# A framework for the management of distributed energy resources to address the imbalance between electricity supply and demand based on social welfare maximisation


**Tamaki Yamazaki[1], Hirotaka Takano[1], Hiroshi Asano[1] and Nguyen Duc Tuyen[2]**

[1] Department of Electrical, Electronic and Computer Engineering, Gifu University, Japan

[2] Department of Electrical Engineering, Hanoi University of Science and Technology, Vietnam



## ABSTRACT

The authors propose a calculation method of parameters to manage distributed energy resource (DER). The proposed method takes into account the balance between power supply and demand. This paper, first, formulates the power transaction between retail electricity suppliers, especially those with the function of energy resource aggregators, and their customers under a framework of social welfare maximisation (SWM). In theory, the customers consume electricity to maximise their economic surplus under given retail electricity prices. The SWM framework enables us to measure the value of changes in the customers' surplus resulting from cooperation in the DER management. On the basis of this characteristic, second, the authors derive rebate levels as the parameters in the DER management. The authors' proposal benefits both the retailers and the customers.



**KEYWORDS** Imbalance between electricity supply and demand; distributed energy resources; incentive-based demand response programmes; rebate levels; social welfare maximisation.



**CONTACT** Hirotaka Takano takano.hirotaka.p3@f.gifu-u.ac.jp



Received 27 February 2024


## 1. Introduction

Retail electricity suppliers, in Japan, are required to notify power transmission and distribution companies (T&Ds) of their electricity supply schedules for each 30-minute period. The retailers must hand in the schedules at least one day before the actual balancing operation of electricity supply and demand. The notified values of the electricity supply can be updated up to one hour before the actual balancing operation. The retailers then have to procure the latest notified electricity from power generation companies and electric power markets. During the actual balancing operation, the T&Ds are responsible for maintaining the balance of power supply and demand in electric power grids. For the adjustment, the retailers must pay an extra charge to make up for the difference between the notified electricity and the actual electricity consumption (Furuta and Matsuhashi, 2019; Ministry of Economy, Trade, and Industry [METI], 2022). This extra charge is the imbalance settlement. This is why the electricity imbalance not only degrades the reliability in the power grids, but also has a negative economic impact on the retailers.

In recent years, the management of distributed energy resources (DERs) has attracted attention as a solution to lessen the negative impacts of the electricity imbalance. A DER is a small-scale resource of electricity connected to the power grids. The management of DERs facilitates the further penetration of renewable energy-based generations, saves power consumption, and improves the flexibility in the power grids (Newcomb et al., 2013). Energy resource aggregators aggregate the DERs from various participants in electric power markets (e.g., small-scale power producers and power consumers) as the resources for balancing power supply and demand (Hansen et al., 2015; Kerscher and Arboleya, 2022).

Power consumption is a key element of the DERs and can be aggregated under the framework of a demand response (DR) programme. A DR programme is a framework that manages power consuming patterns by changing retail electricity prices or giving monetary rebates for DR cooperation (U.S. Department of Energy, 2006). The former is a price-based DR programme, and the latter is an incentive-based DR programme. In Japan, the primary focus of the DER management is the incentive-based DR programme to address the electricity imbalance. This is because the incentive-based DR programmes are available even after the retailers have decided the electricity supply schedules. However, how to set the rebate level, which is the unit price of the rebate, as the parameter in the DER management is still under discussion (Takano et al., 2022). The rebate level should be set as the retailers can gain their customers' cooperation for the DR request.

This paper thus presents a calculation method for the optimal rebate level in the incentive-based DR programme. The proposed DER management is designed for retailers, encompassing the functions of aggregators, to manage their customers' electricity consumption. In this paper, such retail electricity suppliers are referred to as RES-AGs. Section 2 formulates the power transaction between the

RES-AGs and their customers under the balancing operation in Japan. The formulation is based on the framework of social welfare maximisation (SWM). The SWM framework has traditionally been used to represent the models of electric power markets (Sorin et al., 2018; Yan et al., 2013; Zou, 2009). Section 3 presents how to design incentive-based DR programmes to manage the DERs. In theory, customers consume electricity to maximise their economic surplus. The SWM problem formulated in this paper makes it possible to measure the value of changes in the customers' surplus resulting from cooperation in the DER management. That is, by referring to the measured value, the RES-AGs can induce their customers' electricity consumption to the target one in the DER management. Based on these characteristics, the authors derive the optimal rebate level that maximises the total surplus of the RES-AGs and their customers while recovering the decrease in the customers' surplus. Sections 4 and 5 show the results of numerical simulations and validate the authors' proposal.

## 2. Formulation of power transaction under the framework of social welfare maximisation

The SWM framework enables us to formulate the problem of maximising the total surplus of the members of society. In this paper, the RES-AGs and their customers are the members of society, and the sum of their surplus is defined as social surplus.

One hour before the actual balancing operation, the RES-AGs decide how much they procure electricity and notify its value to the T&Ds. The RES-AGs then purchase the notified electricity from the power generation companies and electric power markets. The RES-AGs must also pay wheeling charges to the T&Ds. Hence, the surplus of RES-AGs complying with the balancing regulation is calculated by the difference between the revenue from selling electricity to their customers and the above expenses as follows:

$$RS_0(\hat{s}_{0,t}) = (p_t^* - w_t^*)\hat{s}_{0,t} - C(\hat{s}_{0,t}) \,, \tag{1}$$

where $t$ is the time slot, $RS_0(\cdot)$ is the RES-AGs' surplus function if the electricity supply and demand are balanced, $\hat{s}_{0,t}$ is the notified electricity, $p_t^*$ is the contracted retail electricity price, $w_t^*$ is the wheeling price, and $C(\cdot)$ is the function of electricity procurement cost.

