RIEEM Research Institute for Environmental Economics and Management

Discussion Paper Series No.2303

Impacts of market power in the day-ahead electricity market on incentive-based demand response

Yukihide Kurakawa and Makoto Tanaka

December, 2023

WASEDA

Impacts of market power in the day-ahead electricity market on incentive-based demand response

Yukihide Kurakawa †   Makoto Tanaka ‡

Abstract

This study demonstrates how market power in the day-ahead electricity market influences the balancing cost in incentive-based demand response (DR) programs. The marginal cost of DR in an incentive-based DR program corresponds to the marginal benefit of energy services that might be provided under baseline electricity consumption. We analyze a stylized Cournot oligopoly model and demonstrate that distortion of an imperfectly competitive day-ahead market generates additional social cost (welfare loss) in the balancing period by increasing the cost of DR. We further investigate the case where some firms in the day-ahead market can also benefit from power generation in the balancing period and demonstrate that the strategic behavior of these firms further decreases total supply in an imperfectly competitive day-ahead market. The results indicate that procompetitive policies in the day-ahead market will lower the cost of DR, which makes demand more flexible and yields additional welfare gains, thereby lowering the balancing cost during the balancing period.

Keywords: incentive-based demand response, market power, day-ahead electricity market, demand-side flexibility

JEL classifications: L13, Q41

†Kanazawa Seiryo University, Email: kurakawa@seiryo-u.ac.jp
‡National Graduate Institute for Policy Studies

1 Introduction

Although the liberalization of electricity markets has been underway worldwide since the 1990s, mitigating market power remains a significant issue in many countries. In addition, decarbonization of electric power systems has recently become increasingly important to achieve targets in pursuit of carbon neutrality. Improving flexibility in power systems is a key challenge to enable further increases in renewable energy use. In this context, the balancing cost to address variable renewable energy sources is a relevant factor that needs to be considered when we evaluate the efficiency of electricity markets.

Electricity is difficult to store, and an imbalance between supply and demand causes instability in power systems that can result in large-scale blackouts.[1] Given these characteristics of power systems, coordination between markets for different time periods (e.g., the forward and spot markets) plays pivotal roll in ensuring stable supply and economic efficiency, particularly in the electricity industry. In addition, market power has a considerable impact even in the liberalized electricity markets of many countries.

In this context, many studies on electricity markets have focused on the interrelationship between markets across different time periods. Allaz and Vila (1993) is a pioneering work demonstrating the role of forward markets from the perspective of firms' strategic behavior in oligopoly markets. Although their model is not particular to electricity markets, many subsequent studies have focused on electricity markets (Adilov, 2012; Anderson and Hu, 2008; Holmberg, 2011; Ito and Reguant, 2016). While these studies primarily focus on the supply side, the demand side has also played an increasing role in maintaining the balance between supply and demand in electric power systems (Pinson et al., 2014). The impacts of supply-side market structure on the performance of demand response (DR) programs has attracted less attention in the literature. In addition, the literature on incentive-based DR is sparse, although many previous works focus on price-based DR programs (Boßmann and Eser, 2016; Dahlkea and Prorok, 2019).

In their theoretical study on incentive-based DR, Chao and DePillis (2013) demonstrate how the problem of baseline inflation occurs in a setting where market prices are exogenously given. Their analysis focuses on consumer be-

[1] In this regard, developments and cost reductions in electricity storage and carriage technologies (e.g., storage batteries, production and usage of hydrogen) deserve close attention.

havior but disregards supply-side market structures. By contrast, our study focuses on the impact of supply-side market structure on DR performance. To the best of our knowledge, there are no prior studies adopting this perspective. This study contributes to the literature in that it demonstrates theoretically how the supply-side market structure affects demand-side flexibility and total balancing costs in the framework of an incentive-based DR program.

This study investigates the impact of market power in the day-ahead market on balancing costs in an incentive-based DR program. The marginal cost of demand reduction in a DR program corresponds to the marginal benefit of energy service in baseline electricity consumption. When the baseline consumption level is determined in the day-ahead market, the day-ahead market price dictates the marginal cost of demand reduction in the balancing period. That is, a lower (higher) day-ahead market price leads to a lower (higher) marginal cost of demand reduction in the balancing period.

In this paper, we analyze an orthodox Cournot oligopoly model to examine the impact of strategic firm behavior in an imperfectly competitive day-ahead market on the cost of DR and total balancing cost in the balancing period. An increase (decrease) in the cost of demand reduction leads to an increase (decrease) in thermal power generation during the supply-demand balancing period. The results indicate that the distortion of an imperfectly competitive day-ahead market generates additional social costs (welfare losses) in the balancing period by increasing the cost of DR.

Furthermore, we investigate the case where some firms in the day-ahead market can also benefit from power generation in the balancing period. These firms can indirectly influence the price of thermal power generation in the balancing period via the baseline transaction level determined in the day-ahead market. The results show that the strategic behavior of these firms further decreases total supply in the imperfectly competitive day-ahead market.

The remainder of this paper is organized as follows. Section 2 presents the basic setting of our model and describes the impacts of market power in the day-ahead market. Section 3 analyzes the case of integrated profit maximization where some firms in the day-ahead market can also benefit from thermal power generation in the balancing period. Chapter 4 provides an overall summary and conclusions.

2 The model

2.1 Day-ahead market

The day-ahead market is assumed to be a Cournot oligopoly consisting of homogeneous firms ($i = 1, ..., m$) that supply electricity from nonrenewable energy sources with constant marginal cost c. Let q_i denotes the output of firm i ($i = 1, ..., m$). The total supply in the market is $Q \equiv \sum_i q_i + q_R$, where q_R represents the supply from renewable energy sources, which is assumed to be exogenous.[2]

The profit of firm i is given by

$$\pi_i = p_e(Q)q_i - cq_i, \quad i = 1, ..., m, \tag{1}$$

where $p_e(Q)$ is the inverse demand, which is assumed to be linear: $p_e(Q) = a - bQ$. From the first-order conditions for firms $i = 1, ..., m$, we obtain the equilibrium outcomes as follows: [3]

$$Q^* = \frac{m(a-c) + bq_R}{(m+1)b}, \tag{2}$$

$$p_e^* = \frac{a + mc - bq_R}{m+1}. \tag{3}$$

The equilibrium quantity of the day-ahead market Q^* is used as the baseline for demand reduction in the balancing period as described later.

