Carbon Tariffs: Effects in Settings with Technology Choice and Foreign Production Cost Advantage

David F. Drake

Working Paper 13-021

Carbon Tariffs: Effects in Settings with Technology Choice and Foreign Production Cost Advantage

David F. Drake
Harvard Business School

Working Paper 13-021

Carbon Tariffs: Effects in Settings with Technology Choice and Foreign Production Cost Advantage

David F. Drake
Harvard Business School, Harvard University, Boston, MA 02163
ddrake@hbs.edu

Emissions regulation is a policy mechanism intended to address the threat of climate change. However, the stringency of emissions regulation varies across regions, raising concerns over carbon leakage—an outcome where stringent regulation in one region shifts production to regions with weaker regulation. It is believed that such leakage adversely increases global emissions. It is also believed that leakage can be eliminated by carbon tariffs, which are taxes imposed on imported goods so that they incur the same emissions cost that they would have if they had been produced in the regulated region. Results here contradict these beliefs. This paper demonstrates that carbon leakage *can* arise despite a carbon tariff but, when it does arise under a carbon tariff, it *decreases* emissions. Due in part to this clean leakage, results here indicate that a carbon tariff decreases global emissions. Domestic firm profits, on the other hand, can increase, decrease, or remain unchanged due to a carbon tariff, which suggests that carbon tariffs are not inherently protectionist as some argue. Rather, results here suggest that carbon tariffs improve the efficacy of emissions regulation, enabling it to reduce global emissions in many settings in which it would otherwise fail to do so.

Revised August 23, 2017

1. Introduction

With carbon regulation driving projected production cost increases in excess of 40% in some industries (Drake et al. 2010, Ryan 2012), it can endow facilities located outside the regulated region with a windfall cost advantage. This cost advantage can enable “foreign” competitors to increase their penetration into the emissions-regulated (i.e., “domestic”) market. Carbon regulation can also lead domestic firms to shift facilities offshore to avoid carbon-related costs. Such foreign entry and offshoring are both sources of *carbon leakage*—the displacement of production from the regulated region to offshore locations due to an increase in emissions price.

Carbon leakage could potentially be mitigated by *border adjustments*—tariffs on the carbon emissions of imported goods that would incur carbon costs if produced domestically. However, border adjustments have proven controversial. Proponents of border adjustments—policymakers such as the authors of the Waxman-Markey bill (US Congress, House 2009), Nobel laureate economists (Krugman 2009), and industrial trade associations (Cement Association of Canada 2015)—argue that such a measure would treat domestic and offshore production equivalently and thereby limit environmentally damaging carbon leakage. On the other hand, border adjustment opponents—including politicians such as President Obama (Broder 2009) and China’s Minister of Commerce

(Beattie and Hill 2009), academics (Holmes et al. 2011), and members of the popular press (The Economist 2007)—have raised arguments ranging from concerns that a border adjustment could increase the risk of trade disputes to claiming outright that a border adjustment would be "[trade] protectionism in the disguise of environmental protection." This paper contributes to the debate by assessing the effectiveness of border adjustments as a mechanism to improve the efficacy of emissions regulation, and as a mechanism to improve the profitability of domestic firms.

It is widely reported that carbon leakage increases global emissions, offsetting some or all of the regulation's emission improvements (e.g., Babiker 2005, Demailly and Quirion 2006, Ponssard and Walker 2008, Di Maria and van der Werf 2008, Fowlie 2009, Fowlie et al. 2016). It is also widely believed that a symmetric border adjustment will eliminate the threat of leakage (e.g., Barry 2009; Barber 2010, Ponssard and Walker 2008, Fowlie et al. 2016). However, these assertions implicitly assume that the technology used in foreign production will be at least as emissions-intensive as the technology used in domestic production. As will be demonstrated, this assumption does not hold under a border adjustment if foreign producers can choose their production technology.

