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Fuel diversification among firms and common ownership*

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Abstract

We develop a duopoly model that incorporates fuel diversification, resulting in *ex post* cost asymmetry between firms. We theoretically examine how common ownership influences welfare. Our findings indicate that welfare decreases (increases) with the degree of common ownership when *ex post* cost heterogeneity due to fuel diversification is small (large). Furthermore, we identify a potential U-shaped relationship between the degree of common ownership and welfare, an insight not previously documented in the literature. In addition, we demonstrate that common ownership promotes fuel diversification, which may further enhance welfare.

JEL classification codes: Q4, L13, G23

Keywords: overlapping ownership, welfare-improving production substitution, cost asymmetry, fuel choices

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Highlights

We investigate welfare consequences of fuel diversification.

Welfare effect of common ownership under fuel diversification is examined.

A U-shaped relationship between the degree of common ownership and welfare is found.

Common ownership enhances fuel diversification, which may further improve welfare.

1 Introduction

Firms have repeatedly faced fuel price spikes, with classical examples being the oil shocks of 1973 and 1978. In 2022, the prices of fossil fuels -such as coal, gas, and oil- rose sharply, albeit to varying degrees, altering their relative price rankings. For instance, in Japan, coal had traditionally been cheaper than gas, making coal-fired power plants suitable for baseload generation, while gas-fired power plants were used as flexible, mid-range sources. However, the drastic surge in coal prices in 2022 disrupted this structure, giving gas-fired power plants a cost advantage over coal-fired ones.[1]

The fuel price ranking may be affected by a CO2 price. A higher CO2 price and higher green premium weaken the cost advantage of coal to natural gas, and that of natural gas to green fuels such as hydrogen, bio-gas, and synthetic methane. Because CO2 prices fluctuate highly, the cost advantage of firms using coal (fossil fuels) to those using natural gas (green energy) may be vulnerable. Similar fluctuations of cost advantage will appear even among zero-emission fuels. JERA Co., Inc. that is one of the largest energy companies in Japan, committed to zero-emissions ammonia,[2] whereas Tokyo Gas Co., Ltd. that is the largest city gas company in Japan committed to synthetic methane.[3] The relative advantage of ammonia over synthetic methane will depend on future technological advancements in the production of both fuels, and therefore, considerable uncertainty remains.

In this study, we examine a market characterized by a duopoly in which firms use different types of fuel and therefore have heterogeneous cost structures, an aspect that has received limited attention in the existing literature. It is common to observe situations where one firm enjoys a cost advantage under certain conditions, while the other firm benefits under different circumstances.[4] Given such heterogeneity in cost structures, we investigate how

[1]https://www.enecho.meti.go.jp/about/whitepaper/2022/html/1-3-2.html

[2]https://www.jera.co.jp/en/action/discover/026

[3]https://www.tokyo-gas.co.jp/en/IR/support/pdf/20240319-03e.pdf

[4]The following examples illustrate our framework: firm 1 chooses coal (or other fossil fuels), while firm 2 opts for natural gas (or green fuels). Firm 1 has a cost advantage when the CO2 price is low, whereas firm

common ownership influences overall welfare.

One notable trend in recent financial markets is the increasing dominance of a few large investment firms and institutions. Several huge institutional investors and state-owned institutions own substantial shares in most major publicly listed firms worldwide, and these have significant Network Power Flow (NPF) (Mizuno et al., 2023).[5] Theoretical work by Moreno and Petrakis (2022) suggest that common ownership is a stable long-run outcome. When firms are influenced by the interests of shared owners, they may internalize the profits of competitors, leading to reduced competition (Azar et al., 2018; Moreno and Petrakis, 2022). This has prompted growing scrutiny of common ownership under antitrust legislation (Elhauge, 2016; Backus et al., 2021). Comparable effects have also been observed in cases of cross-ownership (Reynolds and Snapp, 1986; Farrell and Shapiro, 1990).

However, several studies point out possible welfare-improving effects of common ownership. While common ownership lessens competition in product markets and raises prices, common ownership may reduce welfare loss caused by other market failures by internalizing the positive externality of R&D (López and Vives, 2019), by reducing the welfare loss of excessive entries (Sato and Matsumura, 2020; Vives and Vravosinos 2025), by mitigating a double marginalization problem in vertically related markets (Chen et al,, 2024; Matsumura et al., 2025), and by reducing inefficient transportation (Liu and Matsumura, 2024).

In the context of energy and environmental economics, Bárcena-Ruiz and Campo (2017) and Bárcena-Ruiz and Sagasta (2021) investigate how cross-ownership affects the effectiveness of environmental policies. Hirose and Matsumura (2022) examine the relationship between common ownership and firms' environmental CSR commitments, while Hirose and Matsumura (2023) investigate its link to green transformation initiatives. Their findings

2 gains an advantage when the CO2 price is high. Another example involves one firm using fossil fuels and the other relying on electricity. Electricity prices can fluctuate sharply due to an oversupply or shortage of power from variable renewable energy sources, which in turn alters the relative cost competitiveness between firms.

[5]NPF is a measure of owners' corporate control influence to major firms through the global shareholding network, which is developed by Mizuno et al. (2023).

suggest potential welfare gains from common ownership but also a reduced motivation for firms pursue effective emission mitigation. Bui et al. (2025) further show that common ownership influences green licensing strategies and may contribute positively to welfare.

In the bulk of literature discussing energy choices, Stern et al. (2016) identify risk, emergent technologies, nested social hierarchies, and policy regulations as primary influencing factors of energy choices. Shahbaz et al. (2023) propose financial development as a novel determinant of energy diversification in the Australian economy, while Sun et al. (2024) emphasize the significance of globalization and economic growth in strengthening such diversification. Concurrently, other studies explore analytical methods applicable across various levels to both develop empirical knowledge about energy choices and identify promising strategies for change (Geels et al., 2016; Rai and Henry, 2016; Sovacool et al., 2016; Wong-Parodi et al., 2016).

In this study, we investigate the effects of common ownership in the presence of uncertainty regarding the cost advantages associated with specific fuels or energy technologies.[6] We find that common ownership consistently reduces welfare when the degree of heterogeneity among firms due to the fuel choices is small. However, when this heterogeneity is large, welfare may increase with the degree of common ownership (i.e., welfare-improving common ownership), or there may exist a U-shaped relationship between common ownership and welfare (i.e., a nonmonotonic relationship).[7] In the final part of the study, we endogenize firms' fuel choices and show that common ownership promotes fuel diversification, which may enhance welfare. In summary, we identify two previously unexplored welfare-enhancing effects

[6]Lazkano et al. (2017) introduce a directed technological change model within electricity sector, where innovative firms develop advanced electricity storage solutions, which affects the relative competitiveness between renewable and nonrenewable power sources in the energy market. André and Smulders (2014) investigate how to sustain economic growth through directed tehcnology innovation, such as developing new energy sources or energy storage technologies, in the context of peak oil resources and limited supply.