If the RES-AGs are unable to procure electricity that is equivalent to the actual electricity consumption, they must settle the imbalance charges with the T&Ds. Figure 1 illustrates the power transaction without any countermeasures against the electricity imbalance. The surplus of the RES-AGs is then as follows:

$$RS(d_t^*) = (p_t^* - w_t^*)d_t^* - C(\hat{s}_{0,t}) - I(d_t^*) \,, \tag{2}$$

where $RS(\cdot)$ is the RES-AGs' surplus function, $d_t^*$ is the actual electricity consumption, and $I(\cdot)$ is the function of the imbalance charge.

The surplus of customers can be considered as the difference between the utility obtained in exchange for power consumption and the electricity payment, which is paid to the RES-AGs. That is, the customers' surplus and the resulting social surplus are represented as Equations (3) and (4), respectively.

$$CS(d_t^*) = U(d_t^*) - p_t^* d_t^* \,, \tag{3}$$

$$SS(d_t^*) = RS(d_t^*) + CS(d_t^*) \,, \tag{4}$$

where $CS(\cdot)$ is the customers' surplus function, $U(\cdot)$ is the customers' utility function, and $SS(\cdot)$ is the function of social surplus.

When $RS(d_t^*)$ in Equation (2) is less than $RS_0(\hat{s}_{0,t})$ in Equation (1), the surplus of the RES-AGs is less than their surplus expected in the scheduling phase. This paper discusses how to coordinate the electricity consuming patterns to lessen the decrease in the RES-AGs' surplus while contemplating the impacts of the DER management on the customers.

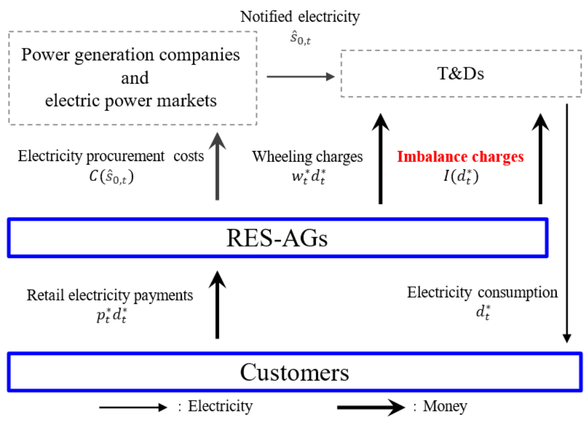


Figure 1. Power transaction without measures against the imbalance between electricity supply and demand.

## 3. Design method of management of distributed energy resources

### *3.1. Purpose of managing power consumption*

If the RES-AGs require their customers to cooperate with an incentive-based DR programme, the RES-AGs must compensate the customers for any negative economic impacts with rebates. Figure 2 shows the power transaction with the DER management, and each surplus in Figure 2 is calculated as follows:

$$RS_1(d_t) = (p_t^* - w_t^*)d_t - C(\hat{s}_{0,t}) - I(d_t) - R(r_t', d_t)\,, \quad (5)$$

$$\widehat{CS}_1(d_t) = \hat{U}_1(d_t) - p_t^* d_t + R(r_t', d_t)\,, \quad (6)$$

$$R(r_t, d_t) = \begin{cases} r_t(\hat{d}_{1,t} - d_t), & \hat{d}_{1,t} > d_t' \\ -r_t(\hat{d}_{1,t} - d_t), & \hat{d}_{1,t} < d_t' \end{cases}, \quad (7)$$

where $RS_1(\cdot)$ is the RES-AGs' surplus function with the DER management, $d_t$ is the electricity consumption, $R(\cdot)$ is the function of the rebate, $r_t'$ is the optimal rebate level defined in this paper, $\widehat{CS}_1(\cdot)$ is the customers' surplus function estimated by the RES-AGs when they request the incentive-based DR programme, $\hat{U}_1(\cdot)$ is the function of estimated customers' utility when the RES-AGs request the incentive-based DR programme, $r_t$ is the rebate level, $\hat{d}_{1,t}$ is the electricity consumption estimated by the RES-AGs when they request the incentive-based DR programme, and $d_t'$ is the target electricity consumption in the DER management.

An increase in the social surplus owing to the DER management can be expected as follows:

$$\Delta\widehat{SS}_{1,t} = \widehat{SS}_1(d_t) - \widehat{SS}_1(\hat{d}_{1,t})\,, \quad (8)$$

$$\widehat{SS}_1(d_t) = RS_1(d_t) + \widehat{CS}_1(d_t)\,, \quad (9)$$

where $\Delta\widehat{SS}_{1,t}(\cdot)$ is the function of the increase of the social surplus owing to the DER management expected when the RES-AGs request the incentive-based DR programme, and $\widehat{SS}_1(\cdot)$ is the function of the social surplus with the DER management expected when the RES-AGs request the incentive-based DR programme.

