Carbon Tax and Border Tax Adjustments with Technology and Location Choices*

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September 2021

Abstract

We develop an international oligopoly model to analyze the home country's unilateral carbon taxes and border tax adjustments (BTAs) when firms can abate emissions. We explore three policy regimes: i) carbon taxes alone (no BTAs); ii) carbon taxes with carbon-content tariffs (partial BTAs); and iii) carbon taxes with both tax refunds for exports and carbon-content tariffs (full BTAs). According to our findings, carbon taxes may not be effective in decreasing global emissions. Interestingly, an increase in the carbon tax rate can increase global emissions. High tax rates may discourage emission abatement. With fixed firm locations, no BTAs or partial BTAs can be more effective in reducing global emissions than full BTAs. When firm locations are endogenous, firms tend to produce in the foreign country to avoid the home carbon tax with no BTAs. However, with BTAs, high tax rates do not necessarily induce foreign production. Global emissions could be largest in the middle range of the tax rate.

Keywords: Carbon pricing; Carbon border adjustments; Carbon leakage; Abatement investments; International oligopoly

JEL classification: F12; F13; F18; H23; Q54

*We wish to thank Keisaku Higashida, Hayato Kato, Kensuke Teshima and seminar participants at Hitotsubashi University and RIETI for their helpful comments and suggestions. Ishikawa acknowledges financial support from the Japan Society of the Promotion of Science through the Grant-in-Aid for Scientific Research (A): Grant Number 17H00986 and 19H00594.

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1 Introduction

International carbon leakage may undermine a country's attempt to cope with climate change. That is, greenhouse-gas (GHG) emission regulations in one country decrease emissions in that location but may increase emissions in other countries. In the Kyoto Protocol, developed countries, called the Annex I Parties, committed to decreasing their GHG emissions. However, developing countries had no obligation to reduce emissions. Thus, carbon leakage was expected between developed and developing countries. In the Paris Agreement, both developed and developing countries submitted GHG reduction targets. However, their targets and countermeasures are diverse because of the lack of coordination among countries. This would also mean a risk of international carbon leakage.

When a country introduces carbon pricing such as carbon taxes and emissions trading, domestic firms lose their competitiveness in markets and in turn their market share. Although GHG emissions from domestic firms decrease, those from foreign rivals are likely to increase. This is a typical channel of international carbon leakage.[1] In particular, it is possible for the latter to dominate the former and for global emissions to increase as a result. However, firms try to mitigate losses from carbon pricing, typically, using two strategies. One is to abate GHG emissions. Firms may adopt or invest in alternative technologies that reduce emissions but are more costly. This may mitigate international carbon leakage. The other strategy is to locate production plants abroad. This is another channel of international carbon leakage,[2] which has been studied extensively.[3]

Under these circumstances, carbon border adjustments (CBAs) have been proposed. CBAs aim at avoiding the offset of emission reductions by increasing emissions outside the jurisdiction through increased imports of more carbon-intensive goods or relocation of production plants. Policy makers are particularly inclined toward CBAs when adopt-

[1]See Copeland and Taylor (2005), Ishikawa and Kiyono (2006), and Ishikawa et al. (2012, 2020), for example.

[2]Changes in the price of fossil fuels can also lead to international carbon leakage (Bohm, 1993; Felder and Rutherford,1993; Kiyono and Ishikawa, 2004, 2013; Hoel, 2005; Eichner and Pethig, 2015b; Kortum and Weisbach, 2021). A decrease in fossil fuel demand caused by GHG emission regulations in one country lowers the global price of fossil fuels, boosting fossil fuel demand and, hence, GHG emissions in other countries.

[3]See Markusen et al. (1993, 1995), Hoel (1997), Kayalica and Lahiri (2005), Zeng and Zhao (2009), Dijkstra et al. (2011), and Ishikawa and Okubo (2011, 2016, 2017), among others. See also Erdogan (2014) for a survey on foreign direct investment (FDI) and environmental regulations.

ing carbon pricing within the jurisdiction.[4] They believe that CBAs can internalize the environmental costs of production and hence can be more effective than carbon pricing alone to deal with global warming. However, various CBAs have been proposed. Some proposals include regulations on only imports. For instance, the American Clean Energy and Security Act of 2009 proposes a cap-and-trade system requiring importers to purchase emission permits, as domestic producers must do.[5] The European Green Deal includes a CBA mechanism aiming to "counteract carbon leakage by putting a carbon price on imports of certain goods from outside the EU".[6] However, other CBAs also allow exemptions from carbon pricing for exports to eliminate cost disadvantages in foreign markets. Elliott et al. (2010) call an emission tax that involves a tax rebate for exports as well as a tax on imports a "full" CBA. Examples include the SB 775 California Global Warming Solutions Act of 2006. Facing different CBA schemes, a legitimate question is determining how their effects vary. This question has not been fully addressed in the existing literature.

Against this background, this study explores the effects of carbon pricing and CBAs on firm behavior and GHG emissions. To this end, we examine a unilateral tax on GHG emissions and border tax adjustments (BTAs) in a simple international oligopoly model. Specifically, we compare the following three policy regimes: i) carbon taxes alone (Regime α); ii) carbon taxes accompanied by carbon-content tariffs (Regime β); and iii) carbon taxes coupled with carbon-tax refunds for exports and carbon-content tariffs (Regime γ). Regime α is the case with no BTAs, Regime γ is the case with full BTAs, and Regime β is the case in between (i.e., partial BTAs).

Our oligopolistic setup captures the features of firms that emit a significant amount of GHGs such as blast furnace steelmakers and chemical manufacturers. In our analysis, we explicitly account for emission abatement activities and production locations. We assume that firms can abate emissions by adopting a clean technology. Regarding firm locations, we consider two cases: fixed and endogenous locations. Thus, our setup is simple but rich enough to analyze firms' reactions to carbon pricing and BTAs that may cause unexpected distortions in addition to cross-border carbon leakage.

With fixed firm locations, we assume that two firms are located in different countries.

[4] For example, on September 16, 2020, Ursula von der Leyen, President of the European Commission, tweeted "Carbon must have its price - because nature cannot pay the price anymore. We are working on a Carbon Border Adjustment Mechanism."

[5] https://www.congress.gov/bill/111th-congress/house-bill/2454

[6] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12228-Carbon-Border-Adjustment-Mechanism The European Commission proposed CBAs on July 14, 2021.

In this case, cross-border carbon leakage is just leakage between the two firms. With endogenous firm locations, however, cross-border carbon leakage is not necessarily leakage between the two firms, because both firms may choose a non-taxing country as a result of the carbon tax. In our model, BTAs mitigate cross-border carbon leakage if the firm locations are fixed. In particular, full BTAs eliminate cross-border carbon leakage. However, the elimination of carbon leakage does not necessarily result in less global GHG emissions. For a given carbon tax rate, partial BTAs lead to lower global GHG emissions (i.e., Regime β) than with no BTAs (i.e., Regime α), while they can be more with full BTAs (i.e., Regime γ) than with partial BTAs. If the firm locations are endogenous, firms are likely to produce abroad in the presence of a tough carbon tax in the domestic country. Thus, carbon leakage can occur even with full BTAs. More importantly, the relationship between the carbon tax rate and global emissions tends to be non-monotonic under BTAs. In particular, high tax rates do not necessarily induce foreign production. Depending on the parameter values, global emissions could be largest in the middle range of the tax rate.

In what follows, Section 2 describes the relationship between our analysis and the previous literature. Section 3 develops the basic model. Section 4 explores the effects of a carbon tax on emissions with and without BTAs when firm locations are fixed. Section 5 extends the analysis to the case with endogenous location choices. Section 6 concludes the paper.

2 Relation to Previous Literature

Emission taxes have been investigated extensively in the framework of international oligopoly. Studies analyzing abatement activities under emission taxes include Conrad (1993), Kennedy (1994), Greaker (2003), Ulph and Ulph (2007), and Yomogida and Tarui (2013), among others. These studies are basically in line with the weak version of the Porter hypothesis in Jaffe and Palmer (1997) that stricter environmental regulations would induce firms to engage in abatement activities. Interestingly, however, we show that the relationship between the carbon tax rate and emission abatement activities may not be straightforward; in other words, a sufficiently high tax rate does not necessarily induce abatement investment. We also show that even if the Porter hypothesis holds, abatement investment can make a carbon tax backfire. That is, a firm's abatement can increase global emissions and an increase in the carbon tax can increase global emissions with a firm's abatement activities.[7]

The rationale of CBAs can be traced back to the discussion about the optimal mix of environmental and trade policies in dealing with pollution. Markusen (1975) argued that two taxes among production, consumption, and trade taxes are sufficient to obtain the first-best result. Since then, CBAs have been shown to be more effective at avoiding or mitigating carbon leakage compared to some other environmental instruments (Elliott et al., 2010; Böhringer et al., 2012; Fischer and Fox, 2012; Yomogida and Tarui, 2013; Ma and Yomogida, 2019; Kortum and Weisbach, 2021), though CBAs' practicality and compatibility with the World Trade Oranization (WTO) rules are still under debate (Ismer and Neuhoff, 2007; Lockwood and Whalley, 2010; Kortum and Weisbach, 2017; Cosbey et al., 2019).

We contribute to the CBA literature by examining and comparing policy distortions under different policy regimes. The previous studies focus primarily on how carbon leakage occurs without CBAs and how (full) CBAs can reduce global emissions effectively. For example, Yomogida and Tarui (2013) employ an international oligopoly model and investigate the optimal emission tax with and without BTAs. They show that an emission tax is more effective with BTAs than that without BTAs because the policy achieves higher national welfare for the taxing country and better environmental quality. In particular, carbon leakage disappears under identical emission intensities across countries. By contrast, we investigate and compare not only emissions but also firms' decisions on locations and abatement investments under the three different policy regimes.

Copeland (1996) points out that a pollution-content tariff is part of the optimal policy mix in the presence of variable abatement technologies in the foreign country. We find that if firm locations are fixed, the carbon-content tariff is more effective in reducing global emissions than a carbon tax alone, but the tax refund may weaken this effect. Conversely, if firm locations are endogenous, they tend to produce in the non-taxing country to avoid the losses from carbon taxes. Thus, BTAs basically discourage firms from choosing locations in the non-taxing country. Furthermore, this effect is stronger with the tax refunds than without them.