[7]The possibility of a U-shaped relationship between common ownership and welfare is a novel finding that has not been addressed in the existing literature on common ownership. Nonmonotonic relationships have been demonstrated by López and Vives (2019) and Sato and Matsumura (2020); however, their results indicate an inverted U-shaped relationship. Therefore, the welfare implications of our analysis differ from those presented in these studies.

of common ownership in the context of fuel diversification.

The remainder of this paper is organized as follows. Section 2 formulates a symmetric duopoly model. Section 3 derives the equilibrium outcomes. Section 4 presents our main result and discuss welfare implications. Section 5 discusses an asymmetric case in which one fuel has cost disadvantage to the other fuel *ex ante*, and endogenizes the fuel choices. Section 6 presents the conclusion.

2 The Model

We formulate a symmetric duopoly model with fuel choices, in which firms 1 and 2 compete in a homogeneous product market. The inverse demand function is $p = a - Q$ where $Q := q_1 + q_2$ and q_i is firm i's output ($i = 1, 2$).

Firms have committed to different fuels and thus have different cost structure. Firm 1(2) committed to fuel A(B). When the price of fuel A(B) is high, firm 1's (firm 2's) marginal cost is c^H. When the price of fuel A(B) is low, firm 1's (firm 2's) marginal cost is c^L. Without loss of generality, we normalize $c^L = 0$, and we denote $c^H = c$. In other words, c implies the cost advantage of the firm using the low-price fuel to the firm using the high-price fuel.

Both fuel prices are high with probability $(1 - x)/4$ (we denote HH) and they are low with the same probability (we denote LL). Only the price of fuel A is low (we denote LH) with probability $(1+x)/4$, and only the price of fuel B is low (we denote HL) with the same probability. $x \in [-1, 1]$ indicates the degree of heterogeneity among two fuels. If $x = -1$ there is a complete positive correlation between the two fuel prices and thus fuel prices are always the same. Thus, two are homogeneous from the economical viewpoint. If $x = 1$, there is a complete negative correlation between the two fuel prices. There is always cost difference among two fuels. We focus on the cases with nonnegative x.

The profits of firm i is $(p - c_i)q_i$ where c_i is firm i's marginal cost. We adopt López and

Vives's (2019) formulation and assume that each firm i has the following objective function:

$$\psi_i = \pi_i + \lambda \pi_j,$$

where π_i is firm i's profit, π_j is its rival's profit, and λ is the degree of common ownership.[8]

Firms choose their output simultaneously (i.e., they face Cournot competition) after observing firms' costs. Welfare W is the sum of the two firms' profits and consumer surplus. It is given by

$$W = \pi_1 + \pi_2 + \frac{(Q)^2}{2}. \tag{1}$$

We assume all players are risk neutral.

3 Equilibrium

Firm i's first-order condition is

$$p' q_i + (p - c_i) + \lambda p' q_j = 0 \ (i, j = 1, 2. \ i \neq j). \tag{2}$$

Substituting $p = a - (q_1 + q_2)$, we obtain the following reaction function:

$$R_i(q_j) = \frac{a - c_i - (1+\lambda) q_j}{2} \ (i, j = 1, 2. \ i \neq j). \tag{3}$$

From (3), we obtain the equilibrium outputs:

$$q_i^*(c_i, c_j) = \frac{(1-\lambda)a - 2c_i + (1+\lambda)c_j}{(3+\lambda)(1-\lambda)}, \tag{4}$$

$$Q^* = \frac{2a - (c_i + c_j)}{3+\lambda} \tag{5}$$

Superscript * denotes the equilibrium outcome. We assume interior solution (i.e., $q_i^* > 0$). Because q_i^* is smallest when $c_i = c$ and $c_j = 0$, we assume $(1-\lambda)a - 2c > 0$. In other words,

[8] Former investigations have examined this type of payoff interdependence through a coefficient-of-cooperation model (Cyert and DeGroot, 1973; Escrihuela-Villar, 2015) and a relative-profit-maximization model (Escrihuela-Villar and Gutiérrez-Hita, 2019; Hamamura, 2021; Matsumura and Matsushima, 2012; Matsumura et al., 2013).

$\lambda < \bar{\lambda} := (a - 2c)/a$. This implies that our analysis does not cover the case where λ is close to 1.

We obtain the following lemma:

Lemma 1 (i) q_i^* increases with λ if and only if $c_i = 0$, $c_j = c$, and $\lambda > \left[a + c - 2\sqrt{c(2a - c)}\right]/(a - c)$. (ii)$\partial q_1^*/\partial\lambda > \partial q_2^*/\partial\lambda$ if and only if $c_1 < c_2$. (iii) Q^* decreases with λ.

Proof See the Appendix

When λ is larger, each firm is more concerned with its rival's profit. Thus, an increase in λ always reduces each firm's output to increase its rival's profit when firms have the same marginal cost. However, under cost heterogeneity (i.e., when $c_1 \neq c_2$), an increase in λ may stimulate the lower-cost firm's production, which seems to be counter intuitive. This is because the lower-cost firm's production is more efficient than that of the rival firm from the viewpoint of joint-profit-maximization. When λ is larger, the equilibrium combination of outputs is close to the cooperative (joint-profit-maximizing) one. Thus, the higher-cost firm has a stronger incentive than the rival firm to reduce its output. Because of the strategic substitutability, a reduction in the higher-cost firm's output increases the lower-cost firm's output. This effect can be significant, especially when the cost difference is high, and may dominate the standard output-reducing effect of common ownership. Consequently, the lower-cost firm's output may increase with λ. Even when both firms' output decreases with λ, the output-reducing effect of common ownership is greater for the higher-cost firm than for the lower-cost firm. This leads to Lemma 1(iii).