When the RES-AGs manage the DER to maximise the social surplus, the target electricity consumption in the DER management can be obtained by solving the following problem.

$$\max_{d_t} \Delta\widehat{SS}_{1,t}\,. \quad (10)$$

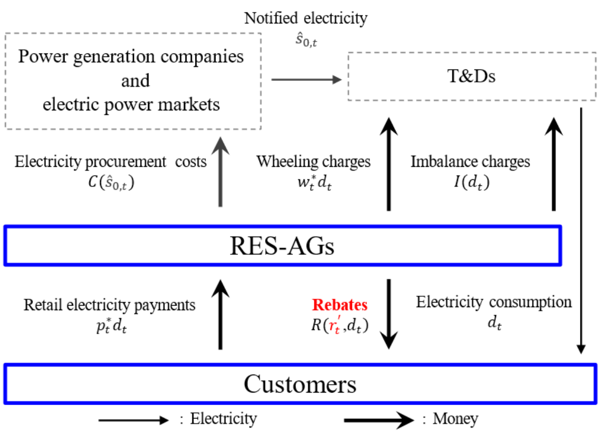


Figure 2. Power transaction under the incentive-based DR programme.

### *3.2. Calculation method of rebate levels*

The RES-AGs must set the rebate level as the parameter in the DER management. Customers, in theory, consume electricity to maximise their surplus, and the cooperation under the incentive-based DR programme decreases their surplus. To compensate for this negative economic impact, the RES-AGs must pay back at least the decreases as rebates.

The RES-AGs need to change the customers' surplus function by setting the rebate level so that the function can be maximised at the target electricity consumption. This condition is represented as:

$$\frac{\partial \widehat{CS}_1(d_t)}{\partial d_t}\Big|_{d_t = d_t'} = 0\,. \quad (11)$$

From Equation (11), we can derive a rebate level that can adequately reward the customers as

$$r_t' = \begin{cases} \frac{\partial \hat{U}_1(d_t)}{\partial d_t}\Big|_{d_t=d_t'} - p_t^*, & \hat{d}_{1,t} > d_t' \\ p_t^* - \frac{\partial \hat{U}_1(d_t)}{\partial d_t}\Big|_{d_t=d_t'}, & \hat{d}_{1,t} < d_t' \end{cases}. \quad (12)$$

The authors define $r_t'$ of Equation (12) as the optimal rebate level in the DER management. By substituting the target electricity consumption into Equation (12), we can obtain the optimal rebate level that maximises the social surplus.

## 4. Numerical simulations

### *4.1 Numerical simulation conditions*

This section presents numerical simulation results for the worst-case economic impact for the RES-AGs caused because of an electricity imbalance, mainly using data in fiscal year (FY) 2017. The actual electricity consumption was the sum of 500 households' usage measured by smart meters. In the numerical simulations, the rebate baseline $\hat{d}_{1,t}$ was replaced by the actual electricity consumption as follows:

$$\hat{d}_{1,t} = d_t^*\,. \quad (13)$$

Table 1 tabulates the rebate baseline and notified electricity, and Figure 3 displays their profiles. Based on the standard baseline (METI, 2020), the notified electricity was set as:

$$\hat{s}_{0,t} = A_t + B_t\,, \quad (14)$$

$$A_t = \frac{\sum_{x=1}^{X} q_{x,t}}{X}\,, \quad (15)$$

$$B_t = \frac{\sum_{\tau=m}^{m+n-1}(d_\tau^* - A_\tau)}{n}\,, \quad (16)$$

where $A_t$ is the electricity consumption estimated by the method called High X of Y, $B_t$ is the adjustment term in the standard baseline, $x$ is the descending rank (1, 2, ..., $X$, ..., $Y$), $q_{x,t}$ is the actual electricity consumption at the same time slot over the past Y days, $m$ is the oldest time slot used to calculate $B_t$, and $n$ is the number of time slots used to calculate $B_t$.

Table 1. Rebate baseline and notified electricity.

| | $\hat{s}_{0,t} < \hat{d}_{1,t}$ | $\hat{s}_{0,t} > \hat{d}_{1,t}$ |
|---|---|---|
| Date | 5 February 2018 | 4 March 2018 |
| Time period | 6:00pm to 6:30pm | 8:30am to 9:00am |
| Rebate baseline (kWh) | 254.92 | 120.02 |
| Notified electricity (kWh) | 233.86 | 154.67 |

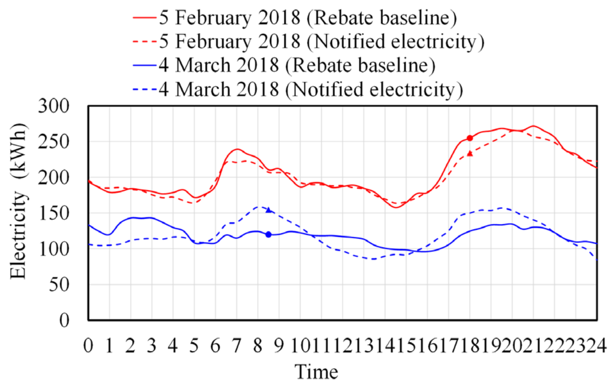


Figure 3. Profiles of rebate baseline and notified electricity.