With endogenous location choices, our analysis is related to the pollution haven effect. Although the hypothesis has been studied extensively, only a few studies investigate it

[7] Perino and Requate (2012) also point out a similar result in a closed economy. However, their mechanisms are different from ours. Their finding is based on the non-monotonicity in the abatement cost difference between the dirty and clean technologies.

with CBAs. Ishikawa and Okubo (2017) use the footloose capital model to show that a carbon tax with BTAs has no impact on firm locations while decreasing the production of each firm in non-taxing countries. Therefore, no carbon leakage occurs under BTAs. Ma and Yomogida (2019) develop a North-South duopoly model and examine how the North's unilateral carbon tax affects the North firm's location and technology choice. They demonstrate that BTAs could encourage the firm to make an FDI with a clean technology, leading to a decrease in global emissions (called "negative" carbon leakage in their paper), and the North may have an incentive to induce such clean FDI to maximize its welfare.

Ma and Yomogida's (2019) study is most closely related to ours, because they account for the North firm's decisions on both production location and technology adoption. However, their focus is on indicating the negative carbon leakage mentioned above and deriving optimal carbon tax. More importantly, asymmetric features for both the countries and firms are crucial to their results. By contrast, we maintain symmetric country and firm characteristics to neutralize the effects stemming from asymmetries such as differences in the cost structure, except that one country unilaterally introduces a carbon tax. In particular, we show that even if both firms choose the non-taxing country as their production base without emission abatement at some tax rate, a higher tax rate can lead one of the firms to not only adopt the clean technology but also produce in the taxing country. We also obtain negative carbon leakage under certain conditions with endogenous locations.

The qualitative features of carbon taxes coupled with full BTAs are similar to those of consumption-based policies such as consumption taxes. Studies examining the efficiency of such policies in mitigating carbon leakage include those by Jakob et al. (2013), Eichner and Pethig (2015 a,b), and Böhringer et al. (2017).[8] Their focus is basically on constructing more practical policies which can achieve the same effectiveness as CBAs in mitigating carbon leakage, considering that the administration costs of CBAs would be too high to be compensated by the benefit from them. However, our concern is how a carbon tax with different BTAs affects firm behaviors and the consequent emissions.

[8]Consumption-based policies are often investigated when consumption causes pollution. In the context of international trade, see Ishikawa and Okubo (2010, 2011) and Tsakiris et al. (2018), for example.

3 The Basic Model

There are two symmetric countries, country h (Home) and country f (Foreign), and two symmetric firms, firms 1 and 2. The firms produce a homogeneous good with the same fixed costs (FCs) and constant marginal costs (MCs). Both FCs and MCs are normalized to zero. The home and foreign markets are segmented and the firms engage in Cournot competition in each market. Trading the good between the two countries requires transportation costs of τ per unit of the traded good. We assume that both firms have a positive supply in each market.

The goods demand is identical between the two markets. Specifically, the inverse demand function is[9]

$$p_i(X_i) = a - \frac{X_i^{1-\varepsilon}}{1-\varepsilon};\ i = h, f, \tag{1}$$

where h and f, respectively, represent Home and Foreign; X_i and p_i are, respectively, the demand and consumer price in country i; and a and ε are parameters. Note that ε is the elasticity of the slope of the inverse demand function, which is assumed to be constant:

$$\varepsilon = -\frac{X_i p''(X_i)}{p'(X_i)}.$$

The (inverse) demand curve is concave if $\varepsilon \leq 0$ and convex if $\varepsilon \geq 0$. If $\varepsilon = 0$, then (1) becomes a linear demand function:

$$p_i = a - X_i;\ i = h, f. \tag{2}$$

In the following analysis, we impose the following assumption, which implies that the outputs are always strategic substitutes; that is, $p' + p'' x_j < 0$, where x_j is the supply of firm j $(j = 1, 2)$, always holds.[10]

Assumption 1 $\varepsilon < 1$.

The goods production is dirty in the sense that one unit of production emits one unit of GHGs. The firms can adopt a clean technology by incurring an FC of $F(> 0)$.[11] We

[9] This demand function is often used in the monopoly and oligopoly literature. It is well known that the elasticity of the slope of the inverse demand function, ε, plays a crucial role in various analyses of monopolies and oligopolies. See Mrázová and Neary (2017).

[10] For details, see Furusawa et al. (2003) and Mrázová and Neary (2017), for example.

[11] Fixed costs of abatement are often assumed in the existing literature. See Perino and Requate (2012) and Forslid et al. (2018), for example.

call the adoption of this technology the abatement investment. The clean technology does not affect production costs but the emissions per unit of production reduce to k ($0 < k < 1$) units. The clean technology is unique and k is exogenously given and fixed. A smaller k means a more efficient abatement. To control emissions, the home government unilaterally sets a specific carbon tax rate of t on domestic production. The home government may introduce BTAs as well.

We now specifically examine three policy regimes. In the first regime (Regime α), the home government imposes a carbon tax on domestic production; in the second regime (Regime β), the home government also imposes a specific carbon-content tariff on the imports of the good; and in the third regime (Regime γ), in addition to the carbon tax and the carbon-content tariff, the home government refunds the carbon tax on exports. The carbon tax, tariff, and refund rates are the same. There is no BAT under Regime α. In Regimes β and γ, we consider two different BTAs, partial and full, respectively. Basically, in the presence of a carbon tax in Home, production in Home is protected by a tariff in Regime β and benefits further from an export subsidy in Regime γ.

The profits of firm j ($j = 1, 2$) depend on its technology and location choices, and the policy regime. If it does not engage in abatement, the profits from producing in Home and Foreign are, respectively, given by

$$\begin{aligned}
\pi_j^{HN} &= (p_h - t)x_{jhh} + (p_f - t - \tau + \gamma t)x_{jhf}, \\
\pi_j^{FN} &= (p_h - \tau - \beta t)x_{jfh} + p_f x_{jff},
\end{aligned}$$

where the first term and the second term are the profits from the home and foreign markets, respectively. The superscripts of π indicate firm location (H for Home and F for Foreign) and abatement status (N for no abatement and A for abatement). The subscripts indicate the firm, production location, and consumption location. For example, "jhf" represents firm j's output produced in Home and consumed in Foreign. We have $\beta = \gamma = 0$ in Regime α; $\beta = 1$ and $\gamma = 0$ in Regime β; and $\beta = \gamma = 1$ in Regime γ. The profits of firm j with abatement are

$$\begin{aligned}
\pi_j^{HA} &= (p_h - kt)x_{jhh} + (p_f - kt - \tau + \gamma kt)x_{jhf} - F, \\
\pi_j^{FA} &= (p_h - \tau - \beta kt)x_{jfh} + p_f x_{jff} - F,
\end{aligned}$$

If firm j incurs the FCs of the abatement investment F, then its carbon tax per unit of output becomes kt.

4 Fixed location

In this section, we investigate the case under fixed firm locations. We specifically assume that firm 1 is in Home while firm 2 is in Foreign. We assume away transportation costs in this section, because they do not play a crucial role under fixed firm locations. There are two stages of decision. In the first stage, taking home environmental policies as given, the firms decide whether to adopt the clean technology (i.e., to invest in emission abatement). In the second stage, the firms compete in both the home and foreign markets.

If the environmental regulation is not very stringent, then the firms have no incentive to abate emissions. However, if the carbon tax is high, the firms may invest in emission abatement to reduce their tax payments. We are particularly interested in how the three policy regimes affect firms' decisions and the consequent emissions.

4.1 Carbon tax with no BTAs (Regime α)

In this regime, the home government sets only a carbon tax on domestic production. When there are no BTAs, firm 2 has no incentive to adopt the clean technology because its abatement does not affect its effective MCs for exports. The profits of each firm without emission abatement are, respectively, given by

$$\begin{aligned}\pi_1^{NN\alpha} &= (p_h^{NN\alpha} - t)x_{1hh}^{NN\alpha} + (p_f^{NN\alpha} - t)x_{1hf}^{NN\alpha},\\ \pi_2^{NN\alpha} &= p_h^{NN\alpha} x_{2fh}^{NN\alpha} + p_f^{NN\alpha} x_{2ff}^{NN\alpha}.\end{aligned}$$

The superscripts indicate firm 1's abatement status, firm 2's abatement status, and the regime. For example, "$NN\alpha$" represents the profits when neither firm is engaged in abatement in Regime α.[12] The profits of each firm with firm 1's abatement are, respectively, given by

$$\begin{aligned}\pi_1^{AN\alpha} &= (p_h^{AN\alpha} - kt)x_{1hh}^{AN\alpha} + (p_f^{AN\alpha} - kt)x_{1hf}^{AN\alpha} - F,\\ \pi_2^{AN\alpha} &= p_h^{AN\alpha} x_{2fh}^{AN\alpha} + p_f^{AN\alpha} x_{2ff}^{AN\alpha}.\end{aligned}$$

With $t = 0$, $\pi_1^{NN\alpha} - \pi_1^{AN\alpha} = F$, implying firm 1 has no incentive for emission abatement. Although both $\pi_1^{NN\alpha}$ and $\pi_1^{AN\alpha}$ are decreasing in t, $\pi_1^{NN\alpha} < \pi_1^{AN\alpha}$ can hold for some $t(> 0)$. With $\pi_1^{NN\alpha} < \pi_1^{AN\alpha}$, firm 1 engages in emission abatement.

Note that $\pi_1^{NN\alpha} = \pi_1^{AN\alpha}$ can hold multiple times. To illustrate this possibility, we consider the case under linear demand (2).[13] To ensure both $x_{1hi} > 0$ and $x_{2fi} > 0$ in

[12] Since firm locations are fixed, H and F are deleted from the superscripts in this section.

[13] The following argument is valid with general demand.

the following analysis, we assume $a - 2t > 0$, i.e., $t < \frac{a}{2} \equiv \bar{t}$ under linear demand. We obtain

$$g^{\alpha}(t) \equiv (\pi_1^{AN\alpha} + F) - \pi_1^{NN\alpha} = \frac{4t}{9}(1-k)(2a - 2t - 2kt),$$

which is an inverted parabola with the vertex at $\left(\frac{a}{2(1+k)}, \frac{2a^2(1-k)}{9(1+k)}\right)$, implying that $\pi_1^{NN\alpha} = \pi_1^{AN\alpha}$ holds twice if $F < \frac{2a^2(1-k)}{9(1+k)}$. We let $t_1^{\alpha S}$ and $t_1^{\alpha L}$ ($t_1^{\alpha S} < t_1^{\alpha L}$) denote the tax rates, at which $\pi_1^{NN\alpha} = \pi_1^{AN\alpha}$ holds. Noting $\bar{t}$, firm 1 with $F < \frac{2a^2(1-k)}{9(1+k)}$ would abate its emissions if $t_1^{\alpha S} < t < \min\{t_1^{\alpha L}, \bar{t}\}$ holds.

