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Market competition and strategic choices of electric power sources under fluctuating demand*

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Abstract

This study investigates how the introduction of a competitor affects the behavior of an incumbent electricity producer who is a former local monopolist. We especially focus on its implications for the incumbent's capacity choice between two different electric power sources: one technology with a relatively high production cost (peak-load technology), which is represented by gas-fired power generation, and the other with a relatively high capacity-building cost (base-load technology), which is represented by nuclear power generation. We assume that the entrant does not have access to the latter technology and also that demand fluctuates over time, as is typically the case with an electricity market. Surprisingly, the introduction of a competitor increases the capacity of nuclear power generation if and only if the nuclear technology is sufficiently *inefficient*. This result also implies that the competition tends to decrease the nuclear capacity when the level of carbon tax, which tends to raise the relative production cost of gas-fired power generation, is sufficiently high.

Keywords: technology choice, carbon-free energy, carbon tax, deregulation, demand uncertainty, capacity commitment, imperfect competition

JEL Classification: Q41, Q42, L13, L43

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1 Introduction

Almost all nuclear power plants in Japan stopped operating following the Fukushima-Daiichi nuclear plant accident, which was triggered by the Great East-Japan Earthquake in March 2011. If left unused, most existing nuclear plants in Japan will become too obsolete to be retrofitted by the middle of this century. At the same time, it would require substantial spending for old nuclear power plants to be replaced with ones that are compliant with much stricter current regulations (The Mainichi, 2019). Together with heightened safety concerns, the expected high costs of operationalizing nuclear power plants on a significant scale and its potential effects of doing so on environmental and other social issues, such as climate change, have made nuclear power one of the most hotly debated subjects in the political arena as well as in the news media in Japan.

Besides nuclear power, there is a variety of other technologies available for electricity provision. Notable examples include coal-fired, gas-fired, hydro-electric, biomass power, wind-power, and solar photovoltaic generations. The choice of technologies for electricity production depends on economic as well as technological, environmental, and social considerations. From an economic viewpoint, market demand and cost structures of the respective technologies are especially important. Demand for electricity fluctuates between day and night,[1] and among seasons. In addition, there are significant fluctuations and uncertainty in electricity demand induced by such factors as states of an economy and weather-related events. Once a large-scale plant using a technology such as nuclear and hydro-electric power is established, there is little cost-saving possibility even if the quantity of electricity supplied to consumers turns out to be below its production capacity. On the other hand, technologies such as gas-fired and biomass power generations yield immediate cost savings when the inputs necessary for electricity production are reduced.

Thus, in order to choose its own cost-minimizing mix of production technologies, a power company uses a more easily adjustable technology (typically referred to as a peak-load technology), such as gas-fired power generation, to cope with the volatile part of the demand, and a

[1] Allcott (2011) estimates electricity demand under fluctuating demand structure.

more rigid technology (a base-load technology), such as nuclear power, plays a central role in providing for a base portion of the demand. This study starts by focusing on a local monopolist's profit-maximizing motive and discusses its optimal selection of two different electric power sources, gas-fired and nuclear (adjustable and rigid) power generation technologies.[2]

Since around the 1990s, regional electricity markets in Japan have transformed from local monopolies to more competitive markets, and the shares of new entrants in formerly monopolized regional electricity markets are gradually increasing across the country. The overall share of new entrants reached 16.2% of the national electricity market in April 2020 (Electricity and Gas Market Surveillance Commission, 2020), and this deregulation trend appears to have accelerated after the Fukushima Daiichi nuclear plant accident.

In the main part of the study, therefore, we investigate how the introduction of competition affects the behavior of electricity producers and discuss its implications for the resulting capacity choice of different electric power sources. In particular, we consider a case in which a new competitor enters a market (and creates a duopoly market) that was originally served by a local monopolist. We suppose that, while the incumbent firm can use both adjustable and rigid technologies in its electricity production, the entrant does not have access to the latter technology that requires a substantial capacity-building cost,[3] represented here by nuclear power generation.

As our main finding, we show that relatively *inefficient* nuclear power generation technology, measured by a sufficiently high cost for becoming operationalized, results in a larger capacity of nuclear power generation than that under the monopoly environment. We also interpret our results from the perspective of environmental policy and conclude that the nuclear capacity tends to decrease with the introduction of a competitor when the level of carbon tax, which is imposed on adjustable technology such as gas-fired power generation, is sufficiently high.

While this study is partially related to the real options theory, which accounts for the cost of losing flexibility while investing under uncertainty (see, among others, Dixit and Pindyck,

[2]How the input of an *ex ante* control and that of an *ex post* control should be chosen are investigated by Hartman (1976) for a competitive market, and Ishii (1979) for a monopoly market under uncertain demand. The main finding of these works is that an *ex ante* "poor" choice could be partially adjusted by controlling *ex post* inputs.

[3]Dixit (1979) demonstrates that the incumbent can create a situation in which a new entrant is inactive if there is a sufficiently large fixed cost to enter the market.

1994), we focus on strategic interactions by employing a game-theoretic approach typically used in the industrial organization literature.[4] In their seminal works, Spencer and Brander (1992) consider a trade-off between flexibility and strategic pre-commitment by introducing demand uncertainty in a Stackelberg model, and Boyer and Moreaux (1997) investigate how technological flexibility choices depend on strategic interactions and industry characteristics in a duopoly model. A relsult closely related to our study is presented by Goyal and Netessine (2007), who analyze both the equilibrium technology choice and capacity investment in a multi-market duopoly model.[5] One of their main findings is that, as the competitor's cost of capacity building decreases and thus, as the competition intensifies, the other firm favors a more costly but flexible production process. Our study differs from these previous works in that we examine the effects of a competitor's market entry on the technology choice, which is based on capacity investment of an incumbent firm. Moreover, we obtain a contrasting result to Goyal and Netessine (2007), in that, when competition intensifies, an incumbent firm can increase the use of a less costly but inflexible production technology (base-load technology).

The underlying economic model employed in this study is most closely related to the two-stage game proposed by Milstein and Tishler (2012), which considers the capacity/technology choice under demand fluctuations in the initial stage of the game and examines the economic implications of the subsequent Cournot competition with two contrasting power-generation technologies.[6] They show that underinvestment in generation capacity realizes due to the rational behaviors of the firms and also that the electricity price spike occurs as an effective substitute for the firms' accumulating excess generation capacities. Whereas we adopt a similar modeling framework, the focus of our study is substantially different from that of Milstein and Tishler

[4] Cardell et al. (1997) analyze strategic interactions in electricity transmission networks.

[5] They consider two products and define the flexible (inflexible) technology as that whose capacity can be used for both the products (must be used for one of the products).

[6] An economic model of optimal capacity choice under demand fluctuations in a game-theoretic context has been developed steadily over the last twenty years or so. With regards to the ones adopting Cournot competition, Gabszewicz and Poddar (1997) investigate the characteristics of a subgame perfect equilibrium of a capacity building game between two symmetric firms under demand uncertainty with finite discrete states. Murphy and Smeers (2005) extend the setting to an asymmetric Cournot model with one firm which builds and operates only base plants and the other firm which builds and operates only peak plants, and derive its subgame perfect equilibrium. Tishler et al. (2008) investigate capacity choice of multiple Cournot firms under demand uncertainty with a continuous density function assuming a single technology, and Milstein and Tishler (2012) extend this model by incorporating two technologies.

(2012) in that we analytically examine how an intensified competition affects the capacity-investment choice of an incumbent firm and especially how it is associated with the relative efficiencies of different technologies.[7]

The rest of this paper is organized as follows. Section 2 sets up our economic model. Section 3 investigates the case of monopoly. Section 4 analyzes the case of duopoly and identifies the effects of introducing a competitor by comparing the results with those in the monopoly case. Section 5 reinterprets our main results and discusses the implications of imposing a carbon tax on fossil-fuel-oriented electricity. Section 6 provides simulation results of our model, focusing on the equilibrium market shares of electricity generated by nuclear technology and the resulting operation rates of a nuclear plant. Section 7 concludes.

2 The model

Consider a local electricity market. We suppose that there are two different types of technologies that produce electric power of a homogeneous quality. Specifically, these are referred to as a nuclear power plant and a gas-fired power plant.[8] A nuclear power plant incurs a higher capacity-building (or set-up, or operationalizing) cost than a gas-fired power plant does while a gas-fired power plant incurs a higher marginal production cost. In the benchmark case presented in the next section, the market is monopolistically served by firm 1. With the entry of firm 2, the market becomes duopolistic, and the two firms essentially play the following sequential game: (i) the capacities of the power plants are determined under demand uncertainty; (ii) the actual demand is revealed; and finally (iii) the firms choose the quantities of electricity supplies.

For the sake of analytical tractability, we make the following simplifying assumptions. Suppose that firm 1 chooses the capacity of its nuclear power plant, $k_1 \in \mathbb{R}_+$, and that firm 1 chooses the total capacity of its gas-fired power plants, $\ell_1 \in \mathbb{R}_+$ (and firm 2 also chooses $\ell_2 \in \mathbb{R}_+$ in the duopoly case).[9] The capacity-building cost of the nuclear plant is given by rk_1, where $r > 0$,

[7] As for the effects of competition in the electricity industry, see also Borenstein et al. (2000, 2002).