The functions of the electricity procurement cost and the imbalance charge were set as:

$$C(s_t) = c_t^* s_t \,, \tag{17}$$

$$I(d_t) = \begin{cases} i_t^-(d_t - \hat{s}_{0,t}), & \hat{s}_{0,t} < d_t \\ i_t^+(d_t - \hat{s}_{0,t}), & \hat{s}_{0,t} > d_t \\ 0 & , \hat{s}_{0,t} = d_t \end{cases} , \tag{18}$$

where $s_t$ is the electricity procured by the RES-AGs, $c_t^*$ is the unit price of the electricity procurement cost, $i_t^-$ is the unit price of the imbalance charge for electricity shortage–the so-called negative imbalance price-and $i_t^+$ is the unit price of the imbalance charge for excess electricity–the so-called positive imbalance price.

The authors assumed that the RES-AGs procure the notified electricity only from Japan Electric Power eXchange (JEPX). To be exact, the unit price of the electricity procurement cost is the weighted average price of the spot market price and the intraday market price. However, for simplicity, the unit price of the electricity procurement cost $c_t^*$ was assumed to be the area price, which is the regional spot market price.

The imbalance prices were calculated using the method specified by METI until the end of March 2022 (METI, 2022).

$$i_t^- = \mu a + b + K \,, \tag{19}$$

$$i_t^+ = \mu a + b + L \,, \tag{20}$$

where $\mu$ is the weighted average price of the spot market price and the intraday market price, $a$ is the adjustment coefficient in accordance with power supply and demand, $b$ is the adjustment constant that reflects regional differences, $K$ is the constant as an economic incentive for electricity shortage, and $L$ is the constant as an economic incentive for excess electricity.

Table 2 tabulates the area prices and the imbalance prices calculated using the data that had been published by JEPX. Figure 4 shows the profiles of the market prices.

The wheeling price during the calculation period was set at 8.65 JPY/kWh, which had been reported by METI.

The acceptable range of the retail price that the RES-AGs set was designed as:

$$\bar{C} + \bar{W} \leq p_t \leq \bar{P} \,, \tag{21}$$

where $\bar{C}$ is the average area price, $\bar{W}$ is the average wheeling price of the low-voltage power service, $p_t$ is the retail price, and $\bar{P}$ is the average retail price in Japan.

In the numerical simulations, the average value of the upper and lower prices in Condition (21), which was 21.08 JPY/kWh, was set as the retail price $p_t^*$ during the calculation period.

Based on Takano et al. (2021), the function of customers' utility $U(\cdot)$ was formulated as:

$$U(d_t) = \alpha_t \log(\beta_t(d_t - \gamma_t)) \,, \tag{22}$$

where $\alpha_t$, $\beta_t$, and $\gamma_t$ are the coefficients of $U(\cdot)$.

In this paper, the coefficients $\alpha_t$, $\beta_t$, and $\gamma_t$ were derived by using the price elasticity of demand. The price elasticity measures how responsive the quantity demanded is for a change in prices (Mankiw, 2016) and is expressed as:

$$e(p_t) = \frac{\partial d_t}{\partial p_t} \frac{p_t}{d_t} \,, \tag{23}$$

where $e(\cdot)$ is the function of the price elasticity of demand.

To find the relationship between the retail price and the electricity consumption in the power transaction, the customers' surplus function was replaced as:

$$CS(p_t, d_t) = \alpha_t \log(\beta_t(d_t - \gamma_t)) - p_t d_t \,. \tag{24}$$

Rational customers consume electricity so that they can maximise their surplus in response to the given retail price. That is, Equation (25) can be obtained from Equation (26).

$$d_t = \frac{\alpha_t}{p_t} + \gamma_t \, , \tag{25}$$

$$\frac{\partial CS(p_t, d_t)}{\partial d_t} = 0 \, . \tag{26}$$

Equations (23) and (25) allow us to define the coefficients $\alpha_t$ and $\gamma_t$. In addition, the customers' utility can be represented as Equation (27) by integrating the marginal utility, expressed as Equation (28).

$$U(d_t) = \alpha_t \log(d_t - \gamma_t) + M, \ d_t > \gamma_t \, , \tag{27}$$

$$\frac{\partial U(d_t)}{\partial d_t} = \frac{\alpha_t}{d_t - \gamma_t} \, , \tag{28}$$

where $M$ is the constant of integration.

Marginal utility is the increase in utility that customers gain from an additional unit of goods and services (Mankiw, 2016). Here, if $(d_t \leq \gamma_t)$, the power transaction cannot be realised. The customers' surplus is then zero.

From Equations (22) and (27), the constant of integration $M$ is defined as:

$$M = \alpha_t \log \beta_t \, . \tag{29}$$

We can obtain the coefficient $\beta_t$ from Equation (30) because the customers' surplus function is a continuous function.

$$0 = \alpha_t \log(\underline{d}_t - \gamma_t) + \alpha_t \log \beta_t - p_t^* \underline{d}_t \, , \tag{30}$$

where $\underline{d}_t$ is the lower bound of electricity consumption.