It is intuitive that firm 1 does not engage in emission abatement if F is too high. Interestingly, however, firm 1 also loses its incentive for emission abatement if $t_1^{\alpha L} < t < \bar{t}$ holds. Although both $\pi_1^{NN\alpha}$ and $\pi_1^{AN\alpha}$ decrease in t, the incentive depends on the gap between $\pi_1^{NN\alpha}$ and $\pi_1^{AN\alpha}$ (i.e., $g^{\alpha}(t) - F$). Thus, the relationship between the carbon tax rate and emission abatement is not very straightforward.

To explore this, let us consider

$$\frac{dg^{\alpha}(t)}{dt} = \frac{4}{3}[(x_{1hh}^{NN\alpha} + x_{1hf}^{NN\alpha}) - k(x_{1hh}^{AN\alpha} + x_{1hf}^{AN\alpha})].$$

$\left.\frac{dg^{\alpha}(t)}{dt}\right|_{t=0} > 0$ because both $x_{1hh}^{NN\alpha} = x_{1hh}^{AN\alpha}$ and $x_{1hf}^{NN\alpha} = x_{1hf}^{AN\alpha}$ hold at $t = 0$. Thus, the marginal benefit from emission abatement is positive when t is sufficiently small. Note that $(x_{1hh}^{AN\alpha} + x_{1hf}^{AN\alpha}) > (x_{1hh}^{NN\alpha} + x_{1hf}^{NN\alpha})$ holds if $t > 0$. When t is large, $k(x_{1hh}^{AN\alpha} + x_{1hf}^{AN\alpha}) > (x_{1hf}^{NN\alpha} + x_{1hf}^{NN\alpha})$ holds. $\frac{dg^{\alpha}(t)}{dt} < 0$ implies that firm 1 may lose its incentive for abatement. We can rephrase this argument intuitively as follows. Emission abatement lowers the tax per unit output but increases the tax base. For firm 1, the former is a positive effect of emission abatement while the latter is a negative effect. The positive effect outweighs the negative effect if t is small, and vice versa if t is large. Thus, firm 1 may not have an incentive for emission abatement if t is large.

Figure 1 illustrates this result. When $F > F_a$, firm 1 does not adopt the clean technology. When $F_c < F \leq F_a$ (say, $F = F_b$), firm 1 adopts the clean technology if the tax rate is in the middle range (i.e., $t_1^{\alpha S} < t < t_1^{\alpha L}$). When $0 < F \leq F_c$, firm 1 would adopt the clean technology if the tax rate is high (i.e., $t_1^{\alpha S} < t < \bar{t}$).

Another interesting point is that a carbon tax may backfire. Without emission abatement, an increase in the carbon tax decreases firm 1's emissions, E_1, but increases firm 2's emissions, E_2. Thus, cross-border carbon leakage occurs but global emissions, E, decrease. However, if firm 1 adopts the clean technology at the lowest tax rate which leads to $\pi_1^{NN\alpha} = \pi_1^{AN\alpha}$, then firm 2's emissions necessarily decrease while firm 1's emissions can increase. The reason is as follows. As firm 1's abatement investment raises

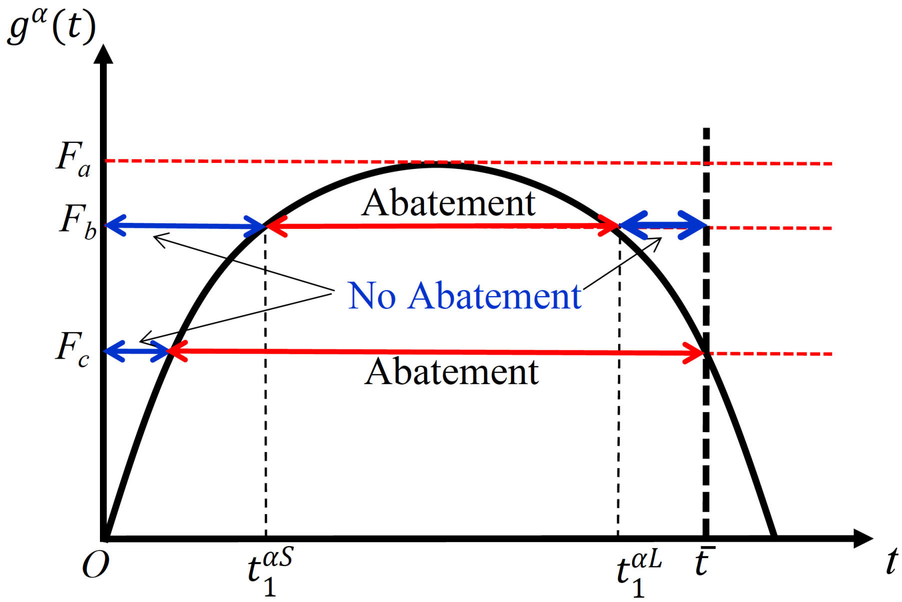

Figure 1: Abatement decisions in Regime α.

its total output, its total emissions can increase even though emissions per unit of firm 1's output decrease.[14] If the increase in firm 1' emissions dominates the decrease in firm 2's emissions, global emissions increase as a result of the abatement investment. We can confirm this result with liner demand (2). For a given t, we have

$$
\begin{aligned}
E_1^{NN\alpha} - E_1^{AN\alpha} &= \frac{1}{3}[(a-2t)+(a-2t)] \\
&\quad -\frac{k}{3}[(a-2kt)+(a-2kt)] \\
&= \frac{1}{3}(1-k)(2a-4t-4kt) < 0 \\
&\Leftrightarrow (2a-4t-4kt) < 0. \\
E^{NN\alpha} - E^{AN\alpha} &= \frac{1}{3}[2(2a-t)] - \frac{1}{3}[(-4t)k^2 + (2a+2t)k + 2a] \\
&= \frac{1}{3}(1-k)(2a-2t-4kt) < 0 \\
&\Leftrightarrow (2a-2t-4kt) < 0. \qquad (3)
\end{aligned}
$$

We can easily find the parameter values (a and k) and $t(<\bar{t})$ for which $E^{NN\alpha} < E^{AN\alpha}$ as well as $E_1^{NN\alpha} < E_1^{AN\alpha}$ holds.

[14] If $k = 0$, firm 1's emissions necessarily decrease. Thus, from the continuity argument, firm 1's emissions decrease as long as k is close to zero.

It is also noteworthy that $E_1^{NN\alpha}$, $E_1^{AN\alpha}$ and $E^{NN\alpha}$ are decreasing in t, while $E^{AN\alpha}$ can be increasing in t. At first glance, it seems counter intuitive that an increase in t increases global emissions, regardless of the presence of the abatement investment. The economic intuition behind this result is as follows. An increase in t decreases firm 1's output and increases firm 2's output. When $k(>0)$ is small, the decrease in firm 1's emissions caused by an increase in the carbon tax is small because it is equal to k times the decrease in firm 1's output. Thus, it can be dominated by the increase in firm 2's emissions caused by an increase in the carbon tax, which is simply equal to the increase in firm 2's output. In the case of linear demand, $E^{AN\alpha}$ is decreasing in t if and only if $k > \frac{1}{2}$.

Thus, we establish the following proposition.

Proposition 1 *A carbon tax can induce firm 1 to invest in emission abatement if the investment cost is not too high. Even if firm 1 has an incentive for emission abatement for some carbon tax rates, it may lose the incentive for higher tax rates. For a given t, firm 1's emission abatement decreases firm 2's emissions, but may increase global emissions as well as firm 1's emissions. If firm 1's emission abatement is highly efficient (i.e., k is small), an increase in t increases global emissions in the presence of firm 1's abatement.*

4.2 Carbon tax with carbon-content tariff (Regime β)

In this regime, a carbon tax is accompanied by a carbon-content tariff at a tax rate equal to the carbon tax rate. The carbon-content tariff affects only firm 2's effective MCs for exports. Without emission abatement, introducing the tariff for a given t increases firm 1's output for the home market and decreases firm 2's output for the home market. Since the decrease dominates the increase, the total output for the home market falls. Thus, for a given t, the carbon-content tariff raises firm 1's emissions and reduces both firm 2's emissions and global emissions, i.e., $E_1^{NN\beta} > E_1^{NN\alpha}$, $E_2^{NN\beta} < E_2^{NN\alpha}$, and $E^{NN\beta} < E^{NN\alpha}$. Note that compared with Regime α, cross-border carbon leakage declines because emissions from firm 2's output for the home market decrease.

Next we consider emission abatement. The profits of each firm with only firm 1's abatement investment are, respectively, given by

$$\pi_1^{AN\beta} = (p_h^{AN\beta} - kt)x_{1hh}^{AN\beta} + (p_f^{AN\beta} - kt)x_{1hf}^{AN\beta} - F,$$
$$\pi_2^{AN\beta} = (p_h^{AN\beta} - t)x_{2fh}^{AN\beta} + p_f^{AN\beta}x_{2ff}^{AN\beta}.$$

The carbon-content tariff affects firm 2's effective MCs, implying that firm 2 may also have an incentive to invest in abatement if t is sufficiently high. The profits of each firm with only firm 2's abatement investment are, respectively,

$$\pi_1^{NA\beta} = (p_h^{NA\beta} - t)x_{1hh}^{NA\beta} + (p_f^{NA\beta} - t)x_{1hf}^{NA\beta},$$
$$\pi_2^{NA\beta} = (p_h^{NA\beta} - kt)x_{2fh}^{NA\beta} + p_f^{NA\beta}x_{2ff}^{NA\beta} - F.$$

The profits with abatement investment by both firms are, respectively,

$$\pi_1^{AA\beta} = (p_h^{AA\beta} - kt)x_{1hh}^{AA\beta} + (p_f^{AA\beta} - kt)x_{1hf}^{AA\beta} - F,$$
$$\pi_2^{AA\beta} = (p_h^{AA\beta} - kt)x_{2fh}^{AA\beta} + p_f^{AA\beta}x_{2ff}^{AA\beta} - F.$$

Whereas firm 1's abatement lowers its effective MCs for its total production, firm 2's abatement decreases its effective MCs only for its exports. Thus, it is more likely that firm 1 has stronger incentive to abate its emissions than firm 2. We can determine if this is actually the case by checking the following sign:

$$\begin{aligned}\Delta\pi_{12}^{\beta} &\equiv (\pi_1^{AN\beta} - \pi_1^{NN\beta}) - (\pi_2^{NA\beta} - \pi_2^{NN\beta}) \\ &= [(p_h^{AN\beta} - kt)x_{1hh}^{AN\beta} - (p_h^{NN\beta} - t)x_{1hh}^{NN\beta}] \\ &\quad +[(p_f^{AN\beta} - kt)x_{1hf}^{AN\beta} - (p_f^{NN\beta} - t)x_{1hf}^{NN\beta}] \\ &\quad -[(p_h^{NA\beta} - kt)x_{2fh}^{NA\beta} - (p_h^{NN\beta} - t)x_{2fh}^{NN\beta}].\end{aligned}$$

The first and the third square brackets are equal. As the second square bracket is positive, we obtain $\Delta\pi_{12}^{\beta} > 0$. Thus, the threshold tax rate between no abatement and abatement is lower for firm 1 than for firm 2.