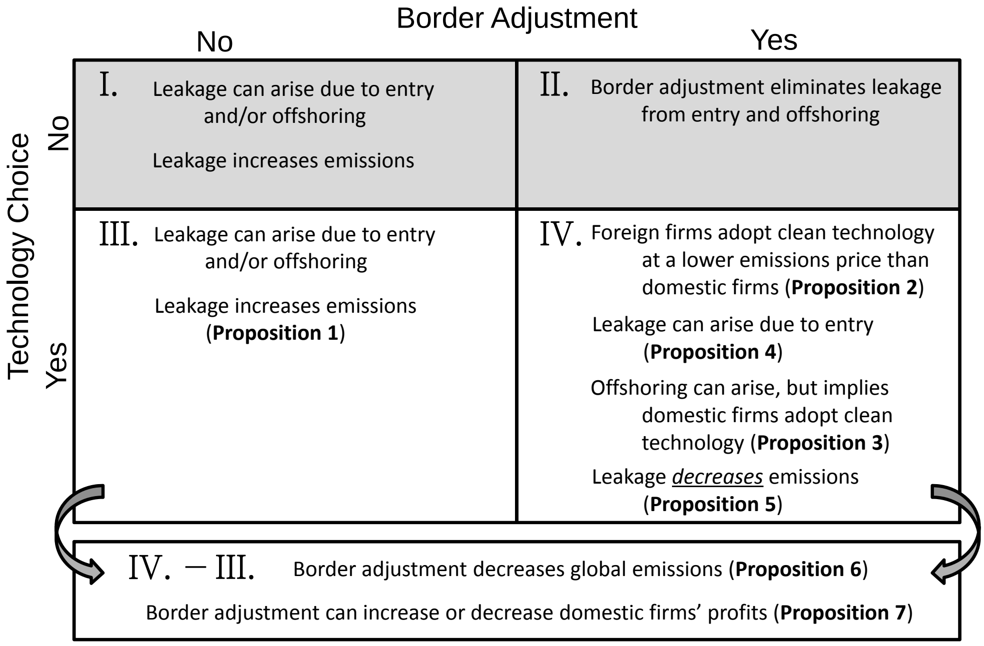
1.1. Preview of model and main results

This paper models imperfect competition between a set of domestic firms and a set of potential foreign entrants in an emissions-regulated market. Foreign firms can enter the market and domestic firms can exit the market, relocate offshore, or compete from within the regulated region. Domestic and foreign firms both choose production technologies and production quantities. Consistent with reports, production costs with established emissions-intensive technology and with nascent clean technology are assumed to be less in the offshore region than in the regulated region (e.g., Boston Consulting Group 2008, IEA Greenhouse Gas Programme 2008). By exploring the effect of border adjustments in a setting where firms can choose their production technologies, this paper contributes two sets of results to the literature.

First, results here contradict the beliefs that leakage always increases global emissions, and that border adjustment will eliminate leakage. This paper demonstrates that, when they hold a production cost advantage, foreign firms adopt clean technology under a border adjustment at lower emissions prices than domestic firms (Proposition 2). Within emissions price intervals in which foreign firms operate cleaner technology than domestic firms, foreign entry increases under some conditions despite a border adjustment (Proposition 4). Further, domestic firms offshore under some conditions despite a border adjustment, but doing so implies that they adopt cleaner technology when they relocate (Proposition 3). As a consequence, when carbon leakage occurs under a border adjustment, offshore technology is cleaner than that used domestically. Therefore, under mild conditions shown to hold in practical settings, carbon leakage *decreases* global emissions when it arises under a border adjustment (Proposition 5). These results demonstrate that carbon leakage can arise despite a border adjustment but, when it does, it can contribute to reduced global emissions. In other words, with a border adjustment, "clean leakage" is possible.

Second, this paper contributes to the ongoing debate as to whether border adjustments are climate policy or trade protectionism. Results here demonstrate that, without border adjustment, global emissions *increase* with emissions price or remain unchanged in any setting in which foreign firms compete or domestic firms offshore (Proposition 1). However, under mild conditions, global emissions are shown to *decrease* as emissions price increases in any setting with border adjustment (Proposition 5). As a consequence, imposing a border adjustment decreases global emissions relative to emissions regulation without a border adjustment (Proposition 6). Domestic firms' profits, on the other hand, can increase, decrease, or remain unchanged due to border adjustment (Proposition 7). These results suggest that a border adjustment is not inherently protectionist. Instead, these results suggest that border adjustments are good environmental policy, enabling emissions regulation to reduce global emissions in settings that it otherwise would not.

Figure 1 summarizes these results, with the contribution of this paper described by boxes III, IV, and IV-III, and the related results established in the literature described by boxes I and II.



I. Leakage can arise due to entry and/or offshoring

Leakage increases emissions

II. Border adjustment eliminates leakage from entry and offshoring

III. Leakage can arise due to entry and/or offshoring

Leakage increases emissions (**Proposition 1**)

IV. Foreign firms adopt clean technology at a lower emissions price than domestic firms (**Proposition 2**)

Leakage can arise due to entry (**Proposition 4**)

Offshoring can arise, but implies domestic firms adopt clean technology (**Proposition 3**)

Leakage *decreases* emissions (**Proposition 5**)

IV. − III. Border adjustment decreases global emissions (**Proposition 6**)

Border adjustment can increase or decrease domestic firms' profits (**Proposition 7**)

Figure 1 **Results from related literature (boxes I and II), and from this paper (boxes III, IV, and IV-III)**

1.2. Relation to the literature

This paper relates to work that explores technology choice under environmental policy, and work that explores carbon leakage under emissions regulation. For purposes here, the latter can be thought of in terms of work that explores carbon leakage strictly in the absence of border adjustment, and work that analyzes border adjustment as a complementary policy to emissions regulation.