In the numerical simulation models, Equation (31) holds because of the assumption in Equation (13).

$$\hat{U}_1(d_t) = U(d_t) \, . \tag{31}$$

Table 2. Electric power market prices.

| | $\hat{s}_{0,t} < \hat{d}_{1,t}$ | $\hat{s}_{0,t} > \hat{d}_{1,t}$ |
|---|---|---|
| Date | 5 February 2018 | 4 March 2018 |
| Time period | 6:00pm to 6:30pm | 8:30am to 9:00am |
| Area price (JPY/kWh) | 49.10 | 8.63 |
| Imbalance price for electricity shortage (JPY/kWh) | 70.54 | 5.01 |
| Imbalance price for excess electricity (JPY/kWh) | 69.35 | 3.82 |

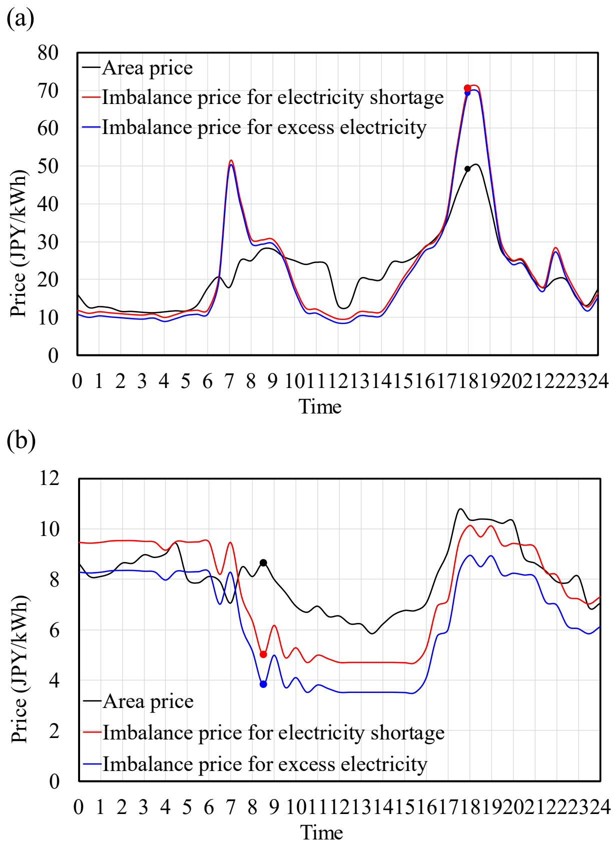


Figure 4. Profiles of electric power market prices: (a) 5 February 2018; and (b) 4 March 2018.

### *4.2. Numerical simulation results*

Figure 5 shows the ratios of the reduction or increase in the electricity consumption owing to the DER management relative to the rebate baseline. The price elasticity at the trading point $e(p_t^*)$ was changed per 0.1 from -1.0 to -0.1. With the change in the price elasticity, the ratios of the reduction from 6:00pm to 6:30pm on 5 February 2018 were from 7.34% (reduction of 18.71 kWh) to 72.97% (reduction of 186.03 kWh). In contrast, the ratios of the increase from 8:30am to 9:00am on 4 March 2018 were from 6.90% (increase of 8.29 kWh) to 54.32% (increase of 65.19 kWh).

Figure 6 shows the optimal rebate levels to maximise the social surplus. The optimal rebate levels from 6:00pm to 6:30pm on 5 February 2018 were calculated in the range from 56.92 JPY/kWh to 58.11 JPY/kWh. From 8:30am to 9:00am on 4 March 2018, on the other hand, the optimal rebate levels were calculated in the range from 7.42 JPY/kWh to 8.61 JPY/kWh.

In this and the next paragraphs, the authors show the results when the price elasticity $e(p_t^*)$ was assumed to be -0.2. Table 3 shows the increase in the social surplus owing to the DER management and its division into the RES-AGs and their customers. As shown in Table 3, the proposed DER management contributed to increasing the social surplus. Moreover, there was no negative economic impact on the RES-AGs and the customers.

Figure 7 compares the customers' surplus functions whether the RES-AGs managed the DER. From Table 3 and Figure 7, it can be confirmed that the electricity consumption that maximises the customers' surplus function was changed from the rebate baseline to the target electricity consumption by the DER management.

From these results, the authors concluded that the authors' proposal could increase the social surplus and lessen the negative economic impact of the electricity imbalance on the RES-AGs.

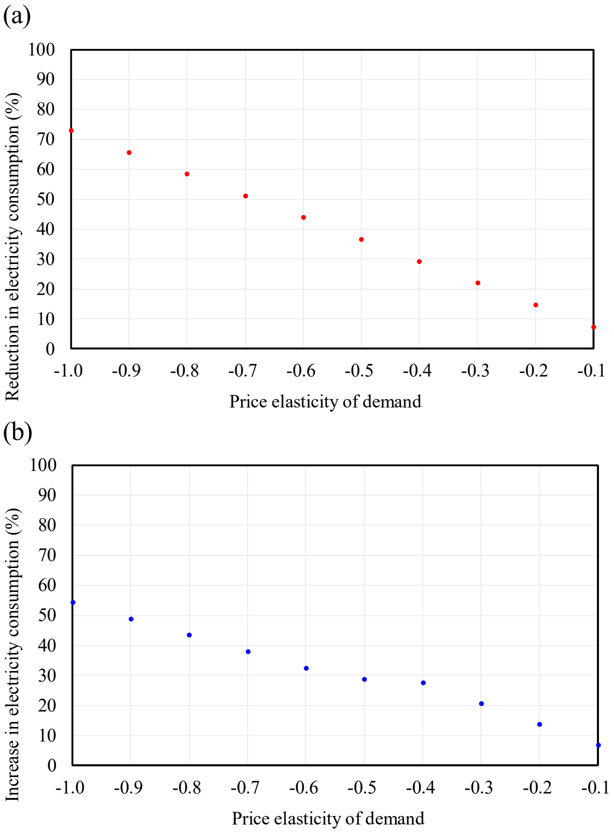


Figure 5. Ratios of reduction or increase in electricity consumption owing to DER management: (a) From 6:00pm to 6:30pm on 5 February 2018; and (b) From 8:30am to 9:00am on 4 March 2018.