The effects of the number of firms m, the marginal cost of nonrenewable energy generation c, and the supply of renewable energy q_R on the equilibrium

[2]We assume that the marginal cost of renewable energy generation is negligibly small.

[3]The supply from nonrenewable energy sources is

$$\sum_{i=1}^{m} q_i = Q^* - q_R = \frac{m(a - c - bq_R)}{(m+1)b}$$

It is reasonable to assume that the supply from nonrenewable energy sources is greater than zero. To ensure this, we assume that $a - c - bq_R > 0$ holds throughout the paper.

outcomes are, respectively, as follows.[4]

$$\frac{dQ^*}{dm} = \frac{a-c-bq_R}{(m+1)^2 b} > 0, \qquad \frac{dp_e^*}{dm} = -\frac{a-c-bq_R}{(m+1)^2} < 0, \tag{4}$$

$$\frac{dQ^*}{dc} = -\frac{m}{(m+1)b} < 0, \qquad \frac{dp_e^*}{dc} = \frac{m}{(m+1)} > 0, \tag{5}$$

$$\frac{dQ^*}{dq_R} = \frac{1}{(m+1)} > 0, \qquad \frac{dp_e^*}{dq_R} = -\frac{b}{(m+1)} < 0. \tag{6}$$

2.2 Demand response

Consider an incentive-based DR program in which a reward (monetary incentive) is paid for the amount of demand reduced from the baseline level. In this section, we formulate the cost and supply functions of demand reduction in DR.

2.2.1 Cost of demand reduction

Suppose that the equilibrium quantity of the day-ahead market Q^* is used as the baseline for demand reduction in the balancing period. The amount of demand reduction subtracted from the baseline is the actual electricity consumption: $Q^{**} = Q^* - q_n$, where Q^{**} and q_n represent the actual electricity consumption and the amount of demand reduction in the balancing period, respectively.

The cost of demand reduction C_n corresponds to the potential benefit of energy services that would be produced from the reduced demand, which is formulated as follows:

$$C_n(q_n) = \int_{Q^*-q_n}^{Q^*} p_e(q)dq = p_e^* q_n + \frac{b}{2} q_n^2. \tag{7}$$

Differentiating Eq. (7) with respect to q_n yields the marginal cost of demand reduction,

$$mc_n(q_n) = p_e^* + bq_n. \tag{8}$$

Eq. (8) shows that the marginal cost of DR depends on the day-ahead market price, p_e^*. An increase (decrease) in the day-ahead market price corresponds to an increase (decrease) in the marginal benefit of energy services

[4] The integer constraint on m is discarded here, but it does not affect the main discussion of this study.

at baseline electricity consumption, resulting in an increase (decrease) in the marginal cost of DR—in other words, a decrease (increase) in demand-side flexibility.

From Eqs. (4)-(6) and Eq. (8), we have

$$\frac{d}{dm} mc_n(q_n) = \frac{dp_e^*}{dm} < 0,$$

$$\frac{d}{dc} mc_n(q_n) = \frac{dp_e^*}{dc} > 0,$$

and

$$\frac{d}{dq_R} mc_n(q_n) = \frac{dp_e^*}{dq_R} < 0.$$

The following proposition summarizes the above results.

Proposition 1

1. *An increase (decrease) in the number of firms in the day-ahead market leads to a decrease (increase) in the marginal cost of DR.*
2. *An increase (decrease) in the marginal cost of nonrenewable electricity generation in the day-ahead market leads to an increase (decrease) in the marginal cost of DR.*
3. *An increase (decrease) in the renewable energy supply in the day-ahead market leads to a decrease (increase) in the marginal cost of DR.*

2.2.2 Consumer's choice

We examine the decision-making on demand reduction. Consider the framework of an incentive-based DR program in which consumers receive a monetary incentive r for each unit of demand reduction in the balancing period.

Let Q^* and Q^{**} denote the baseline and final electricity consumption, respectively. The baseline Q^* is the equilibrium quantity in the day-ahead market. Assuming that $Q^* > Q^{**}$, the amount of demand reduction and the reward consumers receive are given by $q_n = Q^* - Q^{**}$ and $r(Q^* - Q^{**})$, respectively.

A demand-side aggregator acts as consumers' representative and determines the amount of demand reduction to maximize the consumer surplus, taking r as given. The per-unit reward r is determined by the system operator during the balancing period.

The consumer surplus obtained under the final electricity consumption Q^{**} is given by

$$CS = \int_0^{Q^{**}} p_e(q)dq - p_e^* Q^{**} + r(Q^* - Q^{**}). \tag{9}$$

The first term of Eq. (9) is the benefit from electricity consumption, the second term represents the expenditure on it, and the third term represents the monetary incentive paid for demand reduction. Substituting $Q^{**} = Q^* - q_n$ into Eq. (9) and rearranging terms yields

$$CS = \left[\int_0^{Q^*} p_e(q)dq - p_e^* Q^*\right] - C_n(q_n) + (p_e^* + r)q_n. \tag{10}$$

The terms in braces in Eq. (10) represent the surplus at the baseline consumption level, which is determined in the day-ahead market and given in the balancing period. The problem for the demand aggregator in the balancing period is to choose the amount of demand reduction q_n to maximize consumer surplus, given the unit incentive r and the equilibrium price p_e^* in the day-ahead market.

Differentiating Eq. (10) with respect to q_n and rearranging terms yields the first-order condition $C_n'(q_n) = (p_e^* + r)$; the left-hand side is the marginal cost of demand reduction, and the right-hand side is the sum of the electricity price saved and the monetary incentive received per unit of demand reduction. The marginal cost function of demand reduction is given by Eq. (8). Then, we obtain the amount of demand reduction $q_n(r)$ and its inverse $r(q_n)$ as follows:

$$q_n(r) = \frac{r}{b}, \quad r(q_n) = bq_n. \tag{11}$$

In the balancing period, the system operator sets the unit incentive $r(q_n)$ such that the required amount of demand reduction q_n is achieved.