[8] In a different context, a nuclear power plant would be replaced by, e.g., a hydro-electric power plant, and a gas-fired power plant would be replaced by a coal-fired, oil-fired, or biomass power plant.

[9] Note that only the incumbent firm (or firm 1) can use nuclear power technology, and therefore, $k_2 = 0$ in the duopoly case. Furthermore, we ignore inter-temporal considerations to focus on the steady-state outcomes, and the capacity of a nuclear plant is measured in terms of the amount of electricity that the plant can produce in

while the capacity-building cost of the gas-fired plant is assumed to be 0. The inverse demand of the local electricity market is given by $p = A - Q$, where p is the market price and Q is the quantity of electricity demanded in the market. The scale of the market, A, is a random variable that follows a uniform distribution with the support of a positive-valued interval, $[L, H]$,[10] and the exact size of A is revealed after the firms have made their capacity choices. Finally, after observing A, firm 1 chooses the volume of electricity produced from the nuclear power plant, $x_1(A) \in [0, k_1]$, and the volume produced from gas-fired power generation, $y_1(A) \in [0, \ell_1]$ (in the duopoly case, firm 2 also chooses $y_2(A) \in [0, \ell_2]$). Thus, firm 1's aggregate supply is given by $q_1(A) = x_1(A) + y_1(A)$ (and firm 2's total supply is simply $q_2(A) = y_2(A)$). Noted that, since demand is revealed after the capacities are established and before the market clears, the firms' decisions on the quantities of their electricity supply depend on the actual value of A, but their capacities do not. For simplicity, we suppose that the variable production cost of a nuclear power plant is 0 while that of a gas-fired power plant is given by $cy_i(A)$ for firm $i (i = 1, 2)$, where $c = c_0 + t > 0$. Since some carbon tax may be imposed on the fossil fuel, we suppose that the overall marginal cost of the gas-fired power c is composed of a unit carbon tax, $t \geq 0$, and the marginal production cost, $c_0 > 0$. Note that, in the final quantity-setting stage, the firms can adjust these variable costs while the capacity-building cost is considered sunk.

We use a subgame-perfect equilibrium as our equilibrium concept and solve the game backwards. Since the set-up cost of a gas-fired plant's capacity is 0, firm i always chooses a sufficiently large value of ℓ_i so that $y_i(A)$ is not bounded from above by ℓ_i in any subgame-perfect equilibrium. Thus, ℓ_i becomes irrelevant to the other aspects of the equilibrium.

Furthermore, we adopt the following three assumptions, which turn out to be convenient for obtaining the equilibrium results algebraically:

$$\mathbf{A.1}\ \ Var(A) > \frac{(L+2c)^2}{48}, \quad \mathbf{A.2}\ r < c, \quad \mathbf{A.3}\ c < \frac{L}{2}.$$

the steady state.

[10]The assumption of uniform distribution is principally for the tractability of the analysis, but it would not be significantly divergent from actual cases. For instance, Figure 2.1 of Léautier (2018) shows that the load duration curve for France in 2009 generally reflects such a distribution. Tishler et al. (2008) and Milstein and Tishler (2012) also adopt a uniform distribution in the analytical parts of their papers.

A.1 allows us to restrict our attention to the case in which demand is sufficiently volatile.[11] In fact, A.1 is the condition to exclude the case in which firm 1 does not supply a positive amount of gas-oriented power in any situations that satisfy the next two assumptions.[12] According to A.2, for all the conceivable scales of the market demand, nuclear power production technology is more efficient than gas-fired power generation technology in terms of production in the steady state, provided that a nuclear plant has no idle capacity. A.3 is the condition that does not allow firm 1 to become a monopolist whenever there is a potential rival firm in the same market.

3 Monopoly

In this section, as a benchmark case, we consider firm 1 as the sole supplier of electricity in a local market.[13] Firm 1 can utilize both nuclear and gas-fired power generation technologies for producing electricity. We suppose that the price of the electricity is endogenously determined within the market.[14]

3.1 Quantity-setting stage

In the final quantity-setting stage, firm 1's profit maximization problem,

$$\max_{x_1, y_1} \; pq_1 - cy_1 \quad \text{s.t. } x_1 \leq k_1,$$

[11]Since $Var(A) = (H-L)^2/12$, A.1 is equivalent to $2H > 3L + 2c$. This condition is always satisfied if $H \geq 2L$, for instance, holds alongside with A.3. This condition and A.3 imply that $H > 4c$.

[12]Specifically, this is the necessary and sufficient condition for both firms to have interior solutions in terms of generating gas-fired power for some $r \in (0, c)$ in Section 4, and the sufficient condition for the monopolist in Section 3.

[13]The monopoly case can also be regarded as a collusive outcome in which firms 1 and 2 decide their aggregate production capacities to maximize their joint profit.

[14]In reality, the electricity price charged by a local monopolist is often subject to a regulation. Even if we consider a price-regulated monopolist as a benchmark case, our main result still holds (see Appendix B). In order to focus on the issues of technology choice through capacity investment, we does not consider further complex pricing methods for electricity. See Allcott (2011) for hourly real-time pricing and Daruwala et al. (2020) for menu pricing to allow household self-selection.

where $p = A - q_1$ and $q_1 = x_1 + y_1$, yields the equilibrium outcomes for given values of k_1 and A as follows:[15]

$$(x_1^m(k_1;A), y_1^m(k_1;A)) = \begin{cases} \left(k_1, \frac{A-c}{2} - k_1\right) & \text{if } k_1 \in [0, \frac{A-c}{2}] \Leftrightarrow A \in [2k_1 + c, \infty), \\ (k_1, 0) & \text{if } k_1 \in [\frac{A-c}{2}, \frac{A}{2}] \Leftrightarrow A \in [2k_1, 2k_1 + c], \\ \left(\frac{A}{2}, 0\right) & \text{if } k_1 \in [\frac{A}{2}, \infty) \Leftrightarrow A \in (0, 2k_1]. \end{cases} \quad (1)$$

$$q_1^m(k_1;A) = \begin{cases} \frac{A-c}{2} & \text{if } k_1 \in [0, \frac{A-c}{2}], \\ k_1 & \text{if } k_1 \in [\frac{A-c}{2}, \frac{A}{2}], \\ \frac{A}{2} & \text{if } k_1 \in [\frac{A}{2}, \infty). \end{cases} \quad p^m(k_1;A) = \begin{cases} \frac{A+c}{2} & \text{if } k_1 \in [0, \frac{A-c}{2}], \\ A - k_1 & \text{if } k_1 \in [\frac{A-c}{2}, \frac{A}{2}], \\ \frac{A}{2} & \text{if } k_1 \in [\frac{A}{2}, \infty). \end{cases} \quad (2)$$

The superscript "m" represents the equilibrium of each outcome in this monopoly market.

As is seen in (1), firm 1's optimal production plan has three distinct patterns. If the scale of demand is sufficiently large in relation to a nuclear plant's capacity, that is, if $A > 2k_1 + c$, then gas-fired power generation technology is utilized to make up for the shortage of a nuclear plant's capacity. If the scale of demand is small enough to satisfy $A \leq 2k_1 + c$, all the electricity in the market is supplied by nuclear power technology. Moreover, when the scale of demand, A, is smaller than $2k_1$, the nuclear plant ends up having idle capacity, that is, $k_1 > x_1^m(k_1;A)$.

From (1) and (2), we can compute the monopolist's profit excluding the capacity-building cost of a nuclear plant as[16]

$$\pi_1^m(k_1;A) = \begin{cases} \frac{(A-c)^2}{4} + ck_1 & \text{if } k_1 \in [0, \frac{A-c}{2}] \Leftrightarrow A \in [2k_1 + c, \infty), \\ k_1(A - k_1) & \text{if } k_1 \in [\frac{A-c}{2}, \frac{A}{2}] \Leftrightarrow A \in [2k_1, 2k_1 + c], \\ \frac{A^2}{4} & \text{if } k_1 \in [\frac{A}{2}, \infty) \Leftrightarrow A \in (0, 2k_1]. \end{cases}$$

[15] Note that, from the assumption A.3 above, we have an interior solution with respect to q_1 for all $A \in [L, H]$.
[16] $\pi_1^m(k_1;A)$ is a smooth function with respect to k_1.

3.2 Capacity-setting stage

In the initial capacity-setting stage, the firm establishes the capacity of a nuclear power plant under uncertain demand. It attempts to maximize the following expected profit:

$$\max_{k_1} \frac{1}{H-L}\int_L^H \pi_1^m(k_1;a)da - rk_1. \tag{3}$$

Let k_1^m be the solution of this problem, that is, the equilibrium capacity of a nuclear plant in this monopoly case.