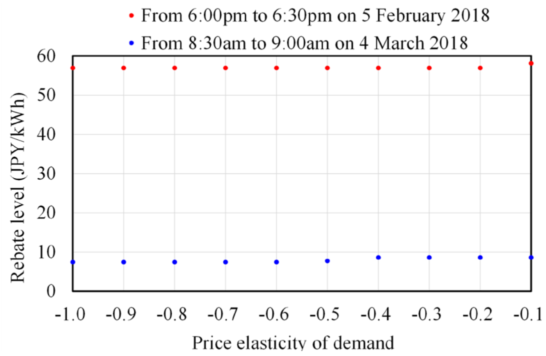


Figure 6. Optimal rebate levels.

Table 3. Increase in surplus owing to DER management ($e(p_t^*) = -0.2$).

| | $\hat{s}_{0,t} < \hat{d}_{1,t}$ | $\hat{s}_{0,t} > \hat{d}_{1,t}$ |
|---|---|---|
| Date | 5 February 2018 | 4 March 2018 |
| Time period | 6:00pm to 6:30pm | 8:30am to 9:00am |
| Rebate level (JPY/kWh) | 56.92 | 8.61 |
| Rebate baseline (kWh) | 254.92 | 120.02 |
| Target electricity consumption (kWh) | 217.72 | 136.59 |
| Increase in social surplus (JPY) | 1520.89 | 58.98 |
| Increase in RES-AGs' surplus (JPY) | 25.11 | 0.00 |
| Increase in customers' surplus (JPY) | 1495.78 | 58.98 |

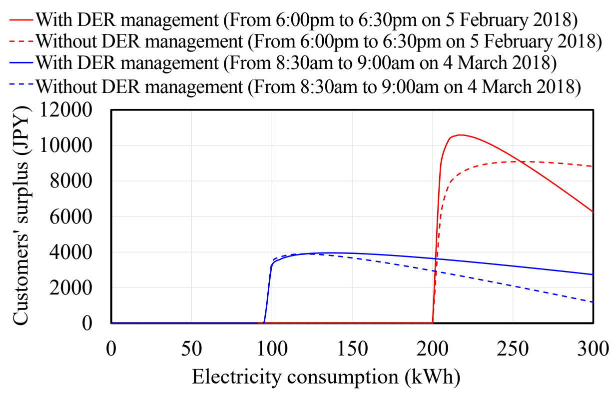


Figure 7. Comparison of customers' surplus functions whether RES-AGs managed DER ($e(p_t^*) = -0.2$).

### 4.3. *Discussion of the numerical simulation results*

In Subsection 4.2, the authors concluded that the proposal functioned well. However, the results also show that the RES-AGs can intentionally cause the electricity imbalance to maximise the social surplus. For example, from 6:00pm to 6:30pm on 5 February 2018, the excess electricity of 16.15 kWh remained if the RES-AGs maximised the social surplus by the DER management. From 8:30am to 9:00am on 4 March 2018, the excess electricity of 18.08 kWh remained if the RES-AGs maximised the social surplus by the DER management.

Table 4 tabulates the social surplus if the RES-AGs managed the DER or not, and if they could procure the actual electricity consumption precisely. Now, suppose that we calculate the surplus of the RES-AGs when the ideal power transaction is realised as:

$$RS_0(d_t^*) = (p_t^* - w_t^*)d_t^* - C(d_t^*) \ . \tag{32}$$

As shown in Table 4, from 6:00pm to 6:30pm on 5 February 2018, the power transaction with the DER management was more beneficial than the ideal power transaction. In other words, society was better off causing the electricity imbalance from the perspective of the social surplus. From 8:30am to 9:00am on 4 March 2018, the propensity of the results was also observed when the customers were more elastic in relation to a change in prices.

Figure 8 displays the frequency distributions of the ratio of the electricity imbalance relative to the notified electricity for all dates and times in FY 2017. The ratio was calculated from Equation (33).

$$(\hat{s}_{0,t} - d_t)/\hat{s}_{0,t} \ . \tag{33}$$

As shown in Figure 8, the amount of electricity shortage was increased by the proposal throughout the year. Moreover, the more elastic the customers were in relation to a change in prices, the stronger the propensity was. The percentage of the dates and times when the amount of electricity imbalance was increased owing to the DER management was 60.31% if the price elasticity $e(p_t^*)$ was assumed to be -0.2. If the price elasticity $e(p_t^*)$ was assumed to be -0.5, the percentage was 74.03%.

These results can pose significant issues in terms of the reliability in the power grids. As a factor of the issues, the authors draw attention to the calculation methods of the imbalance prices. In FY 2017, most of the negative imbalance prices were too low to function as a penalty on the RES-AGs.