2.3 Balancing period

Consider a situation in which renewable power generation causes a supply shortage ΔQ after the equilibrium quantity (the baseline for demand reduction) is set in the day-ahead market.[5] The amount of renewable electricity

[5]Since we are analyzing a linear model, regarding ΔQ as a random variable and taking expected values for each output does not make a significant difference to the results or discussion in this paper. However, note that the expected value of ΔQ may be affected by the renewable energy supply q_R. See Appendix 3 for a discussion on this point.

actually generated is $q_R - \Delta Q$. This causes the total supply to be $Q^* - \Delta Q$, which is ΔQ less than baseline demand. During the balancing period, the system operator takes the role of a social planner to address the imbalances between supply and demand, which threaten the stability of the power system. Incentive-based DR and thermal power generation are utilized for this purpose.

The system operator determines the amount of demand reduction q_n and thermal generation q_f to restore supply-demand balance at minimum cost. Suppose that the system operator, as a social planner, has an information advantage and knows the cost functions for both thermal power generation, $C_f(q_f)$, and demand reduction, $C_n(q_n)$. The cost function of demand reduction $C_n(q_n)$ and its inverse function $r(q_n)$ are given by Eqs. (7) and (11), respectively.

The cost function of thermal power generation in the balancing period is given by the following quadratic function.[6]

$$C_f(q_f) = c_f q_f + \frac{1}{2} b_f q_f^2 \tag{12}$$

The thermal power producer decides the amount of electricity to produce to maximize its profit, given the price p_f set by the system operator.

$$\max_{q_f} p_f q_f - C_f(q_f)$$

From the first-order condition $p_f = C_f'(q_f)$, we obtain the supply function for thermal power generation $q_f(p_f) = (p_f - c_f)/b_f$ and its corresponding inverse function $p_f(q_f) = c_f + b_f q_f$.

2.3.1 System operator's choice

The system operator's objective is to minimize the total cost of balancing, $C_f(q_f) + C_n(q_n)$, while ensuring that the supply-demand balance is restored

[6]We assume a constant marginal cost c in the day-ahead market, whereas in the balancing period, the marginal generation cost is represented as a quadratic function. This is because power generation needs to be more reactive during the balancing period.

by satisfying the constraint $q_f + q_n = \Delta Q$.

$$\begin{aligned} \min_{q_n, q_f} \; & C_f(q_f) + C_n(q_n) \\ \text{s.t.} \quad & q_f + q_n = \Delta Q, \\ & q_f \geq 0, \\ & q_n \geq 0, \end{aligned} \tag{13}$$

We obtain the interior solution for this problem as follows.[7]

$$q_f^{**} = \frac{(p_e^* - c_f) + b\Delta Q}{b + b_f}, \qquad p_f^{**} = \frac{b(c_f + b_f \Delta Q) + b_f p_e^*}{b + b_f}, \tag{14}$$

$$q_n^{**} = \frac{b_f \Delta Q - (p_e^* - c_f)}{b + b_f}, \qquad r^{**} = \frac{b\{b_f \Delta Q - (p_e^* - c_f)\}}{b + b_f}. \tag{15}$$

From Eqs. (14) and (15), the total balancing cost resulting from optimization by the system operator is given by [8]

$$TC_A^{**}(p_e^*) \equiv C_n(q_n^{**}(p_e^*), p_e^*) + C_f(q_f^{**}(p_e^*)). \tag{16}$$

Note that the overall cost of balancing is a function of the day-ahead market price p_e^*, as q_f^{**} and q_n^{**} are both functions of p_e^*.

2.3.2 Impact of m

As Eqs. (14) and (15) indicate, the amounts of demand reduction and thermal power generation during the balancing period are influenced by the day-ahead market price p_e^*. This is because the marginal cost of DR depends on p_e^* as shown by Eq. (8). A higher day-ahead market price leads to a higher marginal cost of DR and less flexible demand, resulting in decreased DR utilization and increased thermal power generation during the balancing period.

[7] To ensure the interior solution, we assume that $c_f - b\Delta Q \leq p_e^* \leq c_f + b_f \Delta Q$. See Appendix 1 for the derivation process and references to the case of corner solutions.

[8] Substituting q_n^{**} obtained in Eq. (15) into Eq. (7), we obtain

$$C_n(q_n^{**}(p_e^*), p_e^*) \equiv p_e^* q_n^{**}(p_e^*) + \frac{1}{2} b q_n^{**}(p_e^*)^2$$

To see how the number of firms in the day-ahead market affects the outputs during the balancing phase, differentiating Eqs. (14) and (15) with respect to m yields

$$\frac{dq_f^{**}}{dm} = \frac{1}{b+b_f}\frac{dp_e^*}{dm} < 0, \quad \frac{dq_n^{**}}{dm} = \frac{-1}{b+b_f}\frac{dp_e^*}{dm} > 0. \tag{17}$$

Regarding the effect on the total balancing cost, taking the derivative of Eq. (16) with respect to m, we obtain [9]

$$\frac{d}{dm}TC_A^{**} = q_n^{**}\frac{dp_e^*}{dm} < 0. \tag{18}$$

The results of Eqs. (17) and (18) are summarized in the following proposition.

Proposition 2
An increase (decrease) in the number of firms in the day-ahead market decreases (increases) the marginal cost of DR, which increases (decreases) DR utilization and decreases (increases) thermal generation during the balancing period, resulting in a decrease (increase) in total balancing cost.

That is, a smaller number of firms in the day-ahead market leads to increased thermal generation and total balancing cost, indicating that distortions caused by imperfect competition in the day-ahead market will spill over into the balancing period, creating additional costs (or welfare losses in other words) by reducing demand-side flexibility. This also means that a procompetitive policy in the day-ahead market will lead to greater use of DR and lower balancing costs.