Given $\frac{L}{2} < \frac{H-c}{2}$ by A.1, firm 1's expected marginal revenue in this stage, $MR^m(k_1)$, is as follows:[17]

$$\frac{d}{dk_1}\frac{1}{H-L}\int_L^H \pi_1^m(k_1;a)da = \begin{cases} c & \text{if } k_1 \in [0, \frac{L-c}{2}], \\ \frac{1}{H-L}\left[\frac{2cH-L^2-c^2}{2} - 2(L-c)k_1 - 2k_1^2\right] & \text{if } k_1 \in [\frac{L-c}{2}, \frac{L}{2}], \\ \frac{1}{H-L}\left[\frac{2cH-c^2}{2} - 2ck_1\right] & \text{if } k_1 \in [\frac{L}{2}, \frac{H-c}{2}], \\ \frac{1}{H-L}\left[\frac{H^2}{2} - 2Hk_1 + 2k_1^2\right] & \text{if } k_1 \in [\frac{H-c}{2}, \frac{H}{2}], \\ 0 & \text{if } k_1 \in [\frac{H}{2}, \infty). \end{cases} \tag{4}$$

The curve ABCD in Figure 1 depicts the shape of this expected marginal revenue.

As Figure 1 suggests, firm 1's expected marginal revenue, $MR^m(k_1)$, is continuous and decreasing with respect to plant size. Since $MR^m(k_1)$ is strictly decreasing in the interval of $(0, c)$ and $r \in (0, c)$ under A.2, the first-order condition,

$$MR^m(k_1) = r,$$

is the necessary and sufficient condition for the expected profit maximization problem of (3). In other words, the curve ICD is the demand curve for a nuclear plant's capacity k_1 if we consider r as the price of the capacity. Solving the last equation for k_1 yields the optimal capacity of the nuclear power plant for the monopolist as follows:

[17] We provide a supplementary material that helps readers to replicate the computation of (4).

Lemma 1 *Suppose A.1–A.3. Then,*

$$k_1^m = \begin{cases} \frac{1}{2}\left(L - c + \sqrt{2(c-r)(H-L)}\right) & \textit{if } r \in \left[c - \frac{c^2}{2(H-L)}, c\right), \\ \frac{c(2H-c)-2r(H-L)}{4c} & \textit{if } r \in \left[\frac{c^2}{2(H-L)}, c - \frac{c^2}{2(H-L)}\right], \\ \frac{1}{2}\left(H - \sqrt{2r(H-L)}\right) & \textit{if } r \in \left(0, \frac{c^2}{2(H-L)}\right]. \end{cases} \tag{5}$$

The first, second, and third lines of (5) correspond to the regions $k_1^m \in (\frac{L-c}{2}, \frac{L}{2}]$, $k_1^m \in [\frac{L}{2}, \frac{H-c}{2}]$, and $k_1^m \in [\frac{H-c}{2}, \frac{H}{2})$, respectively (IJ, JK, and KD in Figure 1, respectively). From this result and (1), $r > \frac{c^2}{2(H-L)}$ guarantees $y_1^m(H) > 0$ while $y_1^m(L)$ is always zero. In other words, unless the nuclear plant is sufficiently efficient, gas-fired power generation technology is utilized when the market demand turns out to be high while nuclear power generation always serves the base-load portion of the demand.

In building up the capacity of a nuclear power plant, firm 1 faces a trade-off between saving its production cost and hedging against risk. If the demand is not so volatile, the firm would prefer to generate electricity from nuclear power, since this mode of production is less costly than gas-fired power generation, as in A.2. However, under uncertain demand, it is risky to build a nuclear plant with an enormous capacity, because a part of its capacity can end up being excessive when demand turns out to be fairly low. The cost of building up this excess capacity cannot be recovered, as it is already sunk when the actual demand size is revealed. Gas-fired power plants are expected to play a role in high demand cases unless the value of r is sufficiently small to dwarf the cost consideration in comparison with this risk-hedge aspect.

The threshold value of r, which guarantees $y_1^m(H) > 0$, can be rearranged as

$$\frac{c^2}{2(H-L)} = \frac{c^2}{4\sqrt{3\,Var(A)}},$$

which implies that, when $Var(A)$ is sufficiently large, gas-fired power generation technology is utilized even for a lower value of r.[18] A high capacity-building cost of a nuclear plant reduces the cost advantage of nuclear power generation. Similarly, a higher volatility of market demand

[18] Note that, since $y_1^m(A)$ is non-decreasing in A by (1), $y_1^m(A) = 0$ for all $A \in [L, H]$ if $y_1^m(H) = 0$.

enhances the risk of increasing the capacity of a nuclear plant. Thus, the values of r and $Var(A)$ have similar effects in the nuclear capacity consideration, and their increases discourage the establishment of a nuclear power plant of a significant scale.

4 Effects of competition

In this section, we analyze the case in which firm 2 enters the electricity market as a new competitor to firm 1. We suppose that, whereas firm 1 can use both nuclear and gas-fired power plants, firm 2 can employ only gas-fired power generation technology in its electricity production.

4.1 Quantity-setting stage

If all the electricity in the market is produced at gas-fired power plants, firm i's reaction function in the final quantity-setting stage is obtained by $\max_{q_i} pq_i - cq_i$ as

$$R_i^F(q_j; A) = \max[\frac{A - c - q_j}{2}, 0],$$

where $i = 1, 2$ and $i \neq j$. However, if all of firm 1's electricity supply is produced at its nuclear power plant, its reaction function in this stage is obtained by $\max_{q_1} pq_1$ as

$$R_1^N(q_2; A) = \max[\frac{A - q_2}{2}, 0].$$

Thus, since $x_1 \leq k_1$, firm 1's reaction function given k_1 and A is

$$R_1(q_2; k_1, A) = \begin{cases} R_1^F(q_2; A) & \text{if } q_2 \leq R_1^{F^{-1}}(k_1; A), \\ k_1 & \text{if } R_1^{F^{-1}}(k_1; A) \leq q_2 \leq R_1^{N^{-1}}(k_1; A), \\ R_1^N(q_2; A) & \text{if } R_1^{N^{-1}}(k_1; A) \leq q_2. \end{cases}$$

As Figure 2 shows, firm 1's reaction function (the bold line) has kinks at the predetermined maximum capacity of its nuclear power plant, k_1.

Since firm 2 cannot use nuclear power generation technology, firm 2's reaction function is always given by $R_2^F(q_1; A)$. The Nash equilibrium outcomes for given k_1 and A are obtained at the intersection of these two reaction functions as follows:[19]

If $k_1 \in [0, \frac{A-c}{3}] \Leftrightarrow A \in [3k_1 + c, \infty)$,

$$\begin{bmatrix} x_1^*(k_1;A) & y_1^*(k_1;A) \\ \cdot & y_2^*(k_1;A) \end{bmatrix} = \begin{bmatrix} k_1 & \frac{A-c}{3} - k_1 \\ \cdot & \frac{A-c}{3} \end{bmatrix}, \quad \begin{bmatrix} q_1^*(k_1;A) \\ q_2^*(k_1;A) \end{bmatrix} = \begin{bmatrix} \frac{A-c}{3} \\ \frac{A-c}{3} \end{bmatrix}, \quad p^*(k_1;A) = \frac{A+2c}{3}. \tag{6}$$

If $k_1 \in [\frac{A-c}{3}, \frac{A+c}{3}] \Leftrightarrow A \in [3k_1 - c, 3k_1 + c]$,

$$\begin{bmatrix} x_1^*(k_1;A) & y_1^*(k_1;A) \\ \cdot & y_2^*(k_1;A) \end{bmatrix} = \begin{bmatrix} k_1 & 0 \\ \cdot & \frac{A-c-k_1}{2} \end{bmatrix}, \quad \begin{bmatrix} q_1^*(k_1;A) \\ q_2^*(k_1;A) \end{bmatrix} = \begin{bmatrix} k_1 \\ \frac{A-c-k_1}{2} \end{bmatrix}, \quad p^*(k_1;A) = \frac{A-c-k_1}{2}. \tag{7}$$

If $k_1 \in [\frac{A+c}{3}, \infty) \Leftrightarrow A \in (0, 3k_1 - c]$,

$$\begin{bmatrix} x_1^*(k_1;A) & y_1^*(k_1;A) \\ \cdot & y_2^*(k_1;A) \end{bmatrix} = \begin{bmatrix} \frac{A+c}{3} & 0 \\ \cdot & \frac{A-2c}{3} \end{bmatrix}, \quad \begin{bmatrix} q_1^*(k_1;A) \\ q_2^*(k_1;A) \end{bmatrix} = \begin{bmatrix} \frac{A+c}{3} \\ \frac{A-2c}{3} \end{bmatrix}, \quad p^*(k_1;A) = \frac{A+c}{3}. \tag{8}$$

Similarly to the monopolist problem in the previous section, firm 1's equilibrium production plan is differentiated into three distinct cases. When $A > 3k_1 + c$ (high-demand case), firm 1 utilizes gas-fired power plants. Otherwise, firm 1 utilizes only nuclear power; when $3k_1 + c > A > 3k_1 - c$ (intermediate case), firm 1's nuclear power plant is at full operation; but when $A < 3k_1 - c$ (low-demand case), the firm ends up with idle capacity. Note that in any of the three cases, firm 2 always produces some electricity by using gas-fired power technology.