There are two ideas regarding the electricity imbalance. One is that each retail electricity supplier should precisely estimate the actual electricity consumption of their customers. The other is to allow the retailers to be unable to procure the actual electricity consumed by their customers if the power supply and demand are balanced across the power grid. This paper takes an approach to the above issue from the former perspective.

To motivate the retailers to reduce the electricity imbalance, Condition (34) must hold, and Condition (35) can be derived as the condition of the imbalance prices.

$$RS_0(\hat{s}_{0,t}) > RS(d_t^*) \ , \tag{34}$$

$$i_t^+ < (p_t^* - w_t^*) < i_t^- \ . \tag{35}$$

Only 4.71% of all dates and times satisfied Condition (35). This means that in most cases, it was more profitable for the RES-AGs to cause an electricity shortage or excess electricity than prevent the electricity imbalance. In addition, when the electricity shortage occurred, the percentage of dates and times when the RES-AGs' surplus was decreased due to the electricity imbalance was 17.26%. The percentage in all cases, meanwhile, was 53.59%.

As a simple example, we can set the negative and positive imbalance prices to 12.44 JPY/kWh and 12.42 JPY/kWh, respectively. This is because the pricings result in the imbalance prices satisfying Condition (35). The authors then confirmed that the RES-AGs could increase the social surplus by reducing the electricity imbalance on all dates and at all times. When the negative imbalance prices were set higher and the positive imbalance prices were set lower, the RES-AGs reduced the electricity imbalance more actively to increase the social surplus.

Furthermore, Condition (35) can be used to correct the imbalance prices as follows:

$$i_t^- = \max(i_t^-, 12.44) \ , \tag{36}$$

$$i_t^+ = \min(i_t^+, 12.42) \ . \tag{37}$$

The RES-AGs could increase the social surplus by reducing the electricity imbalance on all dates and at all times if Equations (36) and (37) are established. These results imply that the imbalance prices satisfying Condition (35) can motivate the RES-AGs to reduce the electricity imbalance. However, extreme pricing may lead new retail electricity suppliers to be reluctant to participate in the retail sector. Therefore, the challenges require further discussion.

Table 4. Comparison of social surplus ($e(p_t^*) = -0.2$).

| | $\hat{s}_{0,t} < d_t^*$ | $\hat{s}_{0,t} > d_t^*$ |
|---|---|---|
| Date | 5 February 2018 | 4 March 2018 |
| Time period | 6:00pm to 6:30pm | 8:30am to 9:00am |
| Without DER management (JPY) | -714.59 | 4185.57 |
| With DER management (JPY) | 806.31 | 4244.54 |
| Ideal power transaction (JPY) | -263.06 | 4352.23 |

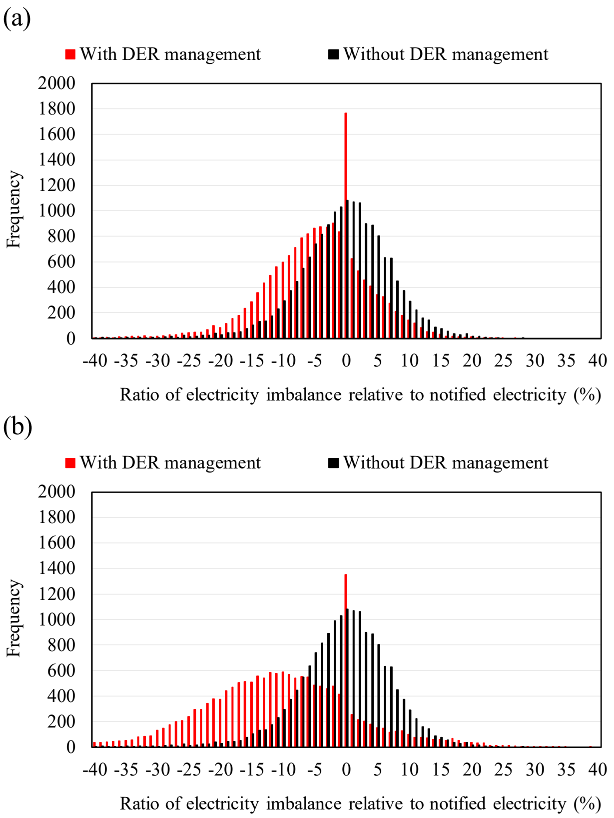


Figure 8. Comparison of frequency distributions of the ratio of electricity imbalance relative to the notified electricity: (a) $e(p_t^*) = -0.2$; and (b) $e(p_t^*) = -0.5$.

## 5. Conclusion

This paper presented a design method for the DER management to maximise the social surplus while lessening the negative economic impact of the electricity imbalance on the RES-AGs. First, the power transaction between the RES-AGs and their customers was formulated under the SWM framework. Second, the authors designed an incentive-based DR programme as the method for managing the DER. The optimal rebate level was derived on the basis of the customers' characteristic that they consume electricity to maximise their surplus.

The numerical simulation results show that the proposed DER management could induce the electricity consumption to the target one. The authors' proposal could also increase the social surplus without any negative economic impacts on the RES-AGs and the customers. Although some challenges, such as the effects of the substitution in Equation (13), still remain, the authors' proposal can be a basic framework to reduce the imbalance settlement.