2.3.3 Impact of c

Differentiating Eqs. (14) and (15) with respect to c yields

$$\frac{dq_f^{**}}{dc} = \frac{1}{b+b_f}\frac{dp_e^*}{dc} > 0, \quad \frac{dq_n^{**}}{dc} = \frac{-1}{b+b_f}\frac{dp_e^*}{dc} < 0. \tag{19}$$

Taking the derivative of Eq. (16) with respect to c, we obtain

$$\frac{d}{dc}TC_A^{**} = q_n^{**}\frac{dp_e^*}{dc} = \frac{m}{m+1}q_n^{**} > 0. \tag{20}$$

The results of Eqs. (19) and (20) are summarized in the following proposition.

[9] See Appendix 2 for the derivation process.

Proposition 3
An increase (decrease) in the marginal cost of nonrenewable power generation in the day-ahead market increases (decreases) the marginal cost of DR, which leads to decreased (increased) DR utilization and increased (decreased) thermal generation during the balancing period, resulting in an increase (decrease) in total balancing cost.

The marginal cost of nonrenewable generation in the day-ahead market is a relevant factor that affects the marginal cost of DR and balancing costs.

2.3.4 Impact of q_R

To determine the effect of renewable energy supply in the day-ahead market on the output of the balancing period, differentiating Eqs. (14) and (15) with respect to q_R yields

$$\frac{dq_f^{**}}{dq_R} = \frac{1}{b+b_f}\frac{dp_e^*}{dq_R} < 0, \quad \frac{dq_n^{**}}{dq_R} = \frac{-1}{b+b_f}\frac{dp_e^*}{dq_R} > 0. \tag{21}$$

Regarding the effect on the total balancing cost, taking the derivative of Eq. (16) with respect to q_R, we obtain

$$\frac{d}{dq_R}TC_A^{**} = q_n^{**}\frac{dp_e^*}{dq_R} < 0. \tag{22}$$

An increase in renewable energy supply in the day-ahead market increases baseline consumption and decreases the marginal cost of DR, leading to increased DR utilization during the balancing period. An increase in renewable energy supply has a similar effect to an increase in the number of firms in that it narrows the strategically controllable range of supply (residual demand) and reduces the influence of market power. However, the overall effect becomes ambiguous when considering the impact of renewable energy supply on ΔQ. Please refer to Appendix 3 for further discussion on this point.

3 Integrated profit

The previous discussion has shown that the day-ahead market price affects the cost of DR and influences the results during the balancing period, assuming that firms in the day-ahead market make their decisions without considering the impact on the balancing period. In this section, we explore a situation where some firms participating in the day-ahead market also have thermal generation resources available in the balancing period and act to maximize the sum of the profits from the day-ahead market and the balancing period. During the balancing period, the system operator, acting as a social planner, determines the amount of thermal generation. However, if an integrated firm that owns the generation resource available during the balancing period influences the day-ahead market price, it can indirectly influence the amount of thermal generation in the balancing period through its impact on the cost of DR.

Suppose that firms $i = 1, ..., k$ ($k \in [1, m]$) participating in the day-ahead market are integrated firms that also have thermal generation resources available for the balancing period. In this section, we analyze a situation where power generation facilities with the same cost structure as in the previous discussion are equally distributed among firms $i = 1, ..., k$.[10] In other words, it is assumed that the following equation holds, where $c_A(x)$ represents the generation cost function of each integrated firm:

$$kc_A(x) = C_f(kx).$$

Then, we obtain the cost function for each firm as follows:[11]

$$c_A(x) = c_f x + \frac{1}{2}(kb_f)x^2. \tag{23}$$

To ensure a total q_f of thermal generation at a minimum cost, the system operator allocates the generation in such a way that the marginal costs of all the integrated firms are equal. Since it is assumed that all integrated firms have identical cost structures, total generation costs are minimized by equally allocating generation. Then, each integrated firm produces $x = q_f/k$, and its production cost is

$$c_A\left(\frac{q_f}{k}\right) = \frac{c_f q_f}{k} + \frac{b_f}{2k}q_f^2 = \frac{1}{k}C_f(q_f). \tag{24}$$

[10]For simplicity, we assume here that the generation resources used in the balancing period are equally divided into k units and owned by each integrated firm, but even if we consider the case where the division is not equal, the discussion in this paper will not make any substantial difference.

[11]The derivation process is shown below.

$$c_A(x) = \frac{1}{k}C_f(kx) = \frac{1}{k}\left[c_f(kx) + \frac{1}{2}b_f(kx)^2\right] = c_f x + \frac{1}{2}(kb_f)x^2.$$

Aggregating the generation costs of all integrated firms yields

$$kc_A\left(\frac{q_f}{k}\right) = C_f(q_f). \tag{25}$$

The system operator determines the amount of thermal generation and demand reduction based on the aggregated generation function given by Eq. (25). Thus, the problem for the system operator is equivalent to that of Eq. (13). From Eq. (14), the amount of thermal generation and the monetary incentive per unit of demand reduction can be represented by the following expressions:

$$q_f(Q) = \frac{\{p_e(Q) - c_f\} + b\Delta Q}{b + b_f}, \tag{26}$$

$$p_f(Q) = \frac{b(c_f + b_f\Delta Q) + b_f p_e(Q)}{b + b_f}. \tag{27}$$

The price and amount of thermal generation in the balancing period are represented as a function of Q; they both depend on the day-ahead market price $p_e(Q)$. Thus, even in the situation where the outcomes in the balancing period are directly determined by the system operator acting as a social planner, the integrated firms can indirectly influence the price and output of thermal generation by influencing the total supply in the day-ahead market.

The profit obtained by each integrated firm $i = 1, ..., k$ from thermal generation in the balancing period is

$$\pi^A(Q) = p_f(Q)\frac{q_f(Q)}{k} - \frac{1}{k}C_f(q_f(Q)) \tag{28}$$

The total profit of each integrated firm is the sum of the profits from the day-ahead market and the balancing period and is represented by

$$\pi_i = p_e(Q)q_i - cq_i + w\pi^A(Q), \quad (i = 1, ..., k), \tag{29}$$

where $w \in [0, 1]$ is a parameter representing the degree of capital relationship that the integrated firms have with the thermal generation resources used in the balancing period.