We present the equilibrium outcomes in the four scenarios (i.e., HH, LL, LH, and HL), where superscripts denote each of these four scenarios.[9]

$$\begin{aligned} q_1^{HH} &= q_2^{HH} = \frac{a-c}{\lambda+3}, \quad Q^{HH} = \frac{2(a-c)}{\lambda+3}, \\ p^{HH} &= \frac{a(1+\lambda)+2c}{\lambda+3}, \quad \pi_1^{HH} = \pi_2^{HH} = \frac{(a-c)^2(\lambda+1)}{(\lambda+3)^2}. \end{aligned} \tag{6}$$

$$\begin{aligned} q_1^{LL} &= = q_2^{LL} = \frac{a}{\lambda+3}, \quad Q^{LL} = \frac{2a}{\lambda+3}, \\ p^{LL} &= \frac{a(\lambda+1)}{\lambda+3}, \quad \pi_1^{LL} = \pi_2^{LL} = \frac{a^2(\lambda+1)}{(\lambda+3)^2}. \end{aligned} \tag{7}$$

$$\begin{aligned} q_1^{LH} &= \frac{a(1-\lambda)+c(1+\lambda)}{(1-\lambda)(3+\lambda)}, \quad q_2^{LH} = \frac{a(1-\lambda)-2c}{(1-\lambda)(3+\lambda)}, \quad Q^{LH} = \frac{2a-c}{\lambda+3}, \\ p^{LH} &= \frac{a(1+\lambda)+c}{\lambda+3}, \quad \pi_1^{LH} = \frac{[a(1+\lambda)+c][a(1-\lambda)+c(1+\lambda)]}{(\lambda+3)^2(1-\lambda)}, \\ \pi_2^{LH} &= \frac{[a(1+\lambda)-c(2+\lambda)][a(1-\lambda)-2c]}{(\lambda+3)^2(1-\lambda)}. \end{aligned} \tag{8}$$

$$\begin{aligned} q_1^{HL} &= \frac{a(1-\lambda)-2c}{(1-\lambda)(3+\lambda)}, \quad q_2^{HL} = \frac{a(1-\lambda)+c(1+\lambda)}{(1-\lambda)(3+\lambda)}, \quad Q^{HL} = \frac{2a-c}{\lambda+3}, \\ p^{HL} &= \frac{a(1+\lambda)+c}{\lambda+3}, \quad \pi_1^{HL} = \frac{[a(1+\lambda)-c(2+\lambda)][a(1-\lambda)-2c]}{(\lambda+3)^2(1-\lambda)}, \\ \pi_2^{HL} &= \frac{[a(1+\lambda)+c][a(1-\lambda)+c(1+\lambda)]}{(\lambda+3)^2(1-\lambda)}. \end{aligned} \tag{9}$$

Both HH and LL take place with probability $(1-x)/4$, and LH and HL take place with probability $(1+x)/4$. The expected consumer surplus (CS^E), profits (π^E) and welfare (W^E) are

[9] According to q_1^* and q_2^* in (12), we substitute the specific c_1 and c_2 of those four scenarios (i.e., HH, LL, LH, HL). To be specific, $c_1 = c_2 = c$ under HH, $c_1 = c_2 = 0$ under LL, $c_1 = 0,\ c_2 = c$ under LH, and $c_1 = c,\ \ c_2 = 0$ under HL, where the first (second) letter represents the fuel A's (B's) price in firm 1 (2). The superscripts in the equilibrium outcomes presented below follow the same rule.

$$
\begin{aligned}
CS^E &= \left(\frac{1-x}{4}\right)\frac{\left(Q^{HH}\right)^2+\left(Q^{LL}\right)^2}{2}+\left(\frac{1+x}{4}\right)\frac{\left(Q^{LH}\right)^2+\left(Q^{HL}\right)^2}{2}=\frac{(2a-c)^2}{2(\lambda+3)^2},\\
\pi_1^E &= \pi_2^E=\pi^E=\left(\frac{1-x}{4}\right)\left(\pi_1^{HH}+\pi_1^{LL}\right)+\left(\frac{1+x}{4}\right)\left(\pi_1^{LH}+\pi_1^{HL}\right)\\
&= \frac{(2a-c)^2(1-\lambda^2)+c^2\left[(1+x)(3\lambda+4)+(1+\lambda^2x)\right]}{4(1-\lambda)(\lambda+3)^2}\\
W^E &= CS^E+\pi_1^E+\pi_2^E. \qquad (10)
\end{aligned}
$$

4 Results

We now discuss how the degree of common ownership influences welfare.

Proposition 1 (i) The expected consumer surplus, CS^E, decreases with λ. (ii) The expected equilibrium profit of each firm, π^E, increases with λ. (iii) $\partial W^E/\partial\lambda < (=,>)0$ if $c < (=,>)\hat{c}(x.\lambda)$, where

$$\hat{c}(x,\lambda) := \frac{2a(1-\lambda)\left(\Omega-\lambda^2-\lambda-1\right)}{13\lambda+13x+15\lambda x+3\lambda^2x+\lambda^3x+7\lambda^2-\lambda^3+13},$$

and

$$\Omega=\sqrt{(\lambda+1)(12\lambda+13x+15\lambda x+3\lambda^2x+\lambda^3x+6\lambda^2+14)}.$$

(iv) $\hat{c}(x,\lambda)$ decreases with x and λ.

Common ownership harms consumer surplus (Proposition 1(i)), and increases firms' profits (Proposition 1(ii)). These standard results are intuitive. Proposition 1(iii,iv) states that common ownership improves (harms) welfare if the cost difference between two fuels is significant (insignificant).[10] We explain the intuition behind this result.

When the fuel A has cost advantage, firm 1's marginal cost is lower than firm 2's. In other words, firm 1's supply is more profitable than that for firm 2. In the presence of common ownership, firm 2 is concerned with firm 1's profit. Thus, firm 2 reduces its supply.

[10] We can show that the solution is interior when $c=\hat{c}$. Thus, there exists c such that an increase in λ improves (harms) welfare.

This reduces the weighted average of the two firms' costs and increases their joint profits. This welfare-improving effect is more pronounced when c is higher, dominating the welfare-reducing effect owing to smaller total output. If x is high, the probability that one fuel has cost advantage is high. Thus, the above welfare-improving case more likely occurs. Therefore, common ownership improves welfare if x and c are high.[11]

Moreover, Proposition 1(iii-iv) suggests a possible nonmonotone relationship between the degree of common ownership and welfare. Because $\hat{c}$ decreases with λ, it is possible that $c < \hat{c}$ ($c > \hat{c}$) holds when λ is small (large). Thus, the relationship between W and λ can be U-shaped. Several studies on common ownership show a possible nonmonotone relationship (López and Vives, 2019; Sato and Matsumura, 2020). However, they suggest that a moderate degree of common ownership improves welfare but a significant degree does not. By contrast, our result suggests that a significant degree of common ownership can improve welfare even if a moderate degree of common ownership harms welfare. This is because an increase in λ more effectively induces welfare-improving production substitution when λ is large.