To elaborate on the firms' abatement decisions, we focus on linear demand (2). First, we can confirm

$$\Delta\pi_{12}^{\beta} = \frac{4t}{9}(1-k)(a-t-kt) > 0$$

for $0 < t < \bar{t}(< \frac{a}{1+k})$. Thus, letting $t_1^{\beta S}$ denote the lowest t that satisfies $\pi_1^{AN\beta} = \pi_1^{NN\beta}$, firm 2 does not abate emissions (i.e., $\pi_2^{NA\beta} < \pi_2^{NN\beta}$) if $t < t_1^{\beta S}$. We can determine firm 1's incentive to invest in abatement given no abatement by firm 2 from the following:

$$g^{\beta}(t) \equiv (\pi_1^{AN\beta} + F) - \pi_1^{NN\beta} = \frac{4t}{9}(1-k)(2a - t - 2kt),$$

which is an inverted parabola with the vertex at $\left(\frac{a}{2k+1}, \frac{4a^2(1-k)}{9(2k+1)}\right)$, implying that $\pi_1^{NN\beta} = \pi_1^{AN\beta}$ holds twice at $t_1^{\beta S}$ and $t_1^{\beta L}$ if $F < \frac{4a^2(1-k)}{9(2k+1)}$. Noting $\bar{t}$, therefore, firm 1 with $F < \frac{4a^2(1-k)}{9(2k+1)}$ would abate its emissions if $t_1^{\beta S} < t < \min\{t_1^{\beta L}, \bar{t}\}$ holds.[15]

Note that once firm 1 adopts the clean technology, firm 2 may change its strategy; it may also adopt the clean technology. Thus, we need to check firm 2's incentive to invest in abatement given firm 1's investment. We have

$$h^{\beta}(t) \equiv (\pi_2^{AA\beta} + F) - \pi_2^{AN\beta} = \frac{4t}{9}(1-k)(a-t),$$

which is an inverted parabola with the vertex at $\left(\frac{a}{2}, \frac{a^2(1-k)}{9}\right)$. Thus, if $F < \frac{a^2(1-k)}{9}$, then there exists the tax rate, $t_2^{\beta}(< \bar{t})$, at which $\pi_2^{AA\beta} = \pi_2^{AN\beta}$ holds.[16] We can readily verify that $g^{\beta}(t) = h^{\beta}(t)$ holds at $t = \frac{a}{2k}(\equiv \widetilde{t})$, which is greater than both $\frac{a}{2k+1}$ and $\frac{a}{2}$. This implies that $g^{\beta}(t) > h^{\beta}(t)$ for $t < \widetilde{t}$ and the slopes of $g^{\beta}(t)$ and $h^{\beta}(t)$ are negative at $\widetilde{t}$. Thus, we obtain $t_1^{\beta S} < t_2^{\beta}$, which means there exists a range of t under which firm 1 would adopt the clean technology but firm 2 would not. In the presence of firm 1's abatement investment, firm 2 would also invest in emission abatement if $t_2^{\beta} < t < \min\{t_1^{\beta L}, \bar{t}\}$.

Conversely, we need to check whether firm 1 would still adopt the clean technology even if firm 2 also adopts the clean technology. For this, we examine firm 1's incentive to invest abatement given firm 2's investment. We have

$$m^{\beta}(t) \equiv (\pi_1^{AA\beta} + F) - \pi_1^{NA\beta} = \frac{4t}{9}(1-k)(2a - 2t - kt).$$

Since $m^{\beta}(t) = h^{\beta}(t)$ holds at $t = \frac{a}{k+1}$, $m^{\beta}(t) > h^{\beta}(t)$ for $0 < t < \bar{t} < \frac{a}{k+1}$. This implies that both firms engage in abatement if firm 2 adopts the clean technology. Thus, unless F is very large, there is a threshold of t below which only firm 1 adopts the clean technology and above which both firms do so.

Just as in the case with a carbon tax alone, as a result of only firm 1's investment in abatement, firm 2's emissions decrease but firm 1's emissions and global emissions can increase. With linear demand, we obtain

$$\begin{aligned} E_1^{NN\beta} - E_1^{AN\beta} &= \frac{1}{3}(1-k)(2a - 3t - 4kt) < 0 \\ &\Leftrightarrow (2a - 3t - 4kt) < 0 \\ E^{NN\beta} - E^{AN\beta} &= \frac{1}{3}(1-k)(2a - t - 4kt) < 0 \\ &\Leftrightarrow (2a - t - 4kt) < 0, \end{aligned}$$

[15] The following is a necessary condition for $t_1^{\beta L} < \bar{t}$: $\frac{a}{2k+1} < \bar{t}$ (i.e., $k > \frac{1}{2}$).

[16] If $F < \frac{(1-k)a^2}{9}$, then there exist two tax rates which lead to $\pi_2^{AA\beta} = \pi_2^{AN\beta}$. However, the higher tax rate is always greater than $\bar{t}$.

for a given t. However, compared with (3), $E^{NN\beta} < E^{AN\beta}$ is less likely. Moreover, $E_2^{AN\beta}$ and $E^{AN\beta}$ are decreasing in t, while $E_1^{AN\beta}$ is decreasing in t if and only if $k > \frac{1}{4}$.

Firm 2's emission abatement does not affect the outputs for the foreign market, meaning the emissions stemming from firm 1's output for the foreign market are constant while those from firm 2's output for the foreign market decrease. Firm 1's output for the home market decreases while firm 2's output for the home market increases. Although the emissions stemming from firm 1's output for the home market decrease, it is generally ambiguous whether those from firm 2's output for the home market decrease. With linear demand, we can readily verify $E_1^{AA\beta} < E_1^{AN\beta}$, $E_2^{AA\beta} < E_2^{AN\beta}$, and $E^{AA\beta} < E^{AN\beta}$. Moreover, with general demands, $E_1^{AA\beta}$ and $E^{AA\beta}$ are decreasing in t, while $E_2^{AA\beta}$ may or may not be decreasing in t.[17]

Next, comparing between Regimes α and β, we examine how the presence of the carbon-content tariff affects firm 1's incentive to invest in abatement. For this, we check the sign of the following:

$$\begin{aligned}\Delta\pi_1^{\alpha\beta} &\equiv (\pi_1^{AN\alpha} - \pi_1^{NN\alpha}) - (\pi_1^{AN\beta} - \pi_1^{NN\beta}) \\ &= (p_h^{AN\alpha} - kt)x_{1hh}^{AN\alpha} - (p_h^{NN\alpha} - t)x_{1hh}^{NN\alpha} - ((p_h^{AN\beta} - kt)x_{1hh}^{AN\beta} - (p_h^{NN\beta} - t)x_{1hh}^{NN\beta}).\end{aligned} \tag{4}$$

If this is negative, the range of t at which firm 1 invests in abatement would expand; that is, firm 1 has an incentive to abate emissions for lower carbon taxes with the carbon-content tariff than without it. Compared to the case with a carbon tax alone, for a given t, firm 1's output for the home market increases while its output for the foreign market remains unchanged. Thus, it is more likely that firm 1 abates emissions for lower carbon taxes. In the case of linear demand, for example, we can confirm that firm 1 has more incentive to invest in emission abatement with a carbon-content tariff than without it.[18] Figure 2 illustrates a possible case where $t_1^{\beta S} < t_1^{\alpha S} < t_2^{\beta} < \bar{t} < t_1^{\alpha L}$ holds.

We now compare the emission level between Regimes α and β when only firm 1 invests in emission abatement (i.e., we compare $E^{AN\alpha}$ and $E^{AN\beta}$). The carbon-content tariff does not affect the emissions stemming from the outputs for the foreign market. With respect to the outputs for the home market, firm 1's output increases but firm 2's output and the total output decrease. This result implies that for a given t, $E_1^{AN\beta} > E_1^{AN\alpha}$, $E_2^{AN\beta} < E_2^{AN\alpha}$, and $E^{AN\beta} < E^{AN\alpha}$ hold.

Thus, we obtain the following proposition.

[17]With linear demand, $E_2^{HFAA\beta}$ is independent of t.

[18]Cheng and Ishikawa (2021) show that $\Delta\pi_1^{\alpha\beta} < 0$ if $\varepsilon \geq 0$.

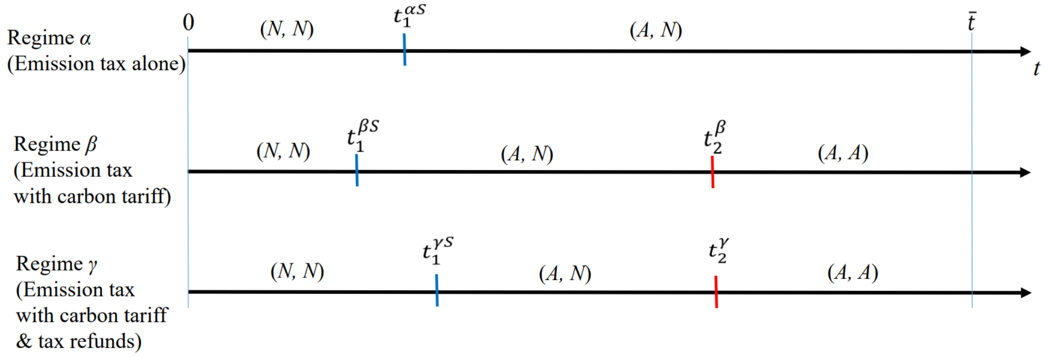

Figure 2: Abatement choices with fixed locations.