The profit of nonintegrated firms, which benefit only from the day-ahead market, is equivalent to that of Eq. (1), represented by

$$\pi_i = p_e(Q)q_i - cq_i. \quad (i = k + 1, ..., m) \tag{30}$$

From Eqs. (29) and (30), the first-order conditions for the integrated and nonintegrated firms are obtained,

$$\frac{\partial \pi_i}{\partial q_i} = (a - bQ) - bq_i - c + w\frac{\partial \pi^A}{\partial q_i} = 0, \quad (i = 1, ..., k) \tag{31}$$

$$\frac{\partial \pi_i}{\partial q_i} = (a - bQ) - bq_i - c = 0. \quad (i = k+1, ..., m). \tag{32}$$

Adding each side of Eqs. (31) and (32) yields

$$m(a - c) + bq_R - (m+1)bQ = -w\sum_{i=1}^{k}\frac{\partial \pi^A}{\partial q_i}. \tag{33}$$

Substituting Eq. (A.18) into Eq. (33), we obtain[12]

$$m(a - c) + bq_R - (m+1)bQ^* = w\frac{bb_f}{b + b_f}q_f(Q^*), \tag{34}$$

where Q^* is the total supply in the day-ahead market in equilibrium.

From Eq. (34), we obtain the following expression, which indicates that an increase in w leads to a decrease in the total supply of the day-ahead market.[13]

$$\frac{dQ^*}{dw} = -\frac{\dfrac{bb_f}{b + b_f}q_f}{\left\{(m+1) - \left(\dfrac{b}{b + b_f}\cdot\dfrac{b_f}{b + b_f}\cdot w\right)\right\}b} < 0 \tag{35}$$

The parameter w represents the degree of capital relationship between the integrated firms and the thermal generation resources to be used in the balancing period. If $w = 0$, indicating the absence of integrated firms in the market, then the total supply in the day-ahead market given by Eq. (34) is equal to that of the Cournot equilibrium, which is given by Eq. (2). When w is greater than 0, meaning that some of the firms participating in the day-ahead market also benefit from thermal generation during the balancing period, the total supply in the day-ahead market becomes even smaller than that in the Cournot equilibrium, and an increase in w results in a further increase in distortion. Then, we obtain the following proposition.

[12]See Appendix 4 for the derivation process.

[13]See Appendix 5 for the derivation process.

Proposition 4
When $w = 0$, it is equivalent to the Cournot equilibrium presented in Eq. (2), and the distortion due to oligopoly is further magnified as w increases.

Note that the right-hand side of Eq. (35) is not dependent on k. This indicates that dividing the power resources utilized during the balancing period among multiple firms does not alleviate the distortions discussed in this context, as shown by the following equation:

$$\frac{d}{dk}\left|\frac{dQ^*}{dw}\right| = 0.$$

Although an increase in k reduces distortions in the behavior of individual firms, the overall impact remains the same because the distortions created by individual firms are aggregated across the market. This can be seen from the fact that the right-hand side of Eq. (34) is derived by adding Eq. (31) for $i = 1, ..., k$.

Proposition 5
Splitting the power generation resources used in the balancing period among multiple firms (increasing k) is not effective in reducing the distortion caused by the increase in w.

The source of the strategic behavior of the integrated firms is the market power in the day-ahead market, which allows them to manipulate the gains in the balancing period by influencing the day-ahead market price $p_e(Q)$. Without market power in the day-ahead market, integrated firms cannot influence output during the balancing period; thus, capital ties would not be a factor that causes distortions. The impact of capital linkages decreases (increases) as m increases (decreases) and converges to zero in a perfectly competitive market, as shown by the following equation.[14]

$$\frac{d}{dm}\left|\frac{dQ^*}{dw}\right| < 0, \quad \lim_{m\to\infty}\left|\frac{dQ^*}{dw}\right| = 0.$$

This indicates that an effective measure for reducing the distortion caused by capital ties is not to increase k (i.e., to split the power generation resources

[14]This is apparent from the fact that the absolute value of the denominator of Eq. (35) is an increasing function of m and the absolute value of the numerator is a decreasing function of m.

used in the balancing period among multiple firms) but to implement measures that mitigate market power in the day-ahead market or to separate the capital ties between the integrated firms and the power resources used in the balancing period. This result is summarized in the following proposition.

Proposition 6
Mitigating the impact of market power in the day-ahead market (increasing m) is effective in alleviating the distortions caused by the increase in w; if the day-ahead market is perfectly competitive, there is no distortion even when w is greater than zero.

Next, let us examine the impact of c. An increase (decrease) in the marginal cost of nonrenewable electricity generation in the day-ahead market increases (decreases) the distortion caused by the strategic behavior of the integrated firms, as shown by the following equation.[15]

$$\frac{d}{dc}\left|\frac{dQ^*}{dw}\right| > 0$$

This can be intuitively interpreted as follows. An increase in the marginal cost of nonrenewable generation in the day-ahead market raises the marginal cost of DR by increasing the day-ahead market price. This leads to a higher price for thermal generation and an increased marginal profit in the balancing period, which accelerates the strategic behavior of integrated firms to reduce supply in the day-ahead market to increase their output in the balancing period. Similarly, an increase in the day-ahead market price caused by an increase in the marginal cost of nonrenewable generation is amplified by the strategic behavior of the integrated firms, because an increased day-ahead market price increases the marginal profit during the balancing period. The effect of c is summarized in the following proposition.

Proposition 7
An increase (decrease) in the marginal cost of nonrenewable power generation in the day-ahead market magnifies (diminishes) the effect of w by increasing (decreasing) the marginal cost of DR and the price of thermal generation in the balancing period.

[15] From Eq. (19), q_f is an increasing function of c. Thus, the numerator of Eq. (35) increases with increasing c.