In summary, there are three (two monotones and one nonmonotone) patterns in the relationship between W and λ. If c is sufficiently low (high), W always decreases (increases) with λ (i.e., monotone relationship appears). If c is moderate, W decreases (increases) with λ when λ is small (large). However, in our analysis, an inverted U-shaped relationship does not appear.

5 Asymmetric costs and endogenous fuel choices

In the previous sections, we formulate a symmetric model where fuels A and B have the symmetric properties. In other words, both fuels are equally efficient *ex ante*. We also assume that firms choose different fuels. The assumption of exogenous fuel choices is innocuous as

[11]See Lahiri and Ono (1988) for discussions of welfare-improving production substitution.

long as the cost structure is symmetric because we can show that firms have incentives to choose different fuels (and we show it in the following Proposition 2). However, this may not be true in the presence of cost asymmetries.

In this section, we modify the model as follows. The model is the same as the previous section except for the cost structure. When the price of fuel A is high(low), the marginal cost of the firm adopting fuel A is $c(0)$. When the price of fuel B is high(low), the marginal cost of the firm adopting fuel B is $c + \varepsilon(\varepsilon)$. In other words, fuel B is inferior to fuel A and ε represents the level of disadvantage. We assume that $0 \leq \varepsilon < c$. Moreover, we assume interior solution. Specifically, we assume $\varepsilon < \bar{\varepsilon} := [a(1-\lambda) - 2c]/2$.

We can show that if one firm chooses fuel B, the other firms prefers fuel A. However, if one firm chooses fuel A, the other firm may or may not prefer fuel B. Thus, without loss of generality, we assume that firm 1 adopts fuel A and only firm 2 chooses whether it uses fuel A or B. The game runs as follows. In the first stage, firm 2 chooses fuel A or fuel B. In the second stage, after observing both firms' realized costs, firms face Cournot competition.

We obtain the following result.

Proposition 2 (i) Firm 2 chooses fuel B in equilibrium (and thus fuel diversification takes place in equilibrium) if and only if $\varepsilon \leq \varepsilon^E$ and

$$\varepsilon^E = \frac{(2a-c)(1-\lambda) - \sqrt{\Phi_1}}{4} > 0,$$

where $\Phi_1 = (2a-c)^2(1-\lambda)^2 - 4c^2(1+\lambda)(1+x)$. (ii) ε^E increases with λ. (iii) Welfare is greater when firm 2 chooses fuel B than when firm 2 chooses fuel A (i.e., fuel diversification improves welfare) if and only if $\varepsilon \leq \varepsilon^W$ and

$$\varepsilon^W = \frac{2(2a-c)(2-\lambda-\lambda^2) - \sqrt{2\Phi_2}}{2(5\lambda+11)} > 0,$$

where $\Phi_2 = 8a(1-\lambda)^2(2+\lambda)^2(a-c) + c^2(-120\lambda - 77x - 69 - 63\lambda^2 - 6\lambda^3 + 2\lambda^4 - 112\lambda x - 57\lambda^2 x - 10\lambda^3 x)$. (iv) $\varepsilon^E < \varepsilon^W$.

Proof See the Appendix.

Proposition 2(i) implies that fuel diversification takes place unless the cost disadvantage of fuel B is too large, and Proposition 2(ii) suggests that common ownership enhances fuel diversification. Specifically, fuel diversification takes place more likely in the presence of common ownership. The intuition is as follows. Although the expected cost of fuel B is higher than fuel A, the realized cost of fuel B could be lower than that of fuel A. In that case, firm 2 obtains a larger market share and profits.[12] Conversely, when fuel A's price is lower than fuel B's price, firm 1 obtains larger profits when firm 2 chooses fuel B than that when firm 2 chooses fuel A. Firm 2 has a stronger incentive to adopt fuel B in the presence of common ownership because firms 2 is concerned with firm 1's profits.[13]

Proposition 2(iii) implies that fuel diversification improves welfare unless the cost disadvantage of fuel B is too large. It is a natural result. Switching firm 2's fuel from A to B induces production substitution from firm 1 to firm 2 when fuel price B is lower than fuel price A, and from firm 2 to firm 1 when fuel price B is higher than fuel price A. Both are welfare improving because the production substitution economizes total costs in the industry (Lahiri and Ono, 1988). Firm 2 takes account in this welfare improving effect only partially, and thus, the incentive is insufficient. This leads to Proposition 2(iv), which suggest that the private incentive for fuel diversification is insufficient for welfare.

Proposition 2 suggests another possible welfare-improving effect of common ownership. Common ownership enhances fuel diversification, which may improve welfare.

6 Concluding remarks

In this study, we investigate how common ownership influences welfare in the presence of fuel diversification. We find that common ownership improves welfare if fuel diversification leads to sufficiently large *ex post* cost asymmetry among firms. We also show a possible U-shaped

[12]This scenario corresponds to the case when fuel A's price is high (c) and fuel B's price is low (ε), with $c > \varepsilon$. See the proof of Proposition 2, case AHBL, in the appendix.

[13]This applies to the cases denoted by superscripts AHBH, ALBL, and ALBH in the proof of Proposition 2 in appendix.

relationship between the degree of common ownership and welfare, which is unknown in the literature. Finally, we endogenize fuel choices of the firms and find that common ownership enhances fuel diversification, which may improve welfare. In other words, we find two unknown welfare-improving effects of common ownership.

In this study, we do not consider environmental policies. We could discuss the emissions tax by change the definition of firms' marginal costs (i.e., each firm's the marginal cost consists of of fuel price plus emissions tax cost). However, many other environmental policies, such as emissions cap and emissions intensity regulations, green portfolio standards, and energy-saving investment subsidies, are prevailing globally.[14] Moreover, this study neglects the voluntary emissions reduction by ESG and SDGs (Bárcena-Ruiz and Sagasta, 2021,2022; Bárcena-Ruiz et al., 2023; Fukuda and Ouchida, 2020; Hirose et al., 2020; Tomoda and Ouchida, 2023; Xu et al., 2022; Xing and Lee, 2024a,b). Integrating environmental policies, firms' voluntary environmental activities, and firms' fuel choices remains for future research.

[14]For recent discussions on policy combinations of emissions taxes and other environmental policies, see Ino and Matsumura (2021a,b, 2024) and Hirose and Matsumura (2025).