From these results, for given values of k_1 and A, we obtain firm 1's profit excluding the cost

[19] Note that, from A.3, we have an interior solution with respect to q_1 and q_2 for all $A \in [L, H]$.

of developing the nuclear plant capacity as[20]

$$\pi_1^*(k_1;A)=\begin{cases}\frac{(A-c)^2}{9}+k_1c & \text{if } k_1\in[0,\frac{A-c}{3}]\Leftrightarrow A\in[3k_1+c,\infty],\\ \frac{k_1(A+c-k_1)}{2} & \text{if } k_1\in[\frac{A-c}{3},\frac{A+c}{3}]\Leftrightarrow A\in[3k_1-c,3k_1+c],\\ \frac{(A+c)^2}{9} & \text{if } k_1\in[\frac{A+c}{3},\infty)\Leftrightarrow A\in(0,3k_1-c].\end{cases}$$

4.2 Capacity-setting stage

Firm 1's expected profit maximization problem in the initial capacity-setting stage is given by

$$\max_{k_1}\ \frac{1}{H-L}\int_L^H \pi_1^*(k_1;a)da - rk_1. \tag{9}$$

Let k_1^* be the solution to this problem; that is, the equilibrium capacity of its nuclear plant under the duopoly with a new entrant.

Given $\frac{H-c}{3}>\frac{L+c}{3}$ by A.1, firm 1's marginal expected revenue in this stage, $MR^*(k_1)$, is given as follows:[21]

$$\frac{\partial}{\partial k_1}\frac{1}{H-L}\int_L^H \pi_1^*(k_1;a)da=\begin{cases}c & \text{if } k_1\in[0,\frac{L-c}{3}],\\ \frac{1}{H-L}\left[\frac{4cH-(L+c)^2}{4}+(L-c)k_1-\frac{3}{4}k_1^2\right] & \text{if } k_1\in[\frac{L-c}{3},\frac{L+c}{3}],\\ \frac{1}{H-L}\left[cH-2ck_1\right] & \text{if } k_1\in[\frac{L+c}{3},\frac{H-c}{3}],\\ \frac{1}{H-L}\left[\frac{(H+c)^2}{4}-(H+c)k_1+\frac{3}{4}k_1^2\right] & \text{if } k_1\in[\frac{H-c}{3},\frac{H+c}{3}],\\ 0 & \text{if } k_1\in[\frac{H+c}{3},\infty].\end{cases} \tag{10}$$

The curve $ABEFCG$ in Figure 1 depicts the shape of this expected marginal revenue.

As Figure 1 shows, although the expected marginal revenue increases above c at first, it is continuous and strictly decreasing when $MR^*(k_1)$ is in the interval of $(0,c)$. Therefore, by A.2, the first-order condition,

$$MR^*(k_1)=r, \tag{11}$$

[20] π_1^* is not differentiable but it is continuous in k_1.

[21] We provide a supplementary material that helps readers to replicate the computation of (10).

is the necessary and sufficient condition for the maximization problem in (9). In other words, the curve MFCG in Figure 1 is firm 1's demand curve for the capacity k_1 in the presence of a competitor. Solving it for k_1 yields the following result:

Lemma 2 *Suppose A.1–A.3. Then,*

$$k_1^* = \begin{cases} \frac{cH - r(H-L)}{2c} & \text{if } r \in \left[c - \frac{c(2H-3L-2c)}{3(H-L)}, c\right), \\ \frac{1}{3}\left(2H + 2c - \sqrt{(H+c)^2 + 12r(H-L)}\right) & \text{if } r \in \left(0, c - \frac{c(2H-3L-2c)}{3(H-L)}\right]. \end{cases} \tag{12}$$

Proof See Appendix A.

If r is within the range of the first line of (12), $k_1^* \in [\frac{L+c}{3}, \frac{H-c}{3}]$ (MF in Figure 1), and, if r is within the range of the second line of (12), $k_1^* \in [\frac{H-c}{3}, \frac{H+c}{3}]$ (FG in Figure 1). Therefore, by (6), $y_1^*(H) > 0$ if and only if $r > c - \frac{c(2H-3L-2c)}{3(H-L)}$.[22] In other words, gas-fired power generation technology is used to meet high demand when the nuclear power plant is not sufficiently efficient. Again, the threshold value of r is obtained as

$$c - \frac{c(2H-3L-2c)}{3(H-L)} = \frac{c(H+2c)}{3(H-L)} = \frac{c(E(A)+2c)}{6\sqrt{3\,Var(A)}} + \frac{c}{6}.$$

Thus, if $Var(A)$ increases while preserving the mean $E(\mathrm{A})$, gas-fired power plants are utilized even with a lower value of r.[23] This is because increasing the capacity of a nuclear plant, while lowering the unit production cost, implies heightened exposure to the risk of carrying idle capacity, similar to the case of a monopolist in the previous section.

4.3 Comparison

The following proposition summarizes how the entry of firm 2 changes the capacity of a nuclear power plant when compared to the monopoly case. The equilibrium capacity of a nuclear power plant expands under competition if and only if the nuclear plant is sufficiently inefficient

[22] This value is strictly smaller than c because $2H - 3L - 2c > 0$ by A.1.

[23] Note that since $y_1^*(A)$ is non-decreasing in A by (6)–(8), $y_1^*(A) = 0$ for all $A \in [L, H]$ if $y_1^*(H) = 0$.

$(r > \hat{r})$.[24]

Proposition 1 *Suppose A.1–A.3. Then, there exists* $\hat{r} \in (0, c)$ *such that*

$$k_1^* \lesseqgtr k_1^m \Leftrightarrow r \lesseqgtr \hat{r}.$$

Proof See Appendix A.

Surprisingly, when a new entrant is introduced to the market, nuclear power generation technology increases its overall presence provided that it is sufficiently *inefficient*. The source of this capacity expansion is a strategic effect against a new competitor, which arises due to the relative cost structures of the nuclear and gas-fired power generation technologies. Since a nuclear plant has a lower marginal production cost in the quantity-setting stage, by raising its capacity, firm 1 can effectively commit itself to a larger production level and deter the production of its competitor (firm 2). This strategic effect encourages firm 1 to develop a larger capacity of its nuclear plant.[25] However, the introduction of a competitor into the market also has an opposing effect. A new entrant competes for a part of the electricity demand in a duopoly market, and this effect alone reduces the capacity of a nuclear power plant of the incumbent (firm 1). In other words, production substitution from firm 1 to firm 2 discourages firm 1 from increasing the capacity of its nuclear plant.[26]

Why does the former strategic effect (positive effect) dominate the latter production substitution effect (negative effect), particularly when the nuclear plant is sufficiently inefficient? The intuition behind this result is as follows. When r is sufficiently large $(r > \hat{r})$, according to the trade-off between cost saving and risk management, only a small portion of firm 1's electricity

[24] If A.1. is violated, that is, $Var(A) \leq (L + 2c)^2/48$, it is possible to have $k_1^* < k_1^m$ for all $r \in (0, c)$. However, even in such a case, if we suppose $r > c$, we have $k_1^* > k_1^m$ unless r is so high that $k_1^* = k_1^m = 0$ holds. This is because, when $r > c$, unless r is extremely high, a nuclear plant is built under duopoly in order to deter firm 2's production (indeed, we have a region where $MR^*(k_1) > c$). If $r > c$, no nuclear plant is established under monopoly, since it has no cost advantage but simply exposes the firm to the risk of carrying an idle capacity.

[25] This strategic effect is essentially the same as the entry deterrence effect of cost-reducing investment studied in Dixit (1980). The investment cost and associated reduction in the marginal production cost in Dixit (1980) corresponds to the relatively high set-up cost and relatively low production cost of a nuclear power plant in our context.

[26] For the general principle of production substitution, see Lahiri and Ono (1988).

r	large ($r > \hat{r}$)	small ($r < \hat{r}$)
strategic effect	$++$	$+$
production substitution effect	$-$	$--$
total effect	$+$	$-$

Table 1: Effects of competition on nuclear capacity

supply is produced by nuclear power technology under a monopoly to begin with. Then, after the entry, an increase in firm 1's nuclear capacity deters firm 2's production more effectively than the case in which a large portion has already been produced by nuclear power because of a smaller r. Hence, the positive strategic effect is relatively large (represented by double + in Table 1) when r is larger. By contrast, the negative effect of production substitution is relatively small (represented by single − Table 1) when nuclear power is a small portion of firm 1's power source. This is because the production substitution effect contributes to a reduction of firm 1's nuclear capacity only when its electricity supply produced by nuclear power is replaced by firm 2's supply produced by gas-fired power. When gas-fired technology is utilized on a large scale, the production substitution effect does not have a significant effect on the nuclear capacity. Therefore, when r is sufficiently large, the former positive strategic effect is more likely to dominate the negative effect of production substitution (represented by single + of total effect in Table 1). In the opposite case, where r is sufficiently small ($r < \hat{r}$), the negative production substitution effect overwhelms the positive strategic effect, as shown in the second column of Table 1.

5 Environmental implications

In the presence of a carbon tax, the marginal production cost, c, is considered to be comprised of two components: c_0, which is the marginal production cost by gas-fired technology, and t, which is a unit tax imposed on carbon emissions (or equivalently, electricity production in our model) by gas-fired power plants. In this section, we reinterpret the previous result with respect to the level of c above, and discuss environmental implications of imposing a carbon tax, in view of $c = c_0 + t$.