4 Conclusion

This paper examines the impact of market power in the day-ahead market on the balancing costs of an incentive-based DR program. An increase (decrease) in the day-ahead market price increases (decreases) the marginal cost of DR, resulting in increased (decreased) thermal generation in the balancing period and total balancing costs. The results indicate that the distortions caused by market power in the day-ahead market spill over into the balancing period and create additional social costs (welfare loss). Conversely, implementing a procompetition policy in the day-ahead market could yield additional benefits by lowering the balancing costs through increased utilization of DR.

Furthermore, we investigate the case where the firms participating in the day-ahead market have a financial interest in the generation resources used in the balancing period and benefit from thermal generation in the balancing period. These integrated firms can increase the marginal cost of DR by influencing the day-ahead market price, thereby increasing the profit from thermal generation in the balancing period. It was shown that the distortion of imperfect competition is further magnified by the strategic behavior of these integrated firms, which accounts for profits in the balancing period. To prevent such strategic behavior by integrated firms, it would be effective to weaken or entirely separate the financial relationship between suppliers in the day-ahead market and generation resources that are used in the balancing period or to implement measures to mitigate market power in the day-ahead market. On the other hand, measures to divide the financial interest of generation resources used in the balancing period between multiple firms were found to be ineffective in deterring such strategic behavior.

The results of this paper suggest that mitigating the influence of market power in the day-ahead market is a factor that increases flexibility on the demand side, leading to greater use of DR in the balancing period and lower balancing costs.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 21K01493.

Appendix 1. Solution of Eq. (13)

In the problem faced by the system operator during the balancing period, the equality constraint $q_n + q_f = \Delta Q$ must be satisfied along with $q_n \geq 0$ and $q_f \geq 0$ to restore the supply-demand balance that is essential for maintaining the stability of the power system. The objective function is given by

$$TC_A(q_n, q_f) \equiv C_n(q_n) + C_f(q_f).$$

The Lagrangian for this problem is written as

$$L(q_n, q_f, \lambda, \mu_1, \mu_2) = C_n(q_n) + C_f(q_f) + \lambda(\Delta Q - q_n - q_f) - \mu_1 q_n - \mu_2 q_f.$$

Then we obtain the KKT (Karush-Kuhn-Tucker) conditions:

$$C_n'(q_n) = \lambda + \mu_1 \tag{A.1}$$

$$C_f'(q_f) = \lambda + \mu_2 \tag{A.2}$$

$$q_n + q_f - \Delta Q = 0 \tag{A.3}$$

$$q_n \geq 0,\ \ \mu_1 \geq 0,\ \ \mu_1 q_n = 0 \tag{A.4}$$

$$q_f \geq 0,\ \ \mu_2 \geq 0,\ \ \mu_2 q_f = 0 \tag{A.5}$$

The following three cases are possible.

(i) If $\mu_1 > 0$, then $q_n = 0$, $q_f = \Delta Q$, and $\mu_2 = 0$. This corresponds to the case of a corner solution where only thermal generation is utilized in the balancing period. From Eqs. (A.1) and (A.2),

$$C_n'(0) > C_f'(\Delta Q)$$

holds. From Eqs. (7) and (12), we obtain

$$C_n'(0) = p_e^* \quad \text{and} \quad C_f'(\Delta Q) = c_f + b_f \Delta Q.$$

To summarize the above, $q_n = 0$ and $q_f = \Delta Q$ if $p_e^* > c_f + b_f \Delta Q$.

(ii) If $\mu_2 > 0$, then $q_f = 0$, $q_n = \Delta Q$, and $\mu_1 = 0$. This corresponds to the case of a corner solution where only DR is utilized in the balancing period. From Eqs. (A.1) and (A.2),

$$C_f'(0) > C_n'(\Delta Q)$$

holds. From Eqs. (7) and (12), we obtain

$$C_f'(0) = c_f \quad \text{and} \quad C_n'(\Delta Q) = p_e^* + b \Delta Q.$$

To summarize the above, $q_n = \Delta Q$ and $q_f = 0$ if $p_e^* < c_f - b \Delta Q$.

(iii) If $\mu_1 = \mu_2 = 0$, then

$$C_n'(q_n) = C_f'(q_f)$$

holds from Eqs. (A.1) and (A.2). This corresponds to the case of an interior solution discussed in the main part of this paper. In this case, q_n and q_f are determined such that the marginal costs of DR and thermal generation are equal. From Eqs. (7) and (12), we obtain $C_n'(q_n) = p_e^* + bq_n$ and $C_f'(q_f) = c_f + b_f q_f$. From this and Eq. (A.3), we obtain the results presented by Eqs. (15) and (14)

$$q_n = \frac{b_f \Delta Q - (p_e^* - c_f)}{b + b_f}, \quad q_f = \frac{b \Delta Q + (p_e^* - c_f)}{b + b_f}.$$

Furthermore, we need

$$p_e^* \leq c_f + b_f \Delta Q \quad \text{and} \quad p_e^* \geq c_f - b\Delta Q$$

to ensure $q_n \geq 0$ and $q_f \geq 0$. To summarize the above, if $c_f - b_f \Delta Q \leq p_e^* \leq c_f + b_f \Delta Q$, we obtain the interior solution where q_n and q_f are determined such that $C_n'(q_n) = C_f'(q_f)$.

In the main part of the paper, we focus on the case of the interior solution presented in (iii) above, where q_n is a strictly monotonically decreasing function of p_e^*. However, even if we account for the corner solutions presented in (i) and (ii), $q_n(p_e^*)$ is still a decreasing function of p_e^*, as shown below.

$$q_n(p_e^*) = \begin{cases} \Delta Q & \text{if } p_e^* < c_f - b\Delta Q, \\ \dfrac{b_f \Delta Q - (p_e^* - c_f)}{b + b_f} & \text{if } c_f - b\Delta Q \leq p_e^* \leq c_f + b_f \Delta Q, \\ 0 & \text{if } p_e^* > c_f + b_f \Delta Q. \end{cases}$$

Thus, discarding corner solutions in the main discussion does not have any essential impact on the implications obtained from the analysis.