Appendix

Proof of Lemma 1

From (4), we obtain

$$[(1-\lambda)(3+\lambda)]^2\frac{\partial q_i^*}{\partial \lambda} = -(a-c_j)\lambda^2 + 2(a-2c_i+c_j)\lambda - (a+4c_i-5c_j). \tag{11}$$

Consider the equation $-(a-c_j)\lambda^2 + 2(a-2c_i+c_j)\lambda - (a+4c_i-5c_j) = 0$. Its discriminant is

$$\Delta_1 = 4(a-2c_i+c_j)^2 - 4(a-c_j)(a+4c_i-5c_j) = 16(c_i-c_j)\overbrace{(c_i-2a+c_j)}^{(-)}.$$

If $c_i > c_j$, we obtain $\Delta_1 < 0$, and thus, $\partial q_i^*/\partial\lambda < 0$ holds. If $c_i = c_j$ we obtain $-(a-c_j)\lambda^2 + 2(a-2c_i+c_j)\lambda - (a+4c_i-5c_j) < 0$ unless $\lambda = 1$ Because we assume $\lambda < 1$, $\partial q_i^*/\partial\lambda < 0$. If $c_i < c_j$ (i.e., $c_i = 0$ and $c_j = c$), we have $(a+c-2\sqrt{c(2a-c)})/(a-c)$ and $(a+c+2\sqrt{c(2a-c)})/(a-c)$ as the two solutions of the equation $-(a-c_j)\lambda^2+2(a-2c_i+c_j)\lambda-(a+4c_i-5c_j) = 0$. The larger solution is greater than 1, and thus, we obtain $\partial q_i^*/\partial\lambda > 0$ if and only if $\lambda > (a+c-2\sqrt{c(2a-c})/(a-c)$. These implies Lemma 1(i).

According to q_i^* presented in (4), we rewrite q_1^* and q_2^* as follows.

$$\begin{aligned} q_1^* &= \frac{a(1-\lambda)-2c_1+c_2(1+\lambda)}{(1-\lambda)(3+\lambda)} \\ q_2^* &= \frac{a(1-\lambda)-2c_2+c_1(1+\lambda)}{(1-\lambda)(3+\lambda)}. \end{aligned} \tag{12}$$

Thus, we take partial derivative of q_1^* and q_2^* in (12) with respect to λ, and find

$$\begin{aligned} \frac{\partial q_1^*}{\partial\lambda} &= \frac{a-c_2}{(1-\lambda)(3+\lambda)} + \frac{2(1+\lambda)[a(1-\lambda)-2c_1+c_2(1+\lambda)]}{[(1-\lambda)(3+\lambda)]^2} \\ \frac{\partial q_2^*}{\partial\lambda} &= \frac{a-c_1}{(1-\lambda)(3+\lambda)} + \frac{2(1+\lambda)[a(1-\lambda)-2c_2+c_1(1+\lambda)]}{[(1-\lambda)(3+\lambda)]^2}, \end{aligned} \tag{13}$$

and

$$\frac{\partial q_1^*}{\partial\lambda} - \frac{\partial q_2^*}{\partial\lambda} = \frac{c_2-c_1}{(1-\lambda)^2}.$$

Thus, Lemma 1(ii) is obtained.

From (5) we have

$$\frac{\partial Q^*}{\partial \lambda} = -\frac{2a - c_1 - c_2}{(\lambda + 3)^2} < 0.$$

Thus, we obtain Lemma 1(iii). Q.E.D.

Proof of Proposition 1

From CS^E presented in (10), we have

$$\frac{\partial CS^E}{\partial \lambda} = -\frac{(2a - c)^2}{(\lambda + 3)^3} < 0.$$

Proposition 1(i) is therefore proved.

From π^E presented in (10), we obtain

$$[4(1-\lambda)^2(\lambda+3)^3]\frac{\partial \pi^E}{\partial \lambda} = k(c), \tag{14}$$

where

$$\begin{aligned} k(c) \;&:=\; (9\lambda + 13x + 15\lambda x + 3\lambda^2 x + \lambda^3 x + 9\lambda^2 - \lambda^3 + 15)c^2 + (4a\lambda^3 - 12a\lambda^2 + 12a\lambda - 4a)c \\ &\quad -4a^2\lambda^3 + 12a^2\lambda^2 - 12a^2\lambda + 4a^2. \end{aligned} \tag{15}$$

Consider the equation $k(c) = 0$. Its discriminant is

$$\Delta_2 = 16a^2(\lambda - 1)^3(12\lambda + 13x + 15\lambda x + 3\lambda^2 x + \lambda^3 x + 6\lambda^2 + 14) < 0,$$

where we use the condition $0 < \lambda < \bar{\lambda} := (a - 2c)/a$. Since the equation (15) is convex in c and its discriminant Δ_2 is negative, we obtain Proposition 1(ii).

From (10) we obtain

$$[2(1-\lambda)^2(\lambda+3)^3]\frac{\partial W^E}{\partial \lambda} = h(c), \tag{16}$$

where

$$\begin{aligned} h(c) \;&:=\; (13\lambda + 13x + 15\lambda x + 3\lambda^2 x + \lambda^3 x + 7\lambda^2 - \lambda^3 + 13)c^2 \\ &\quad +(4a\lambda^3 - 4a\lambda^2 - 4a\lambda + 4a)c - 4a^2\lambda^3 + 4a^2\lambda^2 + 4a^2\lambda - 4a^2. \end{aligned} \tag{17}$$

Consider the equation $h(c) = 0$. Its discriminant is

$$\Delta_3 = 16a^2(\lambda-1)^2(\lambda+1)(12\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+6\lambda^2+14) > 0.$$

Thus, we have two solutions of parameter c for above $\partial W^E/\partial\lambda = 0$. They are

$$\hat{c_1}(x,\lambda) = -\frac{2a(1-\lambda)(\sqrt{(\lambda+1)(12\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+6\lambda^2+14)}+\lambda^2+\lambda+1)}{13\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+7\lambda^2-\lambda^3+13},$$

$$\hat{c}(x,\lambda) \;=\; \frac{2a(1-\lambda)(\sqrt{(\lambda+1)(12\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+6\lambda^2+14)}-\lambda^2-\lambda-1)}{13\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+7\lambda^2-\lambda^3+13}. \tag{18}$$

Apparently, $\hat{c_1}(x,\lambda) < 0$. Furthermore, $\hat{c}(x,\lambda) > 0$ because

$$\sqrt{(\lambda+1)(12\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+6\lambda^2+14)} > (\lambda^2+\lambda+1).$$

Because of the convexity of $\partial W^E/\partial\lambda$ in (16) with respect to c, we have that $\partial W^E/\partial\lambda$ in (16) $< (=,>) 0$ if $c < (=,>) \hat{c}(x.\lambda)$. Therefore, Proposition 1 (iii) holds.