In particular, we find that the nuclear capacity tends to *decrease* with the introduction of a competitor when the prevailing level of carbon tax is sufficiently high, as in the following proposition.[27]

Proposition 2 *Suppose A.1–A.3. Then, there exists* $\hat{c} \in (0, L/2)$ *such that*

$$k_1^* \lesseqqgtr k_1^m \Leftrightarrow c \gtreqqless \hat{c}.$$

if and only if $r < \hat{r}|_{c=L/2}$*, or* $r = \hat{r}|_{c=L/2}$ *and* $Var(A) < 9L^2/48$*, where*

$$\hat{r}|_{c=\frac{L}{2}} = \frac{L}{12}\left(4\sqrt{(H - \frac{L}{2})^2 + L^2} - \frac{4H - 5L}{2}\right) > 0.$$

Proof See Appendix A.

An imposition of a high tax on gas-originated electricity may seem to give a competitive advantage to nuclear power generation technology. However, the capacity of a nuclear plant actually *decreases* when the incumbent anticipates a competitor's entry for a sufficiently high level of carbon tax. In fact, Proposition 2 is a straightforward extension of Proposition 1, which states that the introduction of a competitor decreases nuclear capacity when r is relatively small for a given level of c. In essence, the nuclear capacity shrinks with the entry when the difference between c and r is sufficiently significant.

When a carbon tax has been implemented before the capacity of nuclear power is chosen, such a tax has an additional influence upon the effects of competition in choosing the nuclear capacity. In the circumstance where the level of the carbon tax is sufficiently significant relative to the capacity-building cost of a nuclear power plant, an environmental issue associated with carbon emissions is more pressing. Then, the government would welcome a shift from a carbon-emitting technology to a carbon-free technology. However, when a market deregulation is anticipated or taken place concurrently, the environmental performance of a carbon tax can be compromised because the incumbent reduces its nuclear capacity especially in a case with a high level of the

[27] Note that $c \in (r, L/2)$ by A.2 and A.3. Thus, if $\hat{c} \leq r$, Proposition 2 implies that $k_1^* < k_1^m$ for all the allowed levels of c.

tax.

As a caveat, the necessary and sufficient condition for inducing this result is indicated in the latter part of this proposition, which requires that the capacity-building cost of a nuclear power plant r, as well as the volatility of demand $Var(A)$, should not be too large. If the condition is violated, it is possible that k_1^* never exceeds k_1^m even for a high value of c.

6 Simulation

To obtain further insights from the implications of our model, we conduct simple simulation analyses of two numerical examples: a case with low demand volatility ($H = 4$, $L = 2$, and $c = 0.4$), and one with high demand volatility ($H = 5$, $L = 1$, and $c = 0.4$). The latter case has a higher $Var(A)$ than the former while both cases share the same mean $E(A) = 3$.[28]

First, we discuss how the equilibrium management of the nuclear power plant is affected by the marginal capacity cost and the demand volatility. Figure 3 shows how a change in the value of r affects the expected market shares of electricity generated by nuclear power generation technology in each case, that is, $E_A\left[\frac{x_1^m(k_1^m;A)}{q_1^m(k_1^m;A)}\right]$ in the monopoly case and $E_A\left[\frac{x_1^*(k_1^*;A)}{q_1^*(k_1^*;A)+q_2^*(k_1^*;A)}\right]$ in the duopoly case, and the respective expected operating rates of the nuclear power plant, that is, $E_A\left[\frac{x_1^m(k_1^m;A)}{k_1^m}\right]$ in the monopoly case and $E_A\left[\frac{x_1^*(k_1^*;A)}{k_1^*}\right]$ in the duopoly case. These results can be understood based on the discussion of Lemma 1. As r becomes smaller, the expected market share of the nuclear power generation increases, since gas-fired power plants tend to be utilized at a smaller scale owing to the cost advantage of a nuclear power plant. Nonetheless, the expected operating rate of the nuclear power plant decreases, since the firm cares less about the risk of being saddled with excess capacity when r is relatively small. Demand volatility accelerates these tendencies.

Next, we discuss how competition influences the use of nuclear power technology. We summarize the simulation results of our two cases with high and low demand volatility in Figure 4. The graphs depict how much the respective equilibrium values under duopoly differ from those under monopoly, that is, $k^* - k^m$ for the equilibrium capacity of the nuclear plant,

[28]The volatility sizes are not too far from the actual size reported for France (Léautier, 2018).

$E_A(x_1^*(k^*;A)) - E_A(x_1^m(k^m;A))$ for the expected nuclear power outputs, and so forth.

As Proposition 1 shows, competition increases the equilibrium capacity size of the nuclear plant if and only if r is sufficiently large (top-left panel). Its threshold value, $\hat{r}$, is lower in the case with high demand volatility ($\hat{r}_H$ in the figure) than in the case with low demand volatility ($\hat{r}_L$ in the figure).

The difference in the expected total outputs is always positive (top-right panel). Indeed, as is typically the case with a standard duopoly model, we can analytically show that the expected total output increases because of the added competition,[29] that is,

$$E_A[q_1^*(k_1^*;A) + q_2^*(k_1^*;A)] > E_A[q_1^m(k_1^m;A)]. \tag{13}$$

Note that this is true even when the capacity of a nuclear power plant shrinks.

To obtain a positive difference of the expected outputs generated by the nuclear power technology, r must be higher than $\hat{r}$ in both cases with high and low demand volatility (middle-left panel). Because the new entrant steals a portion of business from the incumbent with a nuclear plant, the output from the nuclear plant does not necessarily increase even when its capacity expands (right-hand side of the dotted line). By contrast, the output of the nuclear plant necessarily decreases if its capacity shrinks (left-hand side of the dotted line). Indeed, we can analytically show that[30]

$$E_A(x_1^*(k^*;A)) < E_A(x_1^m(k^m;A)) \tag{14}$$

if $k^* < k^m$.

Thus, from (13) and (14), if the capacity of a nuclear power plant under duopoly is smaller than that under monopoly ($k^* < k^m$), the market share of nuclear power generation necessarily decreases (left-hand side of each dotted line in bottom-left panel). This implies that, when the nuclear power generation technology is sufficiently efficient, introducing competition decreases the market share of the nuclear technology as an electric power source.

[29] The formal proof is available upon request.
[30] The formal proof is available upon request.

Even if $k^* > k^m$, the market share of the nuclear power may not increase. This is because, as mentioned above, competition always increases the total output, and at the same time can decrease the output of the nuclear plant even when $k^* > k^m$ holds. For instance, in our case with low demand volatility, the difference in the market shares of the nuclear power generation is always negative regardless of the value of r (bottom-left panel). However, for our case with high demand volatility, it is possible for nuclear power to increase its overall market share as a power source when the nuclear power generation technology is sufficiently inefficient (bottom-left panel).

7 Concluding remarks

In this study, we investigated how the introduction of a competitor affects the behavior of an electricity producer and discussed its implications for the resulting market shares of different electric power sources. Specifically, we considered the case in which a new competitor with no access to technologies that require significant capacity-building cost, such as nuclear power, enters a market that was originally served by a local monopolist. As our main result, we found that a sufficiently high cost of operationalizing a nuclear power plant leads to larger capacity for nuclear power generation in the duopoly case than in the monopoly environment. We also reinterpreted this result from a perspective of environmental policy.

The cost of operationalizing a nuclear power plant is becoming significantly higher in Japan especially because stricter regulations are being implemented in the wake of the Fukushima-Daiichi accident in 2011 and opinions against nuclear power generation are gaining further popularity in both the news media and political arenas. Our analysis suggests that this trend may paradoxically lead to larger presence of nuclear power generation when the deregulation of the local electricity market is anticipated. The deregulation of regional power markets in Japan has been under way for quite some time now and has gained steam especially after the accident.

Furthermore, whereas the entry of a competitor into a formerly monopolized electricity market always increases the consumer surplus in our context, our analytical findings would hint at the possibility of welfare-worsening deregulation provided that the cost of developing a nuclear power plant is sufficiently high. A full analytical investigation of welfare-related outcomes is left for future research.[31]

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APPENDIX

A Proofs

Proof of Lemma 2. First, note that $MR^*(k_1) \geq c$ when $k_1 \leq \frac{L+c}{3}$, and also that $MR^*(k_1) = 0$ when $k_1 \geq \frac{H+c}{3}$. The former is true because $MR^*(k_1)$ is quadratic and convex upward in k_1 when $k_1 \in [\frac{L-c}{3}, \frac{L+c}{3}]$ and

$$MR^*\left(\frac{L-c}{3}\right) = c, MR^*\left(\frac{L+c}{3}\right) = c + \frac{c(L-2c)}{3(H-L)} > c.$$

Therefore, we have $k_1^* \in (\frac{L+c}{3} \frac{H+c}{3})$ by A.2 and (11).