Appendix 2: Derivation of Eq. (18)

Taking the derivative of Eq. (16) with respect to m yields

$$\frac{d}{dm} TC_A^{**} = \frac{\partial C_n}{\partial p_e^*} \frac{dp_e^*}{dm} + \frac{\partial C_n}{\partial q_n^{**}} \frac{dq_n^{**}}{dm} + \frac{dC_f}{dq_f^{**}} \frac{dq_f^{**}}{dm}. \tag{A.6}$$

From Eq. (17), then $dq_f^{**}/dm = -dq_n^{**}/dm$. Substituting this into Eq. (A.6) yields

$$\frac{d}{dm}TC_A^{**} = \frac{\partial C_n}{\partial p_e^*}\frac{dp_e^*}{dm} + \left(\frac{\partial C_n}{\partial q_n^{**}} - \frac{dC_f}{dq_f^{*}*}\right)\frac{dq_n^{**}}{dm}. \tag{A.7}$$

From Eq. (7), then $\partial C_n/\partial p_e^* = q_n^{**}$. In addition, as a result of optimization by the system operator, the marginal cost of demand reduction is equal to the marginal cost of thermal generation, so $\partial C_n/\partial q_n^{**} - dC_f/dq_f^{**} = 0$. Substituting these into Eq. (A.7), we obtain Eq. (18),

$$\frac{d}{dm}TC_A^{**} = q_n^{**}\frac{dp_e^*}{dm}.$$

Appendix 3: Case where ΔQ depends on q_R

Even if we regard ΔQ as a random variable, the results and discussions presented in this paper remain valid when we calculate the expected value of each outcome. However, regarding the renewable energy supply q_R, it is considered a factor that will influence the expected value of ΔQ, so we provide additional discussion on this point.

First, we can rewrite Eq. (21), which was obtained by taking the derivative of Eqs. (14) and (15) with respect to q_R, in the following manner.

$$\frac{dq_f^{**}}{dq_R} = \frac{1}{b+b_f}\left(\frac{dp_e^*}{dq_R} + b\frac{d}{dq_R}(\Delta Q)\right) \tag{A.8}$$

$$\frac{dq_n^{**}}{dq_R} = \frac{1}{b+b_f}\left(-\frac{dp_e^*}{dq_R} + b_f\frac{d}{dq_R}(\Delta Q)\right) \tag{A.9}$$

Here, we assume that ΔQ is an increasing function of q_R.[16]

For the effect of q_R on thermal generation in the balancing period, the first term in parentheses in Eq. (A.8) is negative, and the second term is positive; then, the sign of the overall effect depends on which of the effects in the different directions outweighs the other in magnitude. The former is an indirect effect via a decrease in the marginal cost of DR, while the latter is a direct effect due to an increase in ΔQ. If the magnitude of the latter effect

[16]The specific impact of q_R on ΔQ likely depends on the unique conditions of each country or region, including geographical conditions. Even if there were a situation in which an increase in q_R would result in a decrease in ΔQ, the discussion here could easily be extended.

is smaller (larger) than the former, the amount of thermal power generation in the balancing period decreases (increases) due to an increase in renewable energy supply in the day-ahead market. The overall effect is likely to depend on different national and regional conditions, such as geographical conditions.

For the effect of q_R on DR, the overall effect is positive because the signs of the indirect and direct effects represented by the first and second terms in parentheses in Eq. (A.9) are both positive. This indicates that an increase (decrease) in renewable energy supply in the day-ahead market leads to an increase (decrease) in the amount of demand reduction in the balancing period.

Next, we explore the impact on the total balancing cost. For the sake of simplicity, we focus here on the case of the interior solution presented by (iii) in Appendix 1. Considering the case of corner solutions does not make any significant modification to the discussion in the paper, as mentioned in Appendix 1.

To account for the impact of ΔQ, we will modify Eq. (16) as follows.

$$TC_A^{**}(p_e^*, \Delta Q) \equiv C_n(q_n^{**}(p_e^*, \Delta Q), p_e^*) + C_f(q_f^{**}(p_e^*, \Delta Q)). \tag{A.10}$$

A change in q_R has two effects on the balancing cost: the effect via p_e^* and the effect via ΔQ. The former corresponds to the effect of the marginal cost of DR, expressed by (22). The latter is an effect added by considering the influence of q_R on ΔQ.

From Eqs. (A.1) - (A.3), we obtain

$$\frac{\partial C_n}{\partial q_n^{**}} = \frac{dC_f}{dq_f^{**}} = \lambda^{**} > 0 \tag{A.11}$$

$$q_n^{**} + q_f^{**} = \Delta Q \tag{A.12}$$

We can see from Eq. (A.11) that λ^{**} corresponds to the marginal costs of DR and thermal generation at the optimum. Eq. (A.12) holds for any ΔQ and p_e^*, so partially differentiating both sides with respect to each variable maintains equality.

$$\frac{\partial q_n^{**}}{\partial(\Delta Q)} + \frac{\partial q_f^{**}}{\partial(\Delta Q)} = 1, \quad \frac{\partial q_n^{**}}{\partial p_e^*} + \frac{\partial q_f^{**}}{\partial p_e^*} = 0 \tag{A.13}$$

Here, differentiating Eq. (A.10) with respect to q_R yields

$$\begin{aligned}\frac{d}{dq_R}TC_A^{**} &= \frac{\partial TC_A^{**}}{\partial p_e^*}\frac{dp_e^*}{dq_R} + \frac{\partial TC_A^{**}}{\partial(\Delta Q)}\frac{d(\Delta Q)}{dq_R} \\ &= \left\{\left(\frac{\partial C_n}{\partial q_n^{**}}\frac{\partial q_n^{**}}{\partial p_e^*} + \frac{\partial C_n}{\partial p_e^*}\right) + \frac{\partial C_f}{\partial q_f^{**}}\frac{\partial q_f^{**}}{\partial p_e^*}\right\}\frac{dp_e^*}{dq_R} \\ &\quad + \left(\frac{\partial C_n}{\partial q_n^{**}}\frac{\partial q_n^{**}}{\partial(\Delta Q)} + \frac{\partial C_f}{\partial q_f^{**}}\frac{\partial q_f^{**}}{\partial(\Delta Q)}\right)\frac{d(\Delta Q)}{dq_R}\end{aligned} \tag{A.14}$$

Substituting Eqs. (A.11) and (A.13) into Eq. (A.14) yields[17]

$$\frac{d}{dq_R}TC_A^{**} = q_n^{**}\frac{dp_e^*}{dq_R} + \lambda^{**}\frac{d(\Delta Q)}{dq_R} \tag{A.15}$$

The first term on the right-hand side of Eq. (A.15) represents a negative effect due to a decrease in the marginal cost of DR, as shown in Eq. (22). The second term is a positive effect resulting from an increase in ΔQ. When the latter effect exceeds (falls below) the former in magnitude, the balancing cost increases (decreases) due to an increase in renewable energy supply in the day-ahead market.