We have

$$\begin{aligned}
&\overbrace{[\Omega(13\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+7\lambda^2-\lambda^3+13)^2]}^{(+)}\frac{\partial\hat{c}(x,\lambda)}{\partial x}\\
&= a(\lambda+1)^2\overbrace{(\lambda^3+\lambda^2+11\lambda-13)}^{(-)}\\
&\quad [(11\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+5\lambda^2+\lambda^3+15)-2\Omega(1-\lambda)],
\end{aligned}$$

where

$$\Omega = \sqrt{(\lambda+1)(12\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+6\lambda^2+14)} > 0. \tag{19}$$

We examine the sign of the equation $[(11\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+5\lambda^2+\lambda^3+15)-2\Omega(1-\lambda)]$. The squared difference is

$$\begin{aligned}
& (11\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+5\lambda^2+\lambda^3+15)^2-[2\Omega(1-\lambda)]^2\\
= \;& (13\lambda+13x+15\lambda x+3\lambda^2 x+\lambda^3 x+7\lambda^2-\lambda^3+13)^2 > 0,
\end{aligned}$$

which is equivalent to

$$[(11\lambda + 13x + 15\lambda x + 3\lambda^2 x + \lambda^3 x + 5\lambda^2 + \lambda^3 + 15) - 2\Omega(1-\lambda)] > 0. \tag{20}$$

Thus, we obtain $\partial \hat{c}(x, \lambda)/\partial x < 0$.

We investigate $\partial \hat{c}(x, \lambda)/\partial \lambda$. We have

$$\begin{aligned}
&\overbrace{-[\Omega(13\lambda + 13x + 15\lambda x + 3\lambda^2 x + \lambda^3 x + 7\lambda^2 - \lambda^3 + 13)^2]}^{(-)} \frac{\partial \hat{c}(x, \lambda)}{\partial \lambda} \\
&= \overbrace{2a(33\lambda + 14x + 30\lambda x + 18\lambda^2 x + 2\lambda^3 x + 15\lambda^2 + 3\lambda^3 + 13)}^{(+)} * \\
&\overbrace{[(11\lambda + 13x + 15\lambda x + 3\lambda^2 x + \lambda^3 x + 5\lambda^2 + \lambda^3 + 15) - 2\Omega(1-\lambda)]}^{(+) \text{ in } (20)},
\end{aligned}$$

where Ω is in (19). Thus $\partial \hat{c}(x, \lambda)/\partial \lambda < 0$ holds. Therefore, Proposition 1(iv) is obtained. Q.E.D.

Proof of Proposition 2

Let the superscript AA denote the equilibrium outcomes when both firms choose fuel A and the superscript AB denote the equilibrium outcomes when firm 1 adopts fuel A and firm 2 adopts fuel B. Thus, if $\psi_2^{AA} \leq \psi_2^{AB}$, then fuel diversification appears in an equilibrium (i.e., firm 2 chooses fuel B in an equilibrium). If $W^{AA} \leq W^{AB}$, fuel diversification is desirable for welfare.

When both firm 1 and firm 2 choose fuel A, there are two cases. Fuel A's price is high (superscript H) with probability of 0.5 and fuel A's price is low (superscript L) with probability of 0.5, which means

$$\psi_2^{AA} = \frac{1}{2}\psi_2^{AAH} + \frac{1}{2}\psi_2^{AAL},$$

where

$$\psi_2^{AAH} = \pi_2^{HH} + \lambda\pi_1^{HH}, \quad \text{and } \psi_2^{AAL} = \pi_2^{LL} + \lambda\pi_1^{LL}.$$

Additionally, π_2^{HH}, π_1^{HH}, π_2^{LL}, π_1^{LL}, Q^{HH}, and Q^{LL} can be find in (6) and (7) respectively. As such

$$\begin{aligned}
\psi_2^{AAH} &= (1+\lambda)\pi_1^{HH} = \frac{(a-c)^2(1+\lambda)^2}{(\lambda+3)^2} \\
\psi_2^{AAL} &= (1+\lambda)\pi_1^{LL} = \frac{a^2(1+\lambda)^2}{(\lambda+3)^2} \\
\psi_2^{AA} &= \frac{1}{2}\psi_2^{AAH} + \frac{1}{2}\psi_2^{AAL} = \frac{(1+\lambda)^2[a^2+(a-c)^2]}{2(\lambda+3)^2} \\
W^{AA} &= \frac{W^{AAH}+W^{AAL}}{2} = \frac{2\pi_1^{HH}+2\pi_2^{HH}+(Q^{HH})^2+2\pi_1^{LL}+2\pi_2^{LL}+(Q^{LL})^2}{4} \\
&= \frac{(\lambda+2)(2a^2-2ac+c^2)}{(\lambda+3)^2}. \qquad (21)
\end{aligned}$$

Furthermore, there are also four scenarios, HH, LL, LH, and HL under cost asymmetry in this section. The probabilities of these four scenarios are same as those in Section 2. We investigate the equilibrium outcomes of these four scenarios under cost asymmetry when firm 2 chooses fuel B. We utilize H or L followed by A or B to indicate whether fuel k (k=A or B)'s price is high (H) or low (L). For example, the superscript AHBL denotes fuel A's price is high and fuel B's price is low. Therefore,

$$\begin{aligned}
\psi_2^{AB} &= \frac{1-x}{4}(\pi_2^{AHBH}+\lambda\pi_1^{AHBH}) + \frac{1-x}{4}(\pi_2^{ALBL}+\lambda\pi_1^{ALBL}) \\
&\quad + \frac{1+x}{4}(\pi_2^{ALBH}+\lambda\pi_1^{ALBH}) + \frac{1+x}{4}(\pi_2^{AHBL}+\lambda\pi_1^{AHBL}), \\
W^{AB} &= \frac{1-x}{4}(W^{AHBH}+W^{ALBL}) + \frac{1+x}{4}(W^{ALBH}+W^{AHBL}) \qquad (22)
\end{aligned}$$