Next, observe that $MR^*(k_1)$ is strictly decreasing for $k_1 \in [\frac{L+c}{3}, \frac{H+c}{3}]$. The decline of $MR^*(k_1)$ for $k_1 \in [\frac{L+c}{3}, \frac{H-c}{3}]$ is clear by (10) and that for $k_1 \in [\frac{H-c}{3}, \frac{H+c}{3}]$ is implied by the following three facts: (i) $MR^*(k_1)$ is quadratic and convex downward in k_1 for $k_1 \in [\frac{H-c}{3}, \frac{H+c}{3}]$, (ii) $MR^*(\frac{H-c}{3}) > 0$, and (iii) $MR^*(\frac{H+c}{3}) = 0$. Note that $MR^*(\frac{H-c}{3}) > 0$ is induced from the second equality of the following expression:

$$MR^*\left(\frac{H-c}{3}\right) = \frac{c(H+2c)}{3(H-L)} = c - \frac{c(2H-3L-2c)}{3(H-L)}. \tag{A.1}$$

Therefore, the second-order condition is globally satisfied for $k_1 \in [\frac{L+c}{3}, \frac{H+c}{3}]$.

From the third term in (A.1), $MR^*(\frac{H-c}{3}) < c$ by A.1, which is equivalent to $2H-3L-2c > 0$ since $\mathrm{Var}(A) = \frac{(H-L)^2}{12}$. Hence, for $r \in [MR^*(\frac{H-c}{3}), c)$, we have $k_1^* \in (\frac{L+c}{3}, \frac{H-c}{3}]$ and for

$r \in (0, MR^*(\frac{H-c}{3})]$, we have $k_1^* \in [\frac{H-c}{3}, \frac{H+c}{3})$. Notice that this is because $MR^*(k_1)$ is strictly decreasing for $k_1 \in [\frac{L+c}{3}, \frac{H+c}{3}]$. Therefore, by substituting the expression (10) in each case, solving the first-order condition (11) yields the result of Lemma 2. **Q.E.D.**

Proof of Proposition 1. Lemmas 1 and 2 imply

$$\lim_{r \to 0} k_1^* = \frac{H+c}{3} < \lim_{r \to 0} k_1^m = \frac{H}{2}.$$

where the inequality holds by A.3. In other words, we have $k_1^* < k_1^m$ when r is sufficiently close to 0. Furthermore, Lemmas 1 and 2 imply

$$\lim_{r \to c} k_1^* = \frac{L}{2} > \lim_{r \to c} k_1^m = \frac{L-c}{2}.$$

In other words, we have $k_1^* > k_1^m$ when r is sufficiently close to c. Hence, $MR^m(k_1)$ and $MR^*(k_1)$ intersect at least once on $(0, c)$ by their continuity.

Thus, the proof is complete if $MR^m(k_1)$ and $MR^*(k_1)$ intersect exactly at a single point on $(0, c)$ (see figure 1). In terms of absolute values, (i) the slope of $MR^m(k_1)$ is smaller than or equal to $\frac{2c}{H-L}$ for all k_1 by (4) and (ii) the slope of $MR^*(k_1)$ is larger than or equal to $\frac{2c}{H-L}$ when $k_1 > \frac{L+c}{3}$ by (10). Observe that (i) is true since the slope of $MR^m(k_1)$ equals $-\frac{2c}{H-L}$ when $k_1 \in (\frac{L}{2}, \frac{H-c}{2})$, and we have the following relations:

$$\frac{\partial MR^m}{\partial k_1}(k_1) = -\frac{2(L-c)+4k_1}{H-L} > \frac{\partial MR^m}{\partial k_1}\left(\frac{L}{2}\right) = -\frac{2c}{H-L}, \tag{A.2}$$

$$\frac{\partial MR^m}{\partial k_1}(k_1) = -\frac{2H-4k_1}{H-L} > \frac{\partial MR^m}{\partial k_1}\left(\frac{H-c}{2}\right) = -\frac{2c}{H-L}, \tag{A.3}$$

where (A.2) holds for $k_1 \in (\frac{L-c}{2}, \frac{L}{2})$ and (A.3) holds for $k_1 \in (\frac{H-c}{2}, \frac{H}{2})$. Notice that the inequalities of (A.2) and (A.3) hold because $MR^m(k_1)$ is decreasing, and quadratic functions convex upward and downward in respective regions. Furthermore, we observe that (ii) is true since the slope of $MR^*(k_1)$ equals $-\frac{2c}{H-L}$ for $k_1 \in (\frac{L+c}{3}, \frac{H-c}{3})$, and we have

$$\frac{\partial MR^*}{\partial k_1}(k_1) = -\frac{2(H+c)-3k_1}{2(H-L)} < \frac{\partial MR^*}{\partial k_1}\left(\frac{H+c}{3}\right) = -\frac{H+c}{2(H-L)} < -\frac{2c}{H-L}, \tag{A.4}$$

for $k_1 \in (\frac{H-c}{3}, \frac{H+c}{3})$. Notice that the first inequality holds because $MR^*(k_1)$ is a quadratic function convex upward and decreasing for $k_1 \in (\frac{H-c}{3}, \frac{H+c}{3})$ and that the final inequality holds since A.1 and A.3 imply that $H > 4c$. Moreover, if the slopes of both $MR^*(k_1)$ and $MR^m(k_1)$ are equal to $-\frac{2c}{H-L}$ for some k_1, then

$$MR^*(k_1) = \frac{cH - 2ck_1}{H-L} > MR^m(k_1) = \frac{cH-2ck_1}{H-L} - \frac{c^2}{2(H-L)}, \tag{A.5}$$

by (10) and (4). Hence, $MR^*(k_1)$ and $MR^m(k_1)$ never intersect at more than one point. **Q.E.D.**

Proof of Proposition 2. We start by explicitly deriving $\hat{r}$ provided in Proposition 1. In Figure 1, this threshold is obtained as the level of r at intersection C. Let the corresponding level of k_1 at this threshold be $\hat{k}$. From (A.5), we have already seen that the intersection never lies above point F in the figure. Moreover, when $r = c^2/2(H-L)$, by Lemmas 1 and 2, we have

$$k_1^m - k_1^* = \frac{H-c}{2} - \frac{1}{3}\left(2H + 2c - \sqrt{(c+H)^2 + 6c^2}\right) \equiv F(H,c) > 0.$$

Here, the positivity is obtained from $H > 4c$ by A.1 and A.3 as well as $F(4c, c) > 0$, and $\partial F/\partial H > 0$ for $H > 4c$. Thus, MR^m and MR^* must intersect when MR^m (MR^*) is in the case in which $k_1 \in [\frac{L}{2}, \frac{H-c}{2}]$ ($k_1 \in [\frac{H-c}{3}, \frac{H+c}{3}]$). Thus, by solving $MR^m = MR^*$ in these cases, we obtain $\hat{k} = (2(H-c) - \sqrt{\alpha})/3$, where $\alpha = (H-c)^2 - 6c^2$. Note that $\alpha > 0$ by $H - c > 3c$ (recall $H > 4c$ by A.1 and A.3). Plugging $k = \hat{k}$ into MR^m yields $\hat{r}$ as a function of c:

$$\hat{r}(c) = \frac{c}{6}\left(5c - 2H + 4\sqrt{\alpha}\right).$$

In the following, we show the requested result by applying this expression of $\hat{r}$ to Proposition

1. First, it should be noted that $\hat{r}(c)$ is single–peaked at $c = H/5$. This is because we have

$$\frac{\partial \hat{r}(c)}{\partial c} = \frac{(5c - H)\left(\sqrt{\alpha} - 2(H + 2c)\right)}{3\sqrt{\alpha}}.$$

In addition, the value within the second parentheses in the numerator is smaller than $\sqrt{(H-c)^2} - 2(H + 2c) = -H - 5c < 0$. Thus,

$$\frac{\partial \hat{r}}{\partial c} \lesseqgtr 0 \Leftrightarrow 5c - H \gtreqless 0. \tag{A.6}$$

Now, suppose that $r \leq \hat{r}(L/2)$ and $L/2 > H/5$ (or, $Var(A) < 9L^2/48$) where

$$\hat{r}\left(\frac{L}{2}\right) = \frac{L}{12}\left(4\sqrt{(H - \frac{L}{2})^2 + L^2} - \frac{4H - 5L}{2}\right) > 0.$$

Then, because of the single peaked property of $\hat{r}(c)$, we have $r \leq \hat{r}(H/5)$, and $\hat{r}(c)$ is strictly increasing in $c \in (0, H/5]$. Thus, by also noting $r > \hat{r}(0) = 0$,

$$\exists \hat{c} \in (0, H/5], \forall c \in (0, H/5], \hat{r}(c) \gtreqless r \Leftrightarrow c \gtreqless \hat{c}. \tag{A.7}$$

Furthermore, $L/2 > H/5$ implies that for $c \in (H/5, L/2)$, $\hat{r}(c) > \hat{r}(L/2) \geq r$ by (A.6). From this and (A.7), we obtain

$$\exists \hat{c} \in (0, L/2), \forall c \in (0, L/2), \hat{r}(c) \gtreqless r \Leftrightarrow c \gtreqless \hat{c}. \tag{A.8}$$

By Proposition 1, $\hat{r}(c) \gtreqless r$ in (A.8) is equivalent to $k_1^* \lesseqgtr k_1^m$, which is the requested result.