Proposition 2 *A carbon tax accompanied by a carbon-content tariff can induce both firms 1 and 2 to invest in emission abatement if the investment cost is not too high. Firm 1 has more incentive to invest in emission abatement than firm 2. The introduction of the carbon-content tariff for a given t, if it does not change the abatement decisions, increases firm 1's emissions but decreases firm 2's emissions and global emissions. An increase in t decreases global emissions if neither firm or both firms adopt the clean technology, but can increase them if only firm 1 adopts it.*

4.3 Carbon tax with tax refunds at the border and a carbon-content tariff (Regime γ)

When we introduce carbon-tax refunds, the effective MCs to serve the foreign market are independent of the home carbon tax. Thus, firm 1's disadvantage in the foreign market is offset. If neither firm or both firms adopt the clean technology, the two firms obtain the same profits:

$$\begin{aligned}
\pi_1^{NN\gamma} &= (p_h^{NN\gamma} - t)x_{1hh}^{NN\gamma} + p_f^{NN\gamma} x_{1hf}^{NN\gamma} \\
&= (p_h^{NN\gamma} - t)x_{2fh}^{NM\gamma} + p_f^{NN\gamma} x_{2ff}^{NN\gamma} = \pi_2^{NN\gamma};
\end{aligned}$$

$$\begin{aligned}
\pi_1^{AA\gamma} &= (p_h^{AA\gamma} - kt)x_{1hh}^{AA\gamma} + p_f^{AA\gamma} x_{1hf}^{AA\gamma} - F \\
&= (p_h^{AA\gamma} - kt)x_{2fh}^{AA\gamma} + p_f^{AA\gamma} x_{2ff}^{AA\gamma} - F = \pi_2^{AA\gamma}.
\end{aligned}$$

The profits of each firm with only firm 1's abatement investment are, respectively, given by

$$\pi_1^{AN\gamma} = (p_h^{AN\gamma} - kt)x_{1hh}^{AN\gamma} + p_f^{AN\gamma}x_{1hf}^{AN\gamma} - F,$$
$$\pi_2^{AN\gamma} = (p_h^{AN\gamma} - t)x_{2fh}^{AN\gamma} + p_f^{AN\gamma}x_{2ff}^{AN\gamma}.$$

The profits of each firm with only firm 2's abatement investment are analogous:

$$\pi_1^{NA\gamma} = (p_h^{NA\gamma} - t)x_{1hh}^{NA\gamma} + p_f^{NA\gamma}x_{1hf}^{NA\gamma},$$
$$\pi_2^{NA\gamma} = (p_h^{NA\gamma} - kt)x_{2fh}^{NA\gamma} + p_f^{NA\gamma}x_{2ff}^{NA\gamma} - F.$$

Whereas firm 1's abatement decreases its effective MCs only for its domestic production from t to kt, firm 2's abatement decreases its effective MCs only for its exports from t to kt.

When t is small, neither firm has an incentive for abatement investment. Since the profits decrease as t increases, the firms have an incentive for abatement investment at a certain tax rate, $t_1^{\gamma S}$. However, only one of the two firms would adopt the clean technology at $t_1^{\gamma S}$. To see this, we simply assume that if only one firm adopts the clean technology, it is firm 1. Suppose $\pi_1^{NN\gamma} = \pi_1^{AN\gamma}$ holds at $t_1^{\gamma S}$. Then we can verify $\pi_2^{AA\gamma} < \pi_2^{AN\gamma}$ at $t_1^{\gamma S}$, implying only one firm (firm 1) would invest in emission abatement at $t_1^{\gamma S}$. The other firm (firm 2) would invest in emission abatement at a higher tax rate, t_2^{γ}.

We can confirm the above result with linear demand (2). We can determine firm 1's incentive to invest in abatement from the following:

$$g^{\gamma}(t) \equiv (\pi_1^{AN\gamma} + F) - \pi_1^{NN\gamma} = \frac{4t}{9}(1-k)(a-kt),$$

which is an inverted parabola with the vertex at $\left(\frac{a}{2k}, \frac{a^2(1-k)}{9k}\right)$, implying that $\pi_1^{HFNN\gamma} = \pi_1^{HFAN\gamma}$ holds twice at $t_1^{\gamma S}$and $t_1^{\gamma L}$ ($t_1^{\gamma S} < t_1^{\gamma L}$) if $F < \frac{a^2(1-k)}{9k}$. However, $t_1^{\gamma L} > \bar{t}$ holds because $\bar{t} < \frac{a}{2k}$. Thus, with $F < \frac{a^2(1-k)}{9k}$, firm 1 abates its emissions if $t_1^{\gamma S} < t < \bar{t}$ holds.

We now check firm 2's incentive to invest in abatement given firm 1's investment. We have

$$h^{\gamma}(t) \equiv (\pi_2^{AA\gamma} + F) - \pi_2^{AN\gamma} = \frac{4t}{9}(1-k)(a-t) = h^{\beta}(t).$$

If $F < \frac{a^2(1-k)}{9k}$, then there exits a tax rate of $t_2^{\gamma}(< \bar{t})$ at which $\pi_2^{AA\gamma} = \pi_2^{AN\gamma}$ holds. We can readily verify that $g^{\gamma}(t) = h^{\gamma}(t)$ holds at $t = 0$, which implies that $g^{\gamma}(t) > h^{\gamma}(t)$ for $t > 0$.[19] Thus, we obtain $t_1^{\gamma S} < t_2^{\gamma}$, which means there exists a range of t under

[19] The threshold tariff rate between no abatement and abatement for firm 2 is the same for Regimes β and γ, i.e., $t_2^{\gamma} = t_2^{\beta}$ (see Figure 2).

which firm 1 would adopt the clean technology while firm 2 would not. In the presence of firm 1's abatement investment, firm 2 would also invest in emission abatement if $t_2^{\gamma} < t < \min\{t_1^{\gamma L}, \bar{t}\}$.

Conversely, we examine firm 1's incentive to invest in abatement given firm 2's investment. With linear demand, we have

$$m^{\gamma}(t) \equiv (\pi_1^{AA\gamma} + F) - \pi_1^{NA\gamma} = \frac{4t}{9}(1-k)(a-t).$$

As $m^{\gamma}(t) > h^{\gamma}(t)$ holds for $t > 0$, both firms engage in abatement if firm 2 adopts the clean technology.

Thus, unless F is very large, there is a threshold of t below which only firm 1 adopts the clean technology and above which both firms adopt the clean technology. With linear demand, we can also verify that $E_2^{AN\gamma}$ and $E^{AN\gamma}$ are decreasing in t, while $E_1^{AN\gamma}$ is decreasing in t if and only if $k > \frac{1}{2}$.

We now compare Regime γ with Regime α for a given t. In Regime γ, the supplies to both the home and foreign markets by firm 1 are larger, while those by firm 2 are smaller. The total supply to the home market is smaller, while that to the foreign market is larger. In general, it is ambiguous whether global emissions decrease. In the case of linear demand, for example, the shift from Regime α to Regime γ does not affect global emissions if neither firm adopts the clean technology in both regimes but decreases them if only firm 1 adopts the clean technology in both regimes.[20]

Note that firm 1's abatement investment decreases its effective MC for the total output in Regime α but decreases that for the output only for the home market in Regime γ. Thus, the threshold tax rate between no abatement and abatement for firm 1 is likely to be larger in Regime γ than in Regime α. For example, we can confirm this result in the case of linear demand because

$$(\pi_1^{AN\gamma} - \pi_1^{NN\gamma}) - (\pi_1^{AN\alpha} - \pi_1^{NN\alpha}) = 4t(k-1)(a-2t-kt)$$

is likely to be negative.

Also note that introducing a carbon tax under Regime α results in carbon leakage from firm 1 to firm 2 while that under Regime γ results in no carbon leakage.[21] Interestingly, however, a carbon tax under Regime γ is not necessarily superior in terms of reducing global emissions compared to a carbon tax under Regime α.

Thus, we obtain the following proposition.

[20] If k is sufficiently small, the latter result holds for general demand.

[21] Since firm 2's emissions actually decrease, "negative" carbon leakage occurs.

Proposition 3 *Introducing a carbon tax with a border carbon-content tariff and the carbon-tax refunds for exports eliminates the cross-border carbon leakage caused by a carbon tax with no BTAs. However, for a given t, global emissions may not be less under the carbon tax with full BTAs than under the carbon tax with no BTAs.*

Next, we compare Regime γ with Regime β. Since the tax refunds are basically an export subsidy, firm 1's supply to the home market remains the same but its supply to the foreign market increases. Compared with Regime β, firm 1's output for the foreign market increases while firm 2's output for the foreign market decreases. Since the former effect dominates the latter effect, the total output for the foreign market rises. Thus, without emission abatement, we have $E_1^{NN\gamma} > E_1^{NN\beta}$, $E_2^{NN\gamma} < E_2^{NN\beta}$, and $E^{NN\gamma} > E^{NN\beta}$ for a given t. Similarly, with the abatement investment by both firms, we have $E_1^{AA\gamma} > E_1^{AA\beta}$, $E_2^{AA\gamma} < E_2^{AA\beta}$, and $E^{AA\gamma} > E^{AA\beta}$ for a given t. However, global emissions can be lower in Regime γ if only firm 1 adopts the clean technology. In the foreign market, the total supply increases but firm 1's supply (i.e., the supply subject to the carbon tax) increases more than the total supply. Consequently, it is ambiguous whether the total emissions increase. With linear demand (2), for example, we obtain

$$E^{AN\gamma} - E^{AN\beta} = \frac{kt}{3}(2k-1) > 0 \Leftrightarrow k > \frac{1}{2}.$$

When k is small, the increase in the total supply in the foreign market is small, but some of firm 2's supply is replaced by firm 1's supply which is subject to low per-unit emissions. Thus, for a given t, introducing tax refunds can decrease total emissions. Thus, again, a carbon tax under Regime γ which generates no carbon leakage is not necessarily superior in terms of reducing global emissions compared to a carbon tax under Regime β, which generates carbon leakage.

Compared with Regime β, whether or not firm 1 engages in emission abatement, firm 1's effective MCs for exports become zero. Introducing tax refunds does not affect the other MCs. Thus, for a given t, we obtain

$$\begin{aligned} & (\pi_1^{AN\beta} - \pi_1^{NN\beta}) - (\pi_1^{AN\gamma} - \pi_1^{NN\gamma}) \\ = \quad & (p_f^{AN\beta} - kt)x_{1hf}^{AN\beta} - (p_f^{NN\beta} - t)x_{1hf}^{NN\beta} > 0, \end{aligned}$$

implying that the threshold tax rate between no abatement and abatement for firm 1 is larger in Regime γ than in Regime β (see Figure 2).[22] This result is intuitive because the

[22]This result does not depend on linear demand.

tax refunds decrease the benefit of emission abatement. Thus, the tax refunds discourage firm 1's abatement investment. We can also verify

$$(\pi_2^{AA\beta} - \pi_2^{AN\beta}) - (\pi_2^{AA\gamma} - \pi_2^{AN\gamma}) = 0,$$

which means the threshold of the tariff rate between no abatement and abatement for firm 2 is the same in Regime γ and Regime β.