This paper also pointed out the issues about the calculation methods of imbalance prices and presented simple solutions to the issues. The discussion can contribute to motivating the retailers to reduce the electricity imbalance.

## Acknowledgements

The authors would like to acknowledge the support provided by the Japan Society for the Promotion of Science (KAKENHI Grant Number 19K04325).

## Notes on contributors

**Mr Tamaki Yamazaki** received his M. Eng. from Gifu University, Japan, in 2024. He currently works for JERA. His research interest was demand-side management.

**Prof Hirotaka Takano** received his D. Eng. from the University of Fukui, Japan, in 2006. He then became an assistant professor at the National Institute of Technology, Gifu College, until 2011. From 2011 to 2015, he worked as an assistant professor at Kyushu University, and from 2015 to 2018, he was a senior assistant professor at the University of Fukui. In 2018, he transferred to Gifu University as an associate professor. His research interests are the advanced operation and planning of electric power systems, and applications of optimisation techniques and machine learning, especially to energy management systems.

**Prof Hiroshi Asano** received his D. Eng. from the University of Tokyo. He is currently a professor at Gifu University, a research advisor at the Central Research Institute of Electric Power Industry, and a professor at Institute of Science Tokyo. From 1988 to 1989, he was a visiting scholar at the Energy Modeling Forum at Stanford University. His research interests include systems analysis of demand response, smart grid, distributed energy resources and power markets. He is a programme director, Cross-ministerial Strategic Innovation Promotion Programme "Smart Energy Management Systems."

**Prof Nguyen Duc Tuyen** received his Ph.D. degree from Shibaura Institute of Technology, Japan, in 2012. He worked at Chiba University, Tokyo University of Science, and The National Institute of Industrial Science and Technology in Japan until 2018. He is currently an associate professor at Hanoi University of Science and Technology, Vietnam. His current research direction is on renewable energy, smart grid, energy storage, electric vehicles, and energy policies.

## References


[1] Furuta R and Matsuhashi R (2019). Study on Aggregator's Strategy of Controlling Electric Vehicles to Compensate Imbalances in Power Systems Using Reinforcement Learning. *Int. J. Electr. Energy*, 7(2), pp. 67-71.

[2] Hansen TM, Roche R, Suryanaranan S, Maciejewski AA and Siegel HJ (2015). Heuristic Optimization for an Aggregator-Based Resource Allocation in the Smart Grid. *IEEE Transactions on Smart Grid*, 6(4) pp. 1785-1794.

[3] Kerscher S and Arboleya P (2022). The key role of aggregators in the energy transmission under the latest European regulatory framework. *International Journal of Electrical Power and Energy Systems*, 134(3), 107361.

[4] Mankiw NG (2016). Principle of Microeconomics. 8th Edition. [online]. Available at: <https://zalamsyah.staff.unja.ac.id/wp-content/uploads/sites/286/2020/10/Principles-of-Microeconomics-8th-Ed.-GREGORY-MANKIW-1.pdf>. [Accessed on 28 February 2023].

[5] Ministry of Economy, Trade, and Industry (2020). Guidelines for Energy Resource Aggregation Business. [online]. Available at: <https://www.meti.go.jp/press/2020/06/20200601001/20200601001-1.pdf>. [Accessed on 28 February 2023]. (In Japanese).

[6] Ministry of Economy, Trade, and Industry (2022). Imbalance Ryoukin Seido Nado Nitsuite (Regulation of Imbalance Charge). [online]. *Shin Imbalance Ryoukin Seido Setsumeikai (Seminar about New Regulation of Imbalance Penalty)*. Available at: <https://www.emsc.meti.go.jp/info/public/pdf/20220117001b.pdf>. [Accessed on 28 February 2023]. (In Japanese).

[7] Newcomb J, Lacy V, Hansen L and Bell M (2013). Distributed Energy Resources: Policy Implications of Decentralization. *Electr. J.*, 26(8), pp.65-87.

[8] Sorin E, Bobo L and Pinson P (2018). Consensus-Based Approach to Peer-to-Peer Electricity Markets with Product Differentiation. *IEEE Trans. Power Syst*, 34(2), pp. 994-1004.

[9] Takano H, Yoshida N, Asano H, Hagishima A and Tuyen NG (2021). Calculation Method for Electricity Price and Rebate Level in Demand Response Programs. *Appl. Sci. 2021*, 11(15), 6871.

[10] Takano H, Yoshida N and Asano H (2022). Theoretical Design of Economic Incentive in Demand Response Programs. *CIGRE Sci. Eng.*, 26, pp. 1-14.

[11] U.S. Department of Energy (2006). Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them. [online]. *A report to the United States Congress pursuant to section 1252 of the energy policy act of 2005*. Available at: <https://www.energy.gov/oe/articles/benefits-demand-response-electricity-markets-and-recommendations-achieving-them-report>. [Accessed on 28 February 2023].

[12] Yang P, Tang G and Nehorai A (2013). A Game-Theoretic Approach for Optimal Time-of-Use Electricity Pricing. *IEEE Trans. Power Syst*. 2013, 28(2), pp. 884-892.

[13] Zou X (2009). Double-sided auction mechanism design in electricity based on maximizing social welfare. *Energy Policy*, 37(11), pp. 4231-4239.