Next, suppose that $r \leq \hat{r}(L/2)$ and $L/2 \leq H/5$ (or, $Var(A) \geq 9L^2/48$). Then, similarly to (A.7), we obtain

$$\exists \hat{c} \in (0, L/2], \forall c \in (0, L/2], \hat{r}(c) \gtreqless r \Leftrightarrow c \gtreqless \hat{c}. \tag{A.9}$$

In particular, when $r < \hat{r}(L/2)$, we have $\hat{c} < L/2$, and thus, the same result as (A.8) is obtained. However, when $r = \hat{r}(L/2)$, we obtain $\hat{c} = L/2$. Hence, (A.9) implies that for all $c \in (0, L/2)$, we have $\hat{r}(c) < r$, which gives $k_1^* > k_1^m$ by Proposition 1.

Finally, suppose that $r > \hat{r}(L/2)$. Then, if there exists $\hat{c} \in (0, L/2)$ such that $\hat{r}(c) > r$ for all $c \in (\hat{c}, L/2)$, $\hat{r}(L/2) \geq r$ must hold by the continuity of $\hat{r}(c)$, which is a contradiction. **Q.E.D.**

B Price-regulated monopolist

Here, we consider a case where the electricity price charged by a monopolist, firm 1, is capped at $\bar{p} \in [c, L]$. The firm is obligated to meet all the demand under this regulated price.

B.1 Quantity-setting stage

In the production stage, firm 1 must supply $\bar{q}_1(A) = A - \bar{p}$, but they can choose x_1 and y_1 to minimize its variable cost:

$$\min_{x_1, y_1} 0 \cdot x_1 + cy_1 \text{ s.t. } x_1 \leq k_1, \; x_1 + y_1 = \bar{q}_1(A)$$

The equilibrium outcomes for given k_1 and A are as follows.

$$(\bar{x}_1(k_1; A), \bar{y}_1(k_1; A)) = \begin{cases} (k_1, A - \bar{p}) & \text{if } k_1 \in [0, A - \bar{p}] \Leftrightarrow A \in [k_1 + \bar{p}, \infty) \\ (A - \bar{p}, 0) & \text{if } k_1 \in [A - \bar{p}, \infty) \Leftrightarrow A \in (0, k_1 + \bar{p}] \end{cases}$$

Note that in both cases, $q_1 = A - \bar{p}$ and $p = \bar{p}$ due to the price regulation. Then, the monopolist's profit without the set-up cost of capacities is given by

$$\bar{\pi}_1(k_1; A) = \begin{cases} (\bar{p} - c)(A - \bar{p}) + ck_1 & \text{if } k_1 \in [0, A - \bar{p}] \Leftrightarrow A \in [k_1 + \bar{p}, \infty) \\ (A - \bar{p})\bar{p} & \text{if } k_1 \in [A - \bar{p}, \infty) \Leftrightarrow A \in (0, k_1 + \bar{p}]. \end{cases}$$

B.2 Capacity-setting stage

In the capacity-setting stage, firm 1 maximizes the expected profit by choosing the capacity of a base-load technology, i.e.,

$$\max_{k_1} \frac{1}{H-L}\int_L^H \bar{\pi}_1(k_1;a)da - rk_1. \tag{B.1}$$

Let $\bar{k}_1$ be the solution of this problem, that is, the equilibrium capacity of the base-load technology in the monopoly market.

Firm 1's marginal expected revenue in the first stage, $\bar{MR}(k_1)$, is as follows.

$$\frac{d}{dk_1}\frac{1}{H-L}\int_L^H \bar{\pi}_1(k_1;a)da = \begin{cases} c & \text{if } k_1 \in [0, L-\bar{p}] \\ \frac{1}{H-L}\left[c(H-\bar{p}) - ck_1\right] & \text{if } k_1 \in [L-\bar{p}, H-\bar{p}] \\ 0 & \text{if } k_1 \in [H-\bar{p}, \infty) \end{cases} \tag{B.2}$$

Therefore, by A.2, the first order condition, $\bar{MR}(k_1) = r$, is the necessary and sufficient condition for the problem (B.1).

We compare this regulated monopoly outcome with that of the deregulated duopoly that is detailed in Section 4.

Proposition 3 *Suppose A.1-A.3. Then,*

$$\left|\frac{d\bar{MR}(k_1)}{dk_1}\right| < \left|\frac{dMR^*(k_1)}{dk_1}\right|$$

for all k_1 *such that* $\bar{MR}(k_1), MR^*(k_1) \in (0,c)$.

Proof In the proof of Proposition 1, we have already shown that, in terms of its absolute value, the slope of MR^* is larger than or equal to $\frac{2c}{H-L}$ when $MR^* \in (0,c)$ while the slope of $\bar{MR}$ is equal to $\frac{c}{H-L}$ when $\bar{MR} \in (0,c)$ by (B.2). **Q.E.D.**

Thus, if the curves $\bar{MR}(k_1)$ and $MR^*(k_1)$ ever cross, they do so only once, and the similar relationship to Proposition 1 holds: an introduction of competition (accompanied by price deregulation) increases the capacity of a base-load technology if and only if r is sufficiently large.

As a caveat, we must note that $\bar{M}R(k_1)$ and $MR^*(k_1)$ do not necessarily cross because the supply under the price regulation depends on the level of a regulated price. For instance, if the regulated price is sufficiently low (close to c) and the obligated supply becomes sufficiently large, it is possible that $\bar{M}R > MR^*$ holds everywhere, and the capacity of a base-load technology under competition k_1^* never exceeds that under the price-regulated monopoly for all $r \in (0, c)$.

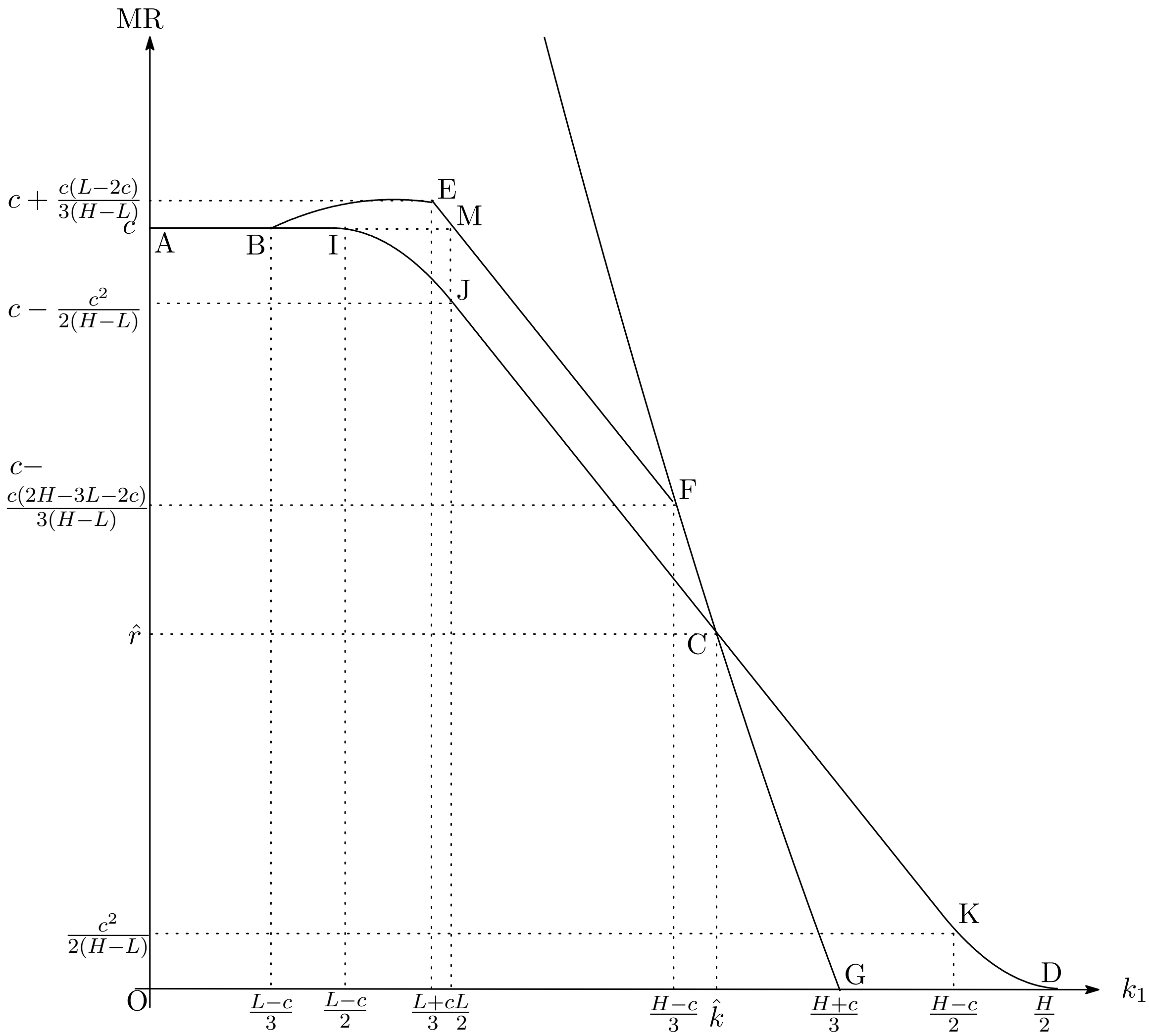

Figure 1: Expected marginal revenue with respect to the nuclear plant's capacity k_1 (ABCD is in the case of monopoly and ABEFCG is in the case of duopoly.

