optimal amounts of ESS investment by each sector by the number of market participants (ω=0).

ESS cap. (MWh)	Number of players (N, M, Z)				
	1	2	10	100	∞
δ^S	2,097	2,796	3,813	4,152	4,194
δ^P	-2,988	603	3,476	4,122	4,194
δ^C	5,688	5,190	4,466	4,223	4,194
δ^W	4,194				

[GWh], respectively. The negative value of the producer's optimum means that the producer installs 2.99 [GWh] of ESS and operates it in the opposite way to the proposed operation strategy in Section 2.2. However, the value should be interpreted as zero because in the assumption, the value of ESS investment is positive. Moreover, the results are the same with the optimal results of collusion by more than one player in each sector.

The market participants modify their investment strategies by considering other players' investment when more than one player exists in each sector. For example, for a customer, changes in prices are affected not only by the ESS invested by the customer, but also by the ESS invested by another, and the customer's demand is reduced by sharing with other players. The total amount of optimal ESS investment is thus different from the values of the monopolistic case. The players' non-cooperative investment strategies can be described as the Nash equilibrium with the best response functions of two symmetric customers, c^1 and c^2, as shown in Fig. 6.

The Nash equilibria for the MSO and producer can also be obtained in a similar manner.

The total optimal amounts of ESS investment by each sector according to the number of market participants from (27)-(29) are tabulated in Table. 3.

Compared with the result for social welfare maximization (δ^W) from CASE 1, customers over-invest in ESS while MSOs and producers under-invest in ESS, and as the number of players increases, the players' investment converges to the result of the social optimum, as proven in [10]. This is because when the number of players becomes infinite, the external effects of customers and producers converge to zero.

We also analyzed the impact the risk-free contracts on investment strategies of the market participants (Fig. 7).

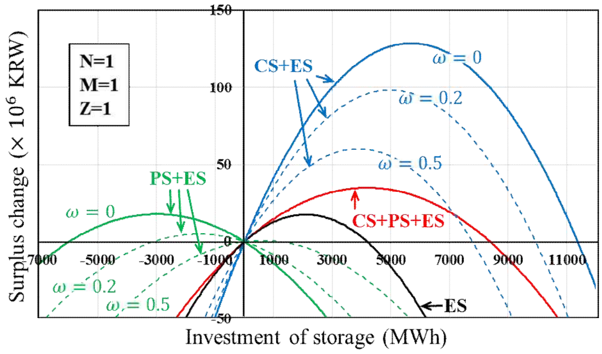

Fig. 7. Impacts of risk-free contracts on surplus of investors

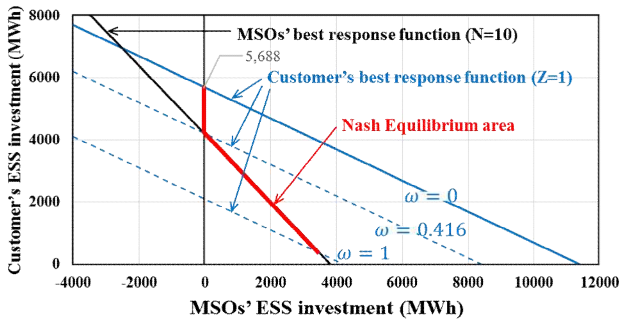

Fig. 8. Best response functions of a customer and ten symmetric MSOs and their Nash equilibria according to risk-free contracts when δ^{MP} is fixed as zero

As the risk-free contracts increase, the optimal amount of ESS investment of customers decreases while the producers' investment approaches the social optimum. This is because the volume of customer's demand and producers' generation traded in the electricity market, which is affected by price changes, decreases. This is similar to the effects of the increase in participants, except that MSOs do not change their strategies according to the risk-free contracts.

CASE 3: Competitive wholesale market: multi-agent type n-player non-cooperative game

The problems in (33) to (35) are modeled in MCP form and solved with PATH solver in GAMS [13, 14].

The optimal results of the total ESS investment of ten symmetric MSOs, six symmetric producers, and a customer are 0[GWh], 0[GWh], and 5.69[GWh], respectively, and the profits are 0[KRW], -98,260,000 [KRW], and 128,840,000 [KRW], respectively. In other words, only the customer invests in ESS, and significant welfare is transferred from the producers to the customer. This is because the only customer gains not only energy arbitrage profit from the ESS the customer invested in, but also a huge external benefit caused by changes in electricity prices. In addition, it enables customers to exercise their market power, which is generally considered on the generation side, by operating their ESS.

Fig. 8 shows the customer's and ten symmetric MSOs' best response functions and their Nash equilibria when the value of producers' investment is fixed as zero.

Given that the value of Nash equilibrium is negative for MSOs when no risk-free contract exist, the optimal investment result is determined at 5.69 [GWh] of the customer's optimum when the MSOs' investment is 0.

The optimal amount of ESS investment varies depending on the amount of risk-free contracts, and we highlight the Nash equilibrium area with a bold red line. When the amount of power traded through risk-free contracts is more than 41.6% of the total demand, MSOs start investing in ESS for energy arbitrage, which can lower the market power of customers.

6. Conclusion

We analyzed the impacts of ESS for energy arbitrage on the changes in the welfare of market participants and determined the optimal amount of ESS investment for three types of ESS investors in different market structures by using the two-period model that we modified.

We applied the model to retail and wholesale market structures under TOU tariff and SMP, respectively, with the assumption that ESOs are price-takers. In the retail market, energy arbitrage using ESS is impossible because the retailers redesign the rate of the tariff to make the energy arbitrage unprofitable. Otherwise, end users and arbitragers invest an unlimited amount in ESS, and retailers experience significant loss. Similar to the case in the retail market, in the wholesale market structure, all market participants will invest in ESS infinitely once the ESS becomes economical, which is contrary to the assumption.

When the prices of electricity begin to change by energy arbitrage using ESS, the value of energy arbitrage is reduced, and the welfare of market participants changes due to the external effects of energy arbitrage. Each market participant is incentivized differently to invest in ESS.

Through numerical studies, we obtain the optimal ESS investment strategies for three types of investors in three different market structures. The optimal amounts of ESS investment are determined by the ratio of risk-free contracts to total demand and the costs of storing. When more than two players exist in the same sector, the players non-cooperatively compete. Compared with the case that maximizes social welfare, the case when the players in only one sector are allowed to invest in ESS, the customers tend to over-invest in ESS, whereas the MSOs and producers under-invest in ESS. In addition, when every player can invest in ESS at the same time in the competitive wholesale market structure (which is simulated reflecting Korean circumstances), only the customers are willing to invest in ESS. This study confirms that significant welfare is transferred from the producers to the customers, and customers are able to to exercise market power by operating ESS. We conclude that an increase in risk-free contracts encourages other market participants to invest in ESS, which reduce customers' market power.

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