Appendix 4: Derivation of the right-hand side of Eq. (33)

From Eq. (28), the gain that each integrated firm obtains in the balancing period is given by

$$\pi^A = \frac{1}{k}\left\{p_f q_f - C_f(q_f)\right\}$$

An integrated firm $i \in \{1, ..., k\}$ can indirectly influence the quantity $q_f(p_e(Q)$ and the price $p_f(p_e(Q)$ of thermal generation in the balancing period by influencing the day-ahead market price $p_e(Q)$. The effect of its supply in the day-ahead market q_i on the profit obtained in the balancing period is represented by the following equation:

$$\begin{aligned}\frac{\partial \pi^A}{\partial q_i} &= \frac{d\pi^A}{dQ}\frac{\partial Q}{\partial q_i} \\ &= \frac{1}{k}\left[\left(p_f - C_f'(q_f)\right)\frac{dq_f}{dp_e}\frac{dp_e}{dQ} + \frac{dp_f}{dp_e}\frac{dp_e}{dQ}q_f\right]\frac{\partial Q}{\partial q_i}\end{aligned} \tag{A.16}$$

[17]Note that $\partial C_n/\partial q_n^{**} = q_n^{**}$ from Eq. (7).

From the optimization during the balancing period, $p_f = C'_f(q_f)$. In addition, we have $\partial Q/\partial q_i = 1$ from $Q \equiv \sum_{i=1}^{m} q_i + q_R$, $dp_e/dQ = -b$ from $p_e(Q) = a - bQ$, and $dp_f/dp_e = b_f/(b+b_f)$ from Eq. (14). Substituting these into Eq. (A.16) yields

$$\frac{\partial \pi^A}{\partial q_i} = \frac{1}{k}\frac{dp_f}{dp_e}\frac{dp_e}{dQ}q_f = -\frac{1}{k}\frac{bb_f}{b+b_f}q_f \tag{A.17}$$

From this, the right-hand side of Eq. (33) is obtained as follows:

$$-w\sum_{i=1}^{k}\frac{\partial \pi^A}{\partial q_i} = w\frac{bb_f}{b+b_f}q_f \tag{A.18}$$

Appendix 5: Derivation of Eq. (35)

Since Eq. (34) holds for any $w \in [0,1]$, the equality still holds when both sides are differentiated by w.

$$-(m+1)b\frac{dQ^*}{dw} = \frac{bb_f}{b+b_f}q_f + w\frac{bb_f}{b+b_f}\frac{-b}{b+b_f}\frac{dQ^*}{dw} \tag{A.19}$$

We can rewrite the right-hand side of Eq. (A.19) as follows:

$$\frac{bb_f}{b+b_f}q_f - b\left(\frac{b}{b+b_f}\cdot\frac{b_f}{b+b_f}\cdot w\right)\frac{dQ^*}{dw} \tag{A.20}$$

Because

$$0 < \frac{b}{b+b_f} < 1, \quad 0 < \frac{b_f}{b+b_f} < 1, \quad w \in [0,1],$$

the value in parentheses in Eq. (A.20) is greater than or equal to 0 but less than 1.

$$0 \le \frac{b}{b+b_f}\cdot\frac{b_f}{b+b_f}\cdot w < 1 \tag{A.21}$$

From Eq. (A.19), we obtain

$$\frac{dQ^*}{dw} = -\frac{\dfrac{bb_f}{b+b_f}q_f}{\left\{(m+1) - \left(\dfrac{b}{b+b_f}\cdot\dfrac{b_f}{b+b_f}\cdot w\right)\right\}b} \tag{A.22}$$

From $m+1 \ge 2$ and Eq. (A.21), the sign of the denominator in Eq. (A.22) is positive. Therefore,

$$\frac{dQ^*}{dw} < 0. \tag{A.23}$$

References

Nodir Adilov. Strategic use of forward contracts and capacity constraints. *International Journal of Industrial Organization*, 30(2):164–173, 2012.

Blaise Allaz and Jean-Luc Vila. Cournot competition, forward markets and efficiency. *Journal of Economic Theory*, 59(1):1–16, 1993.

Edward J Anderson and Xinmin Hu. Forward contracts and market power in an electricity market. *International Journal of Industrial Organization*, 26(3):679–694, 2008.

Tobias Boßmann and Eike Johannes Eser. Model-based assessment of demand-response measures—A comprehensive literature review. *Renewable and Sustainable Energy Reviews*, 57:1637–1656, 2016.

Hung-po Chao and Mario DePillis. Incentive effects of paying demand response in wholesale electricity markets. *Journal of Regulatory Economics*, 43(3):265–283, 2013.

Steve Dahlkea and Matt Prorok. Consumer savings, price, and emissions impacts of increasing demand response in the midcontinent electricity market. *The Energy Journal*, 40(3):243–262, 2019.

Pär Holmberg. Strategie forward contracting in the wholesale electricity market. *The Energy Journal*, pages 169–202, 2011.

Koichiro Ito and Mar Reguant. Sequential markets, market power, and arbitrage. *American Economic Review*, 106(7):1921–1957, 2016.

Pierre Pinson, Henrik Madsen, et al. Benefits and challenges of electrical demand response: A critical review. *Renewable and Sustainable Energy Reviews*, 39:686–699, 2014.