Thus, we obtain the following proposition.

Proposition 4 Introducing *carbon-tax refunds for exports in addition to the border carbon-content tariff makes the threshold tax rate between no abatement and abatement for firm 1 larger but does not change that for firm 2. For a given* t *at which neither firm or both firms adopt the clean technology, global emissions are larger with the carbon-tax refunds than without them (i.e.,* $E^{NN\gamma} > E^{NN\beta}$ *and* $E^{AA\gamma} > E^{AA\beta}$ *hold). However, for a given* t*, at which only firm 1 adopts the clean technology, global emissions can be lower with the tax refunds than without them (i.e.,* $E^{AN\gamma} < E^{AN\beta}$ *can hold) if* k *is small.*

5 Endogenous locations

In this section, we investigate the case where the firms also choose their locations. Note that transportation costs play a crucial role with endogenous firm locations, because a home carbon tax leads both firms to choose Foreign without transportation costs. The decision stages are modified as follows. In the first stage, taking home emission policies as given, the firms choose their locations and technologies simultaneously. In the second stage, the firms compete in both home and foreign markets. We assume that the firms do not incur any cost to choose their locations.[23]

Since there are two locations and two technologies, each firm has four strategies in the first stage: HN (Home and no abatement), HA (Home and abatement), FN (Foreign and no abatement), and FA (Foreign and abatement). The complete analysis of endogenous location and technology choices is rather complicated because there are many possible cases to consider. Thus, in this section, our purpose is not to provide the complete analysis in the presence of endogenous location and technology choices but to show interesting location patterns.

[23] We can introduce a set-up fixed cost; however, if it is the same for Home and Foreign, then the essence of our analysis would not change.

We assume that if the two firms choose different locations, then firms 1 and 2, respectively, choose Home and Foreign. We specifically assume that this is the case with no carbon tax.[24] Obviously, no firm would invest in the clean technology without a carbon tax. In the following, we first show that there can be a threshold tax rate at which both firms choose Foreign. In Regime α, the carbon tax that is above the threshold rate is not effective. In Regimes β and γ, we show that even if both firms choose Foreign for some tax rates, they may choose different locations for higher tax rates.

5.1 Carbon tax with no BTAs (Regime α)

The location pattern in which firms 1 and 2, respectively, choose Home and Foreign remains to be realized as long as t is sufficiently small. When t is relatively large, firm 1 may choose the Foreign location or engage in abatement in Home. Without firm 1's abatement, the threshold tax rate at which firm 1 chooses Foreign is less than τ, because firm 1's effective MCs are t for the home market and $t+\tau$ for the foreign market with (HN, FN), but are τ for the home market and 0 for the foreign market with (FN, FN).[25] With firm 1's abatement, the threshold tax rate at which firm 1 chooses Foreign is higher than without it, but is less than τ/k. However, if k is sufficiently close to zero, firm 1 is unlikely to choose Foreign even with high tax rates. Thus, in the following analysis, we focus on the case where the first-stage equilibrium switches from (HN, FN) to (FN, FN) when the tax rate becomes higher.

If both firms choose Foreign, they have no incentive for emission abatement and become identical. The profits are[26]

$$\pi_j^{FFNN\alpha} = (p_h^{NN\alpha} - \tau)x_{jfh}^{NN\alpha} + p_f^{NN\alpha}x_{jff}^{NN\alpha}, \quad j = 1, 2.$$

As long as both firms are located in Foreign, the emission levels $E_j^{FFNN\alpha}$and $E^{FFNN\alpha}$ are independent of t. At the threshold tax rate, $t_1^{\alpha e}$, at which firm 1 chooses Foreign, emissions stemming from the production for Home decrease because firm 1's effective MC to serve Home increases from t to τ. Emissions stemming from the production for Foreign increase because firm 1's effective MC to serve Foreign decreases from $\tau + t$ to

[24] Cheng and Ishikawa (2021) show that this assumption is satisfied if demand is convex (i.e., $\varepsilon \geq 0$).

[25] Given that firm 1 chooses Foreign at the threshold tax rate, firm 2 would not choose Home at this tax rate, because the two firms are symmetric.

[26] In this section, the superscripts of π_j, E_j ($j = 1, 2$) and E indicate firm 1's location, firm 2's location, firm 1's abatement status, firm 2's abatement status, and the regime. For example, $\pi_j^{FFNN\alpha}$ represents firm j's profits when both firms are in Foreign and neither firm is engaged in abatement in Regime α.

0. Appendix shows the following lemma.[27]

Lemma 1 *$E^{HFNN\alpha} < E^{FFNN\alpha}$ holds for $t > 0$ if $\varepsilon \geq 0$* and for *$t > \widehat{t}$ if $\varepsilon < 0$.*

$E^{HFNN\alpha} < E^{FFNN\alpha}$ means that the pollution haven effect leads to positive carbon leakage between Home and Foreign and increases global emissions.

We obtain the following proposition.

Proposition 5 *The following equilibria are possible with a carbon tax: (HN, FN) with low tax rates and (FN, FN) with high tax rates. Global emissions are greater with (FN, FN) than with (HN, FN) (i.e., $E^{FFNN\alpha} > E^{HFNN\alpha}$) if demand is convex ($\varepsilon \geq 0$).*

5.2 Carbon tax with a carbon-content tariff (Regime β)

We now introduce the carbon-content tariff in addition to the carbon tax. The carbon-content tariff increases the effective MCs to export to Home from Foreign, implying a weaker incentive to choose Foreign as the production location. We can confirm this result from the following relationship:

$$
\begin{aligned}
& (\pi_1^{FFNN\alpha} - \pi_1^{HFNN\alpha}) - (\pi_1^{FFNN\beta} - \pi_1^{HFNN\beta}) \\
= \; & (p_h^{NN\alpha} - \tau)x_{1fh}^{NN\alpha} - (p_h^{NN\alpha} - t)x_{1hh}^{NN\alpha} - ((p_h^{NN\beta} - t - \tau)x_{1fh}^{NN\beta} - (p_h^{NN\beta} - t)x_{1hh}^{NN\beta}),
\end{aligned}
$$

which is positive for a given t. Thus, the (lowest) tax rate at which firm 1 is indifferent between Home and Foreign in Regime β, $t_1^{\beta eS}$, is greater than that in Regime α, $t_1^{\alpha eS}$. Moreover, $E^{HFNN\beta} < E^{HFNN\alpha}$ holds for a given t, because the outputs for the home market decrease but those for the foreign market do not change. Lemma 1 is valid in Regime β and hence $E^{HFNN\beta} < E^{FFNN\beta}$ for $t > 0$ (i.e., global emissions with (FN, FN) are greater than those with (HN, FN)) if $\varepsilon \geq 0$. Thus, if $\varepsilon \geq 0$, then the carbon-content tariff is effective at reducing global emissions because it makes firm 1 less likely to locate itself in Foreign.

In the rest of this subsection, we specifically show that an increase in t can switch the equilibrium not only from (HN, FN) to (FN, FN) but also from (FN, FN) to (HA, FN). To this end, we assume linear demand.

[27] $\widehat{t}$ is a threshold tax rate defined in Appendix.

If both firms choose Foreign as their production locations, then the firms are identical. In Regime α, both firms are independent of t if they produce in Foreign. In Regime β, however, the profits decrease as t increases. At a certain tax rate, t_1^{β}, the firms have an incentive to abate emissions. However, only one of the two firms would adopt the clean technology at t_1^{β}. To see this, we simply assume that if only one firm adopts the clean technology, it is firm 1. Suppose $\pi_1^{FFNN\beta} = \pi_1^{FFAN\beta}$ holds at t_1^{β}. Then we can verify $\pi_2^{FFAA\beta} < \pi_2^{FFAN\beta}$ at t_1^{β}, implying only one firm (firm 1) would invest in emission abatement at t_1^{β}. The other firm (firm 2) would invest in emission abatement at a higher tax rate, t_2^{β}.

It should be pointed out that firm 1 has an incentive not only to adopt the clean technology but also to produce in Home at $t_1^{\beta e+}$, where $\pi_1^{FFNN\beta} = \pi_1^{HFAN\beta}$ holds. More importantly, $t_1^{\beta e+} < t_1^{\beta}$ can hold. Since we obtain

$$\pi_1^{HFAN\beta} - \pi_1^{FFAN\beta} = \frac{4}{9}\left(k^2t^2 + (\tau - ak)\,t + \tau^2\right),$$

$\pi_1^{HFAN\beta} > \pi_1^{FFAN\beta}$ holds for any $t(>0)$ if $\tau \geq ak$.[28] Thus, as t rises, the equilibrium can shift from (HN, FN) to (FN, FN) and then to (HA, FN). Figure 3 (a) illustrates this case.[29]

We examine how the equilibrium shift from (FN, FN) to (HA, FN) changes emissions. We obtain

$$E^{HFAN\beta} - E^{FFNN\beta} = -\frac{(1-k)(2a-\tau) + k(4k-3)t}{3}.$$

Noting $a - 2(t+\tau) > 0$, $E^{HFAN\beta} < E^{FFNN\beta}$ holds for a given t. Thus, the relationship between the tax rate and the emission level is non-monotonic.

It is noteworthy that the equilibrium may switch from (HA, FN) to (FA, FN) as t further increases. This case is illustrated in Figure 4.[30] The equilibrium switch from (HA, FN) to (FA, FN) increases firm 1's emissions by $\frac{2k^2t}{3}$ and decreases firm 2's emissions by $\frac{kt}{3}$, leading to

$$E^{HFAN\beta} - E^{FFAN\beta} = \frac{kt(1-2k)}{3}.$$

[28] $\pi_1^{HFAN\beta} > \pi_1^{FFAN\beta}$ holds for any t if $(\tau - ak)^2 - 4k^2\tau^2 < 0$.