$c_1^{AH} = c,\ c_2^{BH} = c+\varepsilon$, and $c_1^{AL} = 0,\ c_2^{BL} = \varepsilon$. Substituting these into firm i's ($i = 1,\ 2$) equilibrium output in (4) and (5), we obtain the equilibrium outcomes in the four scenarios (i.e., AHBH, ALBL, ALBH, and AHBL) as follows.

$$\begin{aligned}
q_1^{AHBH} &= \frac{(a-c)(1-\lambda)+\varepsilon(1+\lambda)}{(1-\lambda)(3+\lambda)}, \quad q_2^{AHBH} = \frac{(a-c)(1-\lambda)-2\varepsilon}{(1-\lambda)(3+\lambda)}, \\
Q^{AHBH} &= \frac{2(a-c)-\varepsilon}{\lambda+3}, \quad p^{AHBH} = \frac{a+2c+a\lambda+\varepsilon}{\lambda+3}, \\
\pi_1^{AHBH} &= \frac{[(a-c)(\lambda+1)+\varepsilon][(a-c)(1-\lambda)+\varepsilon(1+\lambda)]}{(1-\lambda)(3+\lambda)^2}, \\
\pi_2^{AHBH} &= \frac{[(a-c)(\lambda+1)-\varepsilon(\lambda+2)][(a-c)(1-\lambda)-2\varepsilon]}{(1-\lambda)(3+\lambda)^2}, \\
\psi_1^{AHBH} &= \pi_1^{AHBH} + \lambda\pi_2^{AHBH}, \\
\psi_2^{AHBH} &= \pi_2^{AHBH} + \lambda\pi_1^{AHBH}, \\
W^{AHBH} &= \pi_1^{AHBH} + \pi_2^{AHBH} + \frac{(Q^{AHBH})^2}{2}. \qquad (23)
\end{aligned}$$

$$\begin{aligned}
q_1^{ALBL} &= \frac{a(1-\lambda)+\varepsilon(1+\lambda)}{(1-\lambda)(3+\lambda)}, \quad q_2^{ALBL} = \frac{a(1-\lambda)-2\varepsilon}{(1-\lambda)(3+\lambda)}, \\
Q^{ALBH} &= \frac{(2a-\varepsilon)}{\lambda+3}, \quad p^{ALBL} = \frac{a(1+\lambda)+\varepsilon}{\lambda+3}, \\
\pi_1^{ALBL} &= \frac{[a(1+\lambda)+\varepsilon)][a(1-\lambda)+\varepsilon(1+\lambda)]}{(1-\lambda)(3+\lambda)^2} \\
\pi_2^{ALBL} &= \frac{[a(1-\lambda)-2\varepsilon][a(1+\lambda)-\varepsilon(\lambda+2)]}{(1-\lambda)(3+\lambda)^2} \\
\psi_1^{ALBL} &= \pi_1^{ALBL} + \lambda\pi_2^{ALBL}, \\
\psi_2^{ALBL} &= \pi_2^{ALBL} + \lambda\pi_1^{ALBL}, \\
W^{ALBL} &= \pi_1^{ALBL} + \pi_2^{ALBL} + \frac{(Q^{ALBL})^2}{2}. \qquad (24)
\end{aligned}$$

$$
\begin{aligned}
q_1^{ALBH} &= \frac{a(1-\lambda)+(c+\varepsilon)(1+\lambda)}{(1-\lambda)(3+\lambda)}, \quad q_2^{ALBH} = \frac{a(1-\lambda)-2(c+\varepsilon)}{(1-\lambda)(3+\lambda)} \\
Q^{ALBH} &= \frac{2a-c-\varepsilon}{\lambda+3}, \quad p^{ALBH} = \frac{a(1+\lambda)+c+\varepsilon}{\lambda+3}, \\
\pi_1^{ALBH} &= \frac{[a(\lambda+1)+c+\varepsilon][a(1-\lambda)+(c+\varepsilon)(1+\lambda)]}{(1-\lambda)(3+\lambda)^2}, \\
\pi_2^{ALBH} &= \frac{[a(1+\lambda)-(c+\varepsilon)(\lambda+2)][a(1-\lambda)-2(c+\varepsilon)]}{(1-\lambda)(3+\lambda)^2}, \\
\psi_1^{ALBH} &= \pi_1^{ALBH} + \lambda\pi_2^{ALBH}, \\
\psi_2^{ALBH} &= \pi_2^{ALBH} + \lambda\pi_1^{ALBH}, \\
W^{ALBH} &= \pi_1^{ALBH} + \pi_2^{ALBH} + \frac{(Q^{ALBH})^2}{2}. \qquad (25)
\end{aligned}
$$

$$
\begin{aligned}
q_1^{AHBL} &= \frac{a(1-\lambda)-2c+\varepsilon(1+\lambda)}{(1-\lambda)(3+\lambda)}, \quad q_2^{AHBL} = \frac{a(1-\lambda)+c(1+\lambda)-2\varepsilon}{(1-\lambda)(3+\lambda)}, \\
Q^{AHBL} &= \frac{2a-c-\varepsilon}{\lambda+3}, \quad p^{AHBL} = \frac{a(1+\lambda)+c+\varepsilon}{\lambda+3}, \\
\pi_1^{AHBL} &= \frac{[a(1+\lambda)-c(\lambda+2)+\varepsilon][a(1-\lambda)-2c+\varepsilon(1+\lambda)]}{(1-\lambda)(3+\lambda)^2}, \\
\pi_2^{AHBL} &= \frac{[a(\lambda+1)-\varepsilon(2+\lambda)+c][a(1-\lambda)+c(1+\lambda)-2\varepsilon]}{(1-\lambda)(3+\lambda)^2}, \\
\psi_1^{AHBL} &= \pi_1^{AHBL} + \lambda\pi_2^{AHBL}, \\
\psi_2^{AHBL} &= \pi_2^{AHBL} + \lambda\pi_1^{AHBL}, \\
W^{AHBL} &= \pi_1^{AHBL} + \pi_2^{AHBL} + \frac{(Q^{AHBL})^2}{2}. \qquad (26)
\end{aligned}
$$