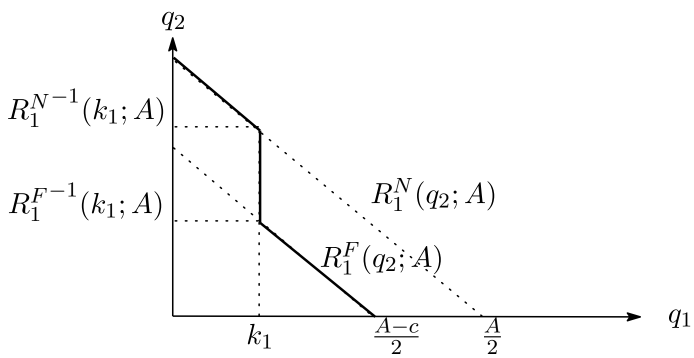

Figure 2: Reaction function of firm 1 given its nuclear plant's capacity k_1

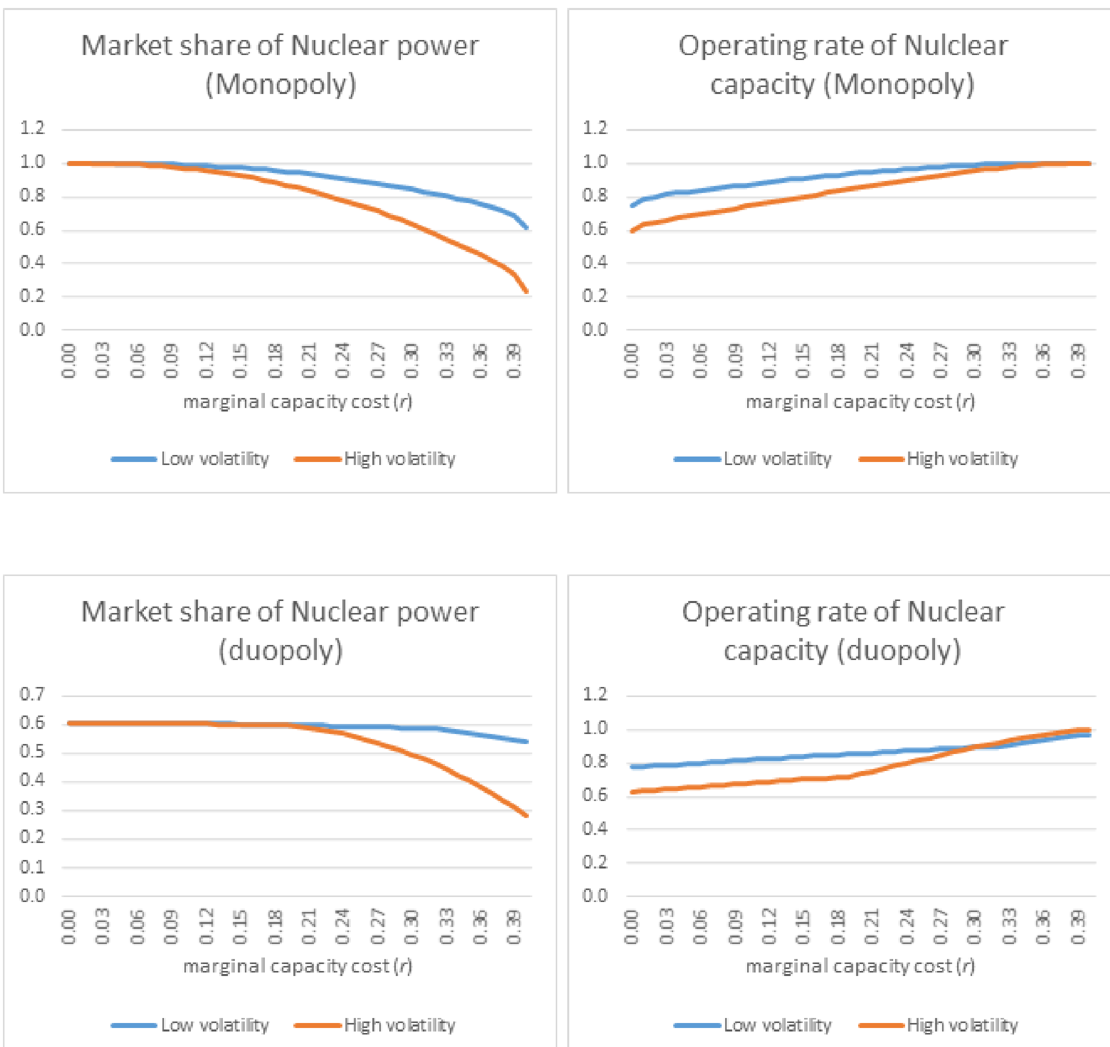

Figure 3: Equilibrium management of nuclear power ("Low volatility" simulates a case with low demand volatility, and "High volatility" simulates a case with high demand volatility.)

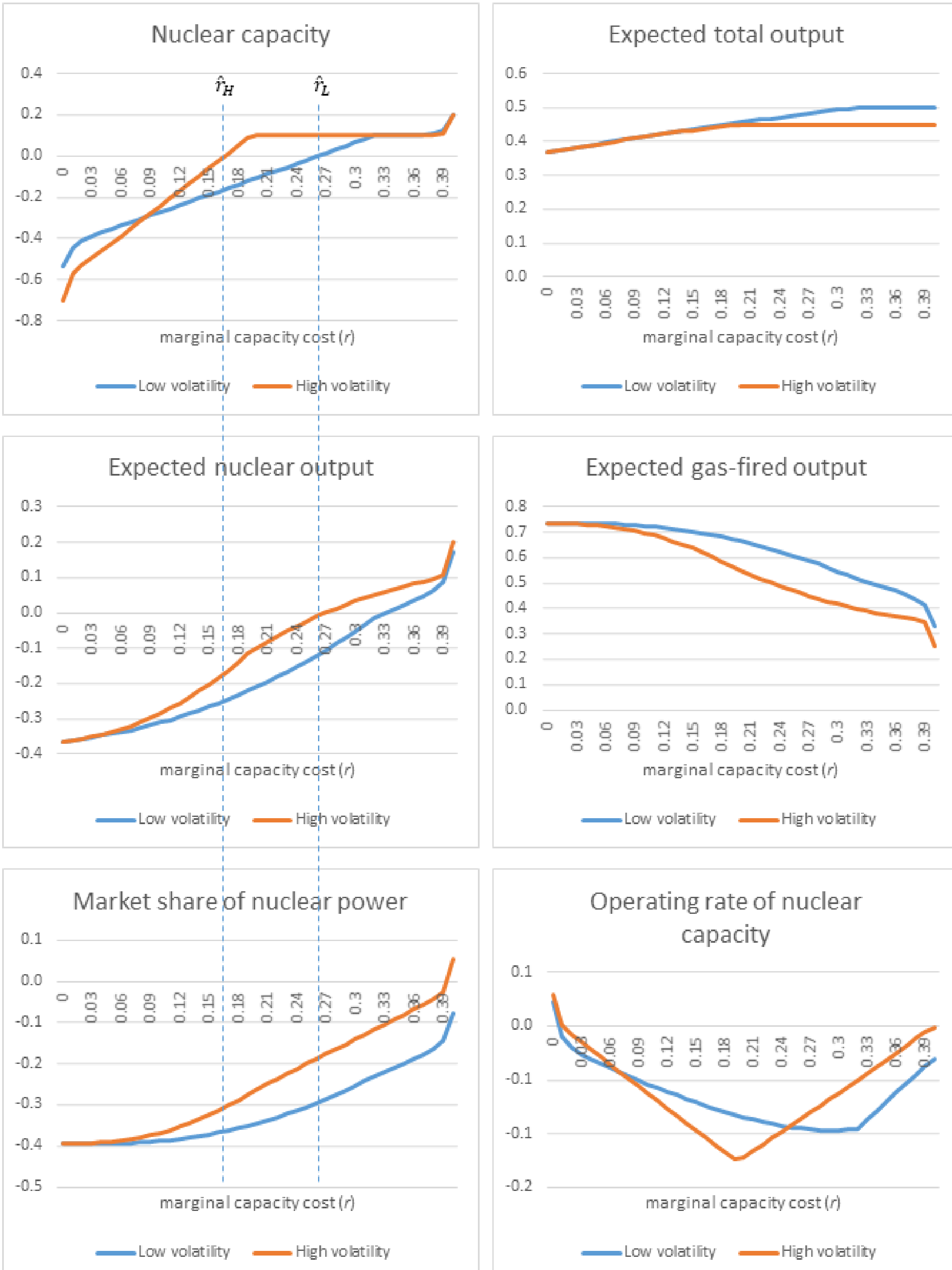

Figure 4: Effect of competition (The graphs depict how much the respective equilibrium values under duopoly differ from those under monopoly.)