A rich literature explores technology choice in emissions-regulated settings (e.g., İşlegen and Reichelstein 2011, Krass et al. 2013, Drake et al. 2016, with Popp et al. 2009 providing a review of literature related to technology change under environmental policy). In general, work in this area explores how firms' ability to select production technologies affects economic and environmental outcomes under various environmental policies. For example, İşlegen and Reichelstein (2011) estimate the adoption threshold for carbon capture and storage (CCS) technologies in power generation and conclude that retail electricity prices would increase by at most 30% as a consequence of emissions regulation. While each of the papers in this body of work focus on technology choice, none address carbon leakage or border adjustment. This paper contributes to the stream by revealing the role that technology decisions play in determining the magnitude and environmental effect of carbon leakage and how border adjustment moderates this effect.

In literature exploring carbon leakage without border adjustment, most focuses on leakage due only to foreign entry (e.g., Demailly and Quirion 2006, Di Maria and van der Werf 2008, Fowlie 2009, and İşlegen et al. 2016). Work in this stream finds that: i) carbon leakage diminishes the environmental benefits derived from emissions regulation; and ii) carbon leakage increases in regional emissions price asymmetry. For example, Fowlie (2009) studies leakage when firms operate different but exogenous technologies and finds that leakage eliminates two-thirds of the emissions reduction obtained by a uniform policy. Di Maria and van der Werf (2008) study leakage in a setting where firms in the regulated region can choose their technology. They find that the ability to change technology attenuates leakage. Babiker (2005) considers leakage due to offshoring in addition to foreign entry, finding that leakage *increases* global emissions by 30% relative to a baseline case without emissions regulation. In each of these papers, imported units are more emissions-intensive (inclusive of transport emissions) than the domestically-produced units they displace. This paper reveals the potential for "clean leakage." When leakage arises under border adjustment, it implies that imports are produced by technology that is cleaner than that used in the regulated region. It is shown here that, in practical settings, the benefit of producing with cleaner technology offshore exceeds the additional emissions generated from transport. Therefore, rather than diminishing emissions improvements, leakage contributes to additional emissions reduction under a border adjustment.

Condon and Ignaciuk (2013) review work that explores border adjustment. Among the reviewed papers, none incorporate technology choice and most explore economy-wide computable general equilibrium models that assume perfect competition. In addition to these papers, Sunar and Plambeck (2016) explore emissions allocation rules when products are co-produced in a fixed ratio by a foreign supplier. They find that border adjustment can increase or decrease emissions, depending on how emissions are allocated among co-products. In more closely related work, Ponssard and Walker (2008) model emissions regulation of the EU cement industry and Fowlie et al. (2016) study the potential effects of emissions regulation as it relates to the US cement industry. Both find that emissions regulation without border adjustment results in emissions-increasing leakage. Both also find that a border adjustment eliminates carbon leakage, an outcome contradicted by results in this paper. Neither Ponssard and Walker (2008) nor Fowlie et al. (2016) allow for technology choice. By endogenizing technology choice, this paper finds that, under border adjustment, foreign firms adopt clean technology at lower emissions prices than domestic firms. Over emissions price intervals in which foreign firms operate cleaner technology than domestic firms, it is shown that "clean leakage" arises despite a border adjustment.

Table 1 summarizes central elements of this paper that are included in the most-related literature.

Paper	**Carbon leakage due to...**		**Technology Choice**	**Border Adjustment**
	Foreign entry	**Offshoring**		
Babiker (2005)	X	X		
Demailly and Quirion (2006)	X			
Ponssard and Walker (2008)	X			X
Di Maria and van der Werf (2008)	X		X	
Fowlie (2009)	X			
Fowlie et al. (2016)	X			X
İşlegen et al. (2016)	X			

Table 1 Central aspects of this paper included in the most closely related literature

2. Firm Decisions and Performance *without* Border Adjustment

Under existing emissions regulation, domestic production incurs emissions costs while offshore production does not, altering the competitive balance between domestic and foreign firms.