Substituting the equilibrium profits and welfares in (23), (24), (25), and (26) into (22), we obtain the equilibrium ψ_2^{AB} and W^{AB}. They are

$$
\begin{aligned}
[4(1-\lambda)(\lambda+3)^2]\psi_2^{AB} &= 8c\varepsilon - 16a\varepsilon - 4ac + 4a^2\lambda + 9c^2\lambda + 12\varepsilon^2\lambda + 4c^2x + 4a^2 \\
&\quad +6c^2 + 16\varepsilon^2 - 4a^2\lambda^2 - 4a^2\lambda^3 + 2c^2\lambda^2 - c^2\lambda^3 + 4\varepsilon^2\lambda^2 \\
&\quad +7c^2\lambda x + 4c^2\lambda^2 x + c^2\lambda^3 x - 4ac\lambda + 4a\varepsilon\lambda - 2c\varepsilon\lambda + 4ac\lambda^2 \\
&\quad +4ac\lambda^3 + 8a\varepsilon\lambda^2 + 4a\varepsilon\lambda^3 - 4c\varepsilon\lambda^2 - 2c\varepsilon\lambda^3. \qquad (27)
\end{aligned}
$$

$$
\begin{aligned}
[4(1-\lambda)(\lambda+3)^2]W^{AB} &= 8c\varepsilon - 16a\varepsilon - 16ac - 8a^2\lambda + 3c^2\lambda + 10\varepsilon^2\lambda + 7c^2x + 16a^2 \\
&\quad +15c^2 + 22\varepsilon^2 - 8a^2\lambda^2 - 2c^2\lambda^2 + 7c^2\lambda x + 2c^2\lambda^2 x + 8ac\lambda \\
&\quad +8a\varepsilon\lambda - 4c\varepsilon\lambda + 8ac\lambda^2 + 8a\varepsilon\lambda^2 - 4c\varepsilon\lambda^2. \qquad (28)
\end{aligned}
$$

Comparing ψ_2^{AA} in (21) and ψ_2^{AB} in (27), we obtain

$$\left[\frac{4(1-\lambda)(3+\lambda)^2}{(\lambda^2+3\lambda+4)}\right](\psi_2^{AB}-\psi_2^{AA}) = f(\varepsilon), \qquad (29)$$

where $f(\varepsilon) := 4\varepsilon^2 - (4a-2c)(1-\lambda)\varepsilon + c^2(\lambda + x + 1 + \lambda x)$. We can show that $f(0) > 0$ and $f(c) < 0$.[15] This implies that the equation $f(\varepsilon) = 0$ has two solutions. One is a positive and smaller than c, and the other is larger than c. $(\psi_2^{AB} - \psi_2^{AA}) \geq 0$ holds if and only if $f(\varepsilon) \geq 0$ holds. $f(\varepsilon) \geq 0$ holds if and only if $\varepsilon < \varepsilon^E$, where ε^E is the smaller solution of the equation $f(\varepsilon) = 0$ and it is given by

$$\varepsilon^E = \frac{(2a-c)(1-\lambda) - \sqrt{\Phi_1}}{4}, \qquad (30)$$

where

$$\Phi_1 = 4a(a-c)(1-\lambda)^2 - 4c^2(\lambda + x + 1 + \lambda x) + c^2(1-\lambda)^2. \qquad (31)$$

Note that we assume $\varepsilon < c$. This implies Proposition 2(i).

We obtain

$$\frac{\partial \varepsilon^E}{\partial \lambda} = \frac{(2a-c)[(2a-c)(1-\lambda) - \sqrt{\Phi_1}] + 2c^2(1+x)}{4\sqrt{\Phi_1}} > 0,$$

since $0 < \sqrt{\Phi_1} < (2a-c)(1-\lambda)$. Therefore, Proposition 2(ii) is proved.

Comparing W^{AA} in (21) and W^{AB} in (28), we obtain

$$[4(1-\lambda)(3+\lambda)^2](W^{AB} - W^{AA}) = g(\varepsilon), \qquad (32)$$

where $g(\varepsilon) := (10\lambda + 22)\varepsilon^2 - 4(2a-c)(1-\lambda)(2+\lambda)\varepsilon + (7c^2\lambda + 7c^2x + 7c^2 + 2c^2\lambda^2 + 7c^2\lambda x + 2c^2\lambda^2 x)$. We can show that $g(0) > 0$ and $g(\bar{\varepsilon}) < 0$, where $\varepsilon < \bar{\varepsilon} := [a(1-\lambda) - 2c]/2$.[16]

[15] The proof is available upon request for the authors.

[16] The proof is available upon request for the authors.

This implies that the equation $g(\varepsilon) = 0$ has two solutions. One is a positive and smaller than $\bar{\varepsilon}$, and the other is larger than $\bar{\varepsilon}$. $(W^{AB} - W^{AA}) \geq 0$ holds if and only if $g(\varepsilon) \geq 0$ holds. $g(\varepsilon) \geq 0$ holds if and only if $\varepsilon < \varepsilon^W$, where ε^W is the smaller solution of the equation $g(\varepsilon) = 0$ and it is given by

$$\varepsilon^W = \frac{2(2a-c)(2-\lambda-\lambda^2) - \sqrt{2\Phi_2}}{2(5\lambda+11)}, \tag{33}$$

where

$$\begin{aligned}\Phi_2 \;&=\; 8a(1-\lambda)^2(2+\lambda)^2(a-c) + c^2(-120\lambda - 77x - 69 - 63\lambda^2 - 6\lambda^3 + 2\lambda^4 \\ &\quad -112\lambda x - 57\lambda^2 x - 10\lambda^3 x).\end{aligned} \tag{34}$$

Note that we assume $\varepsilon < \bar{\varepsilon} := [a(1-\lambda) - 2c]/2$. These imply Proposition 2(iii).

Finally, we show that the inequality $W^{AB} - W^{AA} > 0$ holds when $\varepsilon = \varepsilon^E$. Note that $W^{AB} - W^{AA} = 0$ when $\varepsilon = \varepsilon^W$ and $W^{AB} - W^{AA} > 0$ if and only if $\varepsilon < \varepsilon^W$. From (29), when $\varepsilon = \varepsilon^E$, $4\varepsilon^2 + c^2(1+\lambda)(1+x) = 2(2a-c)(1-\lambda)\varepsilon$. As such, multiplying $-2(2+\lambda)$ on both sides of the above equality, we obtain $-8(2+\lambda)\varepsilon^2 - 2c^2(1+\lambda)(1+x)(2+\lambda) = -4(2a-c)(1-\lambda)(2+\lambda)\varepsilon$. Using this equality in (32), we find

$$[4(1-\lambda)(3+\lambda)^2](W^{AB} - W^{AA}) = (6+2\lambda)\varepsilon^2 + c^2(3-2\lambda) + 2c^2\lambda^2(1+x) > 0$$

when $\varepsilon = \varepsilon^E$. Therefore, Proposition 2(iv) is proved. Q.E.D.

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