[29] In Figure 3, we set parameter values as follows: $a = 20$, $\tau = 1.5$, $k = 1/9$, and $F = 15$. Then we obtain $\bar{t} = 8.5$, $t_1^{\beta eS} = 0.122$, $t_1^{\beta S} = 1.019$, $t_1^{\beta e+} = 2.026$, $t_1^{\gamma e} = 1.5$, $t_1^{\gamma S} = 1.782$, $t_1^{\gamma e+} = 1.807$, and $t_2^{\beta} = t_2^{\gamma} = 2.645$.

[30] In Figure 4, we set parameter values as follows: $a = 20$, $\tau = 1.5$, $k = 1/6$, and $F = 7.5$. Then we obtain $\bar{t} = 8.5$, $t_1^{\beta eS} = 0.122$, $t_1^{\beta S} = 0.536$, $t_1^{\beta e+} = 1.086$, $t_1^{\beta e++} = 1.251$, and $t_2^{\beta} = 1.289$. $t_1^{\beta e++}$ is the threshold tax rate between (HA, FN) and (FA, FN).

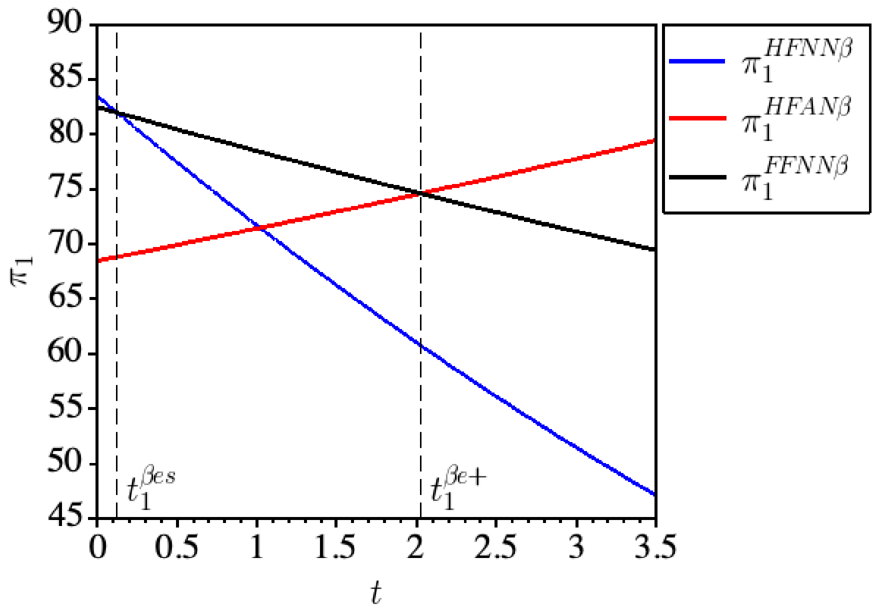

Figure 3(a): Regime β: $(HN, FN) \rightarrow (FN, FN) \rightarrow (HA, FN)$.

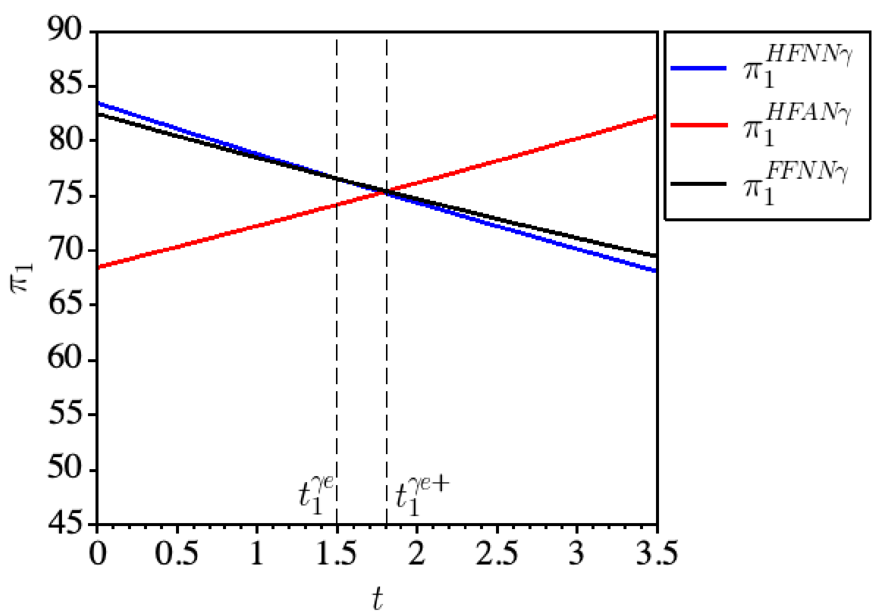

Figure 3(b): Regime γ: $(HN, FN) \rightarrow (FN, FN) \rightarrow (HA, FN)$.

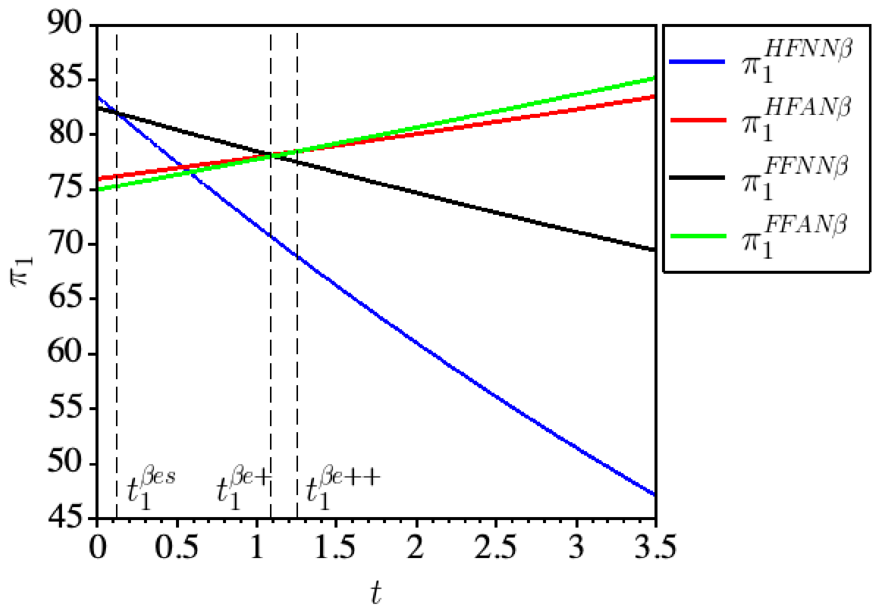

Figure 4: Regime β: $(HN, FN) \to (FN, FN) \to (HA, FN) \to (FA, FN)$.

Thus, $E^{HFAN\beta} < E^{FFAN\beta}$ holds for a given t if and only if $k > \frac{1}{2}$. The change in global emissions depends on firm 1's abatement efficiency. If the decrease in firm 2's output is replaced by firm 1's output produced with high abatement efficiency, global emissions decrease.[31]

The analysis above establishes the following proposition.

Proposition 6 *The following equilibria are possible if a carbon tax is accompanied by a carbon-content tariff:* (HN, FN) *with low tax rates,* (FN, FN) *with medium tax rates, and* (HA, FN) *with high tax rates; and* $E^{HFNN\beta} < E^{FFNN\beta} > E^{HFAN\beta}$. *The carbon-content tariff weakens firm 1's incentive to locate itself in Foreign (i.e.,* $t_1^{\beta eS} > t_1^{\alpha eS}$*). A further increase in* t *may switch the equilibrium from* (HA, FN) *to* (FA, FN)*. In this case,* $E^{HFAN\beta} > E^{FFAN\beta}$ *can hold if* k *is small.*

[31]This result corresponds to negative carbon leakage in Ma and Yomogida (2019).

5.3 Carbon tax coupled with tax refunds at the border and a carbon-content tariff (Regime γ)

We now introduce carbon-tax refunds in addition to the carbon-content tariff. As in Regime β, the equilibrium can switch from (HN, FN) to (FN, FN) and then to (HA, FN) as t increases. Figure 3 (b) illustrates this case.

As firm 1's effective MCs for its exports become just τ, its incentive to choose Foreign for production location weakens. That is, $t_1^{\gamma e} > t_1^{\beta eS} > t_1^{\alpha eS}$ (see Figure 3).[32] We can confirm this result because the following holds for a given t:

$$\begin{aligned} & (\pi_1^{FFNN\beta} - \pi_1^{HFNN\beta}) - (\pi_1^{FFNN\gamma} - \pi_1^{HFNN\gamma}) \\ = \quad & (p_f^{NN\gamma} - \tau)x_{1hf}^{NN\gamma} - (p_f^{NN\beta} - t - \tau)x_{1hf}^{NN\beta} > 0. \end{aligned}$$

Although $t_1^{\gamma e} > t_1^{\beta e}$, the total emissions with (HN, FN) are larger in Regime γ than in Regime β for a given t (i.e., $E^{HFNN\gamma} > E^{HFNN\beta}$ for a given t).

When both firms choose Foreign for their production locations, Regime γ and Regime β are equivalent. Thus, $\pi_1^{FFNN\gamma} = \pi_1^{FFAN\gamma}$ at t_1^{β} holds. However, regarding the threshold tax rate at which firm 1 has an incentive not only to abate emissions but also to locate itself in Home, $t_1^{\gamma e+} < t_1^{\beta e+}$ holds because we have

$$\begin{aligned} & (\pi_1^{FFNN\beta} - \pi_1^{HFAN\beta}) - (\pi_1^{FFNN\gamma} - \pi_1^{HFAN\gamma}) \\ = \quad & (p_f^{AN\gamma} - \tau)x_{1hf}^{AN\gamma} - (p_f^{AN\beta} - kt - \tau)x_{1hf}^{AN\beta} > 0 \end{aligned}$$

for a given t (compare Figure 3 (a) and (b)).

Note that as in Regime β, the equilibrium may switch from (HA, FN) to (FA, FN) as t further increases (see Figure 5).[33] With linear demand, we can readily verify

$$\begin{aligned} E^{HFNN\gamma} &= E^{FFNN\gamma} (= E^{FFNN\beta}), \\ E^{HFAN\gamma} - E^{FFNN\gamma} &= -\frac{(1-k)(2a - \tau - 2kt)}{3} < 0, \\ E^{HFAN\gamma} &= E^{FFAN\gamma}. \end{aligned}$$

We obtain the following proposition.

[32] We can readily verify $t_1^{\gamma e} = \tau$ with linear demand.

[33] In Figure 5, we set parameter values as follows: $a = 20$, $\tau = 1.5$, $k = 3/4$, and $F = 5$. Then we obtain $\bar{t} = 8.5$, $t_1^{\gamma e} = 1.5$, $t_1^{\gamma S} = 2.273$, $t_1^{\gamma e+} = 2.667$, $t_1^{\gamma e++} = 3$, and $t_2^{\gamma} = 3.280$. $t_1^{\gamma e++}$ is the threshold tax rate between (HA, FN) and (FA, FN).

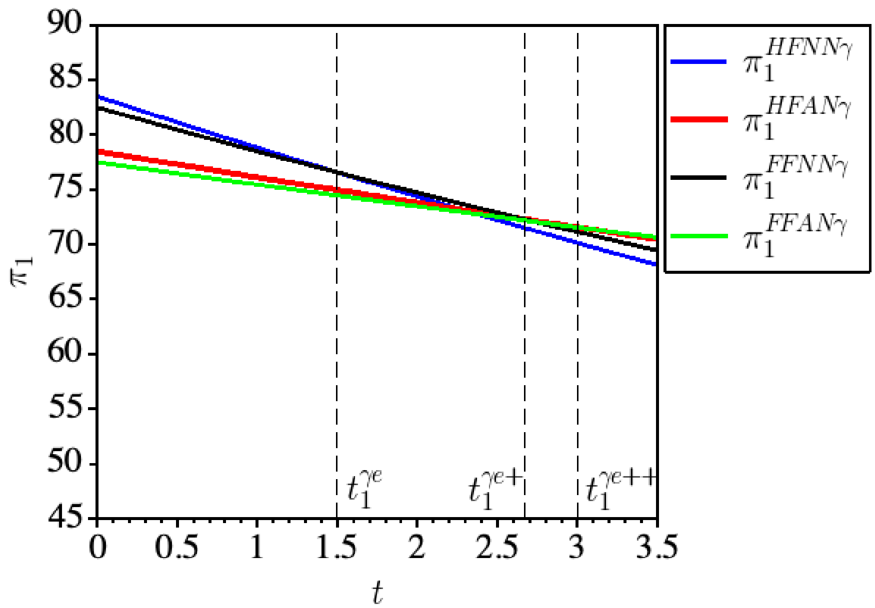

Figure 5: Regime γ: $(HN, FN) \to (FN, FN) \to (HA, FN) \to (FA, FN)$.

Proposition 7 *The following equilibria are possible if a carbon tax is coupled with a carbon-content tariff and carbon-tax refunds for exports:* (HN, FN) *with low tax rates,* (FN, FN) *with medium tax rates, and* (HA, FN) *with high tax rates. However, introducing carbon-tax refunds reduces the range of the tax rate within which firm 1 produces in Foreign. That is,* $t_1^{\alpha eS} < t_1^{\beta eS} < t_1^{\gamma e}$ *and* $t_1^{\gamma e+} < t_1^{\beta e+}$ hold.

6 Conclusion

We have developed a simple two-country, two-firm model to examine how carbon taxes with BTAs affect outputs, emissions, and the locations of firms in the presence of an emission-abatement technology (i.e., a clean technology). The two countries (Home and Foreign) are identical except that only Home introduces carbon pricing. The two firms are also identical. We specifically examined three policy regimes: i) carbon taxes alone (no BTAs); ii) carbon taxes accompanied by carbon-content tariffs (partial BTAs); and iii) carbon taxes coupled with carbon-tax refunds for exports and carbon-content tariffs (full BTAs).

If the firm locations are fixed, the firms' strategic reaction to a carbon tax is to determine whether or not to abate emissions by adopting the clean technology. According to our findings, carbon taxes may not be effective in decreasing global emissions. Interestingly, a higher carbon tax rate can result in greater global emissions even with fixed firm locations. Additionally, high tax rates decrease the incentive to invest in abatement. Another important message is that cross-border carbon leakage is eliminated in Regime γ (i.e., full BTAs) but global emissions can be greater than in Regime α (i.e., no BTAs) or Regime β (i.e., partial BTAs) where cross-border carbon leakage is partially eliminated. Thus, from the viewpoint of global emission control, carbon leakage is not necessarily problematic. Moreover, the carbon-tax refund restores the competitiveness of the home firm in the foreign market but discourages it from making abatement investments.

Under endogenous firm locations, both firms are likely to produce in Foreign in the presence of a tough carbon tax in Home. Thus, global emissions can increase. BTAs encourage firms to invest in emission abatement and discourage firms from producing overseas. This effect is stronger under Regime γ (i.e., full BTAs) than under Regime β (i.e., partial BTAs). The effect of carbon taxes on global emissions can be non-monotonic under BTAs. In particular, global emissions could be largest in the middle range of the tax rate.

Our findings suggest that carbon taxes should be designed with discretion, because their effects could be different from the conventional wisdom. In particular, carbon taxes are not very effective in reducing carbon emissions under certain situations. Moreover, BTAs should be applied cautiously. Even if BTAs eliminate cross-border carbon leakage and cost disadvantages for domestic firms, global emissions could increase. Thus, BTAs may become a disguised form of protection. The practicality of BTAs and their compatibility with the World Trade Organization (WTO) rules should be deliberated carefully.

In concluding the paper, two final remarks are in order. First, we have not examined the optimal policies. This is because the optimal policies depend crucially on how to evaluate damages from global warming, which in turn depends crucially on a damage function. For example, if the evaluation of GHG emissions is large enough to dominate other positive welfare components, then zero emissions are obviously optimal. We can claim the following with respect to each welfare component.[34] The home carbon tax harms firm 1 unless it adopts the clean technology. The introduction of BTAs for a given

[34] For details, see Cheng and Ishikawa (2021).

tax rate benefits firm 1 if it produces in Home. Global warming is mitigated if and only if global GHG emissions are reduced. A higher tax does not necessarily result in lower emissions because the firms may switch their technologies and/or production locations. Unless firms change technology, less outputs lead to less emissions. However, less outputs hurt either home or foreign consumers, at the very least. The welfare effects of adopting the clean technology are less obvious.

Second, to avoid rather straightforward results, we assumed that the two countries and two firms are symmetric. For example, if firm 2's emissions per unit of output are much greater than firm 1's, carbon leakage from firm 1 to firm 2 should be blocked. In this case, carbon pricing with assistance for firm 1 is the most likely desirable setup to cope with climate change. Progress in research on carbon pricing is expected in the future.

Appendix

To prove Lemma 1, we show that the total output (demand) is greater with (FN, FN) than with (HN, FN) if $\varepsilon \geq 0$. From the FOCs of profit maximization, we have

$$\begin{aligned}
x_{1hh}^{HFNN\alpha} &= (p_h^{HFNN\alpha} - t)(X_h^{HFNN\alpha})^{\varepsilon}, x_{2fh}^{HFNN\alpha} = (p_h^{HFNN\alpha} - \tau)(X_h^{HFNN\alpha})^{\varepsilon}, \\
x_{1hf}^{HFNN\alpha} &= (p_f^{HFNN\alpha} - t - \tau)(X_f^{HFNN\alpha})^{\varepsilon}, x_{2ff}^{HFNN\alpha} = (p_f^{HFNN\alpha})(X_f^{HFNN\alpha})^{\varepsilon}, \\
x_{1fh}^{FFNN\alpha} &= x_{2fh}^{FFNN\alpha} = (p_h^{FFNN\alpha} - \tau)(X_h^{FFNN\alpha})^{\varepsilon}, \\
x_{1ff}^{FFNN\alpha} &= x_{2ff}^{FFNN\alpha} = (p_f^{FFNN\alpha})(X_f^{FFNN\alpha})^{\varepsilon}.
\end{aligned}$$

Noting $x_{1hi}^{HFNN\alpha} + x_{2fi}^{HFNN\alpha} = X_i^{HFNN\alpha}$ $(i = h, f)$ and $x_{1hi}^{FFNN\alpha} + x_{2fi}^{FFNN\alpha} = X_i^{FFNN\alpha}$, we have

$$\begin{aligned}
(X_h^{HFNN\alpha})^{1-\varepsilon} &= 2p_h^{HFNN\alpha} - t - \tau, \\
(X_f^{HFNN\alpha})^{1-\varepsilon} &= 2p_f^{HFNN\alpha} - t - \tau, \\
(X_h^{FFNN\alpha})^{1-\varepsilon} &= 2(p_h^{FFNN\alpha} - \tau), \\
(X_f^{FFNN\alpha})^{1-\varepsilon} &= 2p_f^{FFNN\alpha}.
\end{aligned}$$

Using (1), we have

$$\begin{aligned}
p_h^{HFNN\alpha} &= p_f^{HFNN\alpha} = \frac{a(1-\varepsilon) + t + \tau}{3 - \varepsilon}, \\
p_h^{FFNN\alpha} &= \frac{a(1-\varepsilon) + 2\tau}{3 - \varepsilon}, p_f^{FFNN\alpha} = \frac{a(1-\varepsilon)}{3 - \varepsilon}.
\end{aligned}$$

Substituting these into the above equations, we obtain

$$\begin{aligned}
X_h^{HFNN\alpha} &= \left(\frac{(2a-t-\tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}, \\
X_f^{HFNN\alpha} &= \left(\frac{(2a-t-\tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}, \\
X_h^{FFNN\alpha} &= \left(\frac{2(a-\tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}, \\
X_f^{FFNN\alpha} &= \left(\frac{2a(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}.
\end{aligned}$$

Suppose $\varepsilon \geq 0$. Then the following holds for any $t(>0)$:

$$\begin{aligned}
E^{FFNN\alpha} &= X_h^{FFNN\alpha} + X_f^{FFNN\alpha} \geq 2\left(\frac{(2a-\tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} \\
&> X_h^{HFNN\alpha} + X_f^{HFNN\alpha} = E^{HFNN\alpha}.
\end{aligned}$$

Next suppose $\varepsilon < 0$. If $t = \tau$, then $X_h^{FFNN\alpha} = X_h^{HFNN\alpha} = X_f^{HFNN\alpha}$ holds and hence $X_h^{FFNN\alpha} + X_f^{FFNN\alpha} > X_h^{HFNN\alpha} + X_f^{HFNN\alpha}$. If $t = 0$, then $X_h^{FFNN\alpha} + X_f^{FFNN\alpha} < X_h^{HFNN\alpha} + X_f^{HFNN\alpha}$. Thus, there exists a threshold tax rate, $\widehat{t}$, between 0 and τ, above which $X_h^{FFNN\alpha} + X_f^{FFNN\alpha} > X_h^{HFNN\alpha} + X_f^{HFNN\alpha}$ holds.

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