2.1. Model development

A regulator imposes an emissions price ε for each unit of emissions generated through domestic production. Through Cournot competition, n_d domestic firms compete with n_f foreign firms. The domestic market is assumed to be mature prior to the implementation of emissions regulation, with N_d incumbent domestic firms; domestic firms can choose to exit, but no new domestic firms enter the market due to emissions regulation, i.e., $n_d \leq N_d$. Each domestic firm chooses a location, $l \in \{r, o\}$, where r indicates production in the regulated region and o indicates production offshore. Domestic firms choosing to offshore incur fixed cost $F_o \geq 0$. Foreign firms enter the domestic market only if they can earn at least operating profit $F_e > 0$, where F_e represents a fixed entry cost. Each unit imported into the domestic market incurs transport cost $\tau > 0$.

Both domestic and foreign firms choose a non-proprietary production technology $k \in \{1, 2\}$, with unit production and capital recovery cost $\gamma_k > 0$ and emissions intensity $\alpha_k \geq 0$. Without loss of generality, technology 1 is the more emissions-intensive technology, $\alpha_1 > \alpha_2$. Emissions intensity for a given production technology is assumed to be the same whether it is utilized domestically or offshore. However, imports generate an additional $\alpha_\tau > 0$ emissions per unit through transport. A discount factor δ represents the relative production and capital recovery cost in offshore versus domestic regions.

Three empirically-supported assumptions are made with respect to technology costs.

Assumption 1. *The production and capital recovery cost for each given technology is less in the offshore region than in the domestic region;* $\delta \in (0,1)$ *so that* $\delta\gamma_k < \gamma_k, \forall k \in \{1,2\}$.

Assumption 1 states that it is less costly to produce with each technology in the offshore (exporting) region than in the emissions-regulated region. Practical examples support this assumption. Figure 2 illustrates the production and capital recovery cost advantage for likely cement importers to the EU under carbon leakage scenarios. These cost advantages stem from structural advantages in labor, material, electricity, maintenance, and investment costs (Boston Consulting Group 2008).

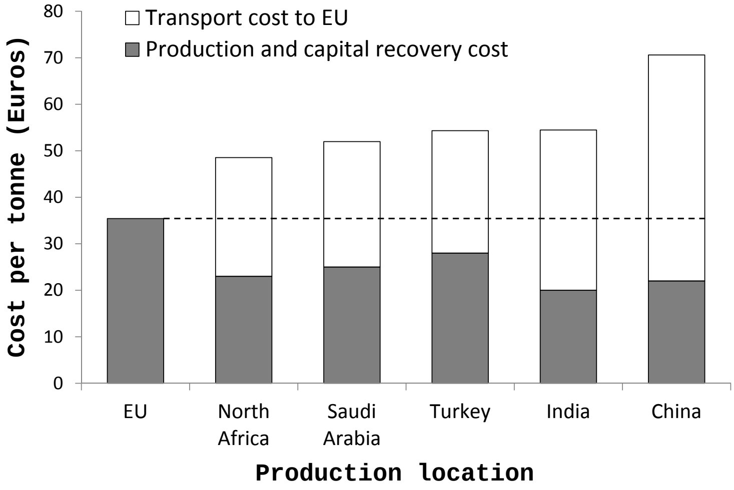


Figure 2 Regional production and transport costs per tonne of cement (source: Boston Consulting Group 2008)

While Figure 2 presents costs for established kiln technologies, emerging CCS kiln technology is also expected to be substantially less costly in regions likely to be exporters under carbon leakage scenarios than it is in developed regions such as Europe (IEA Greenhouse Gas Programme 2008).

Assumption 2. *The domestic production cost of the dirty technology is less than the transport plus offshore production cost of the dirty technology;* $\gamma_1 < \delta\gamma_1 + \tau$.

This assumption, supported by the cement costs in Figure 2, implies that domestic firms produce locally if emissions are unregulated. In general, the assumption is reasonable for carbon-regulated sectors (domestic regulation of the sector would not be imposed if it operated offshore when $\varepsilon = 0$).

Assumption 3. *The production and capital recovery cost of the dirty technology is less than the production and capital recovery cost of the clean technology;* $\gamma_1 < \gamma_2$.

Given $\alpha_1 > \alpha_2$, Assumption 3 ensures that technology 1 is not trivially discarded. Returning to cement as an example, the most promising abatement technology in that sector is CCS. In agreement with Assumption 3, a CCS kiln is more costly in terms of investment and operating costs than traditional precalciner kilns (European Cement Research Academy 2012).

Without a border adjustment, the total operating cost of foreign firms' preferred technology will be referred to as c_f, with production cost and emissions intensity γ_f and α_f. The total operating cost of domestic firms' preferred technology will be referred to as $c_d(\varepsilon)$, with production cost and emissions intensity γ_d and α_d, respectively. Table 2 summarizes cost and emissions parameters.

Parameter	Description
ε	Price per unit of CO_2 emissions
δ	Discount factor for offshore production
F_o, F_e	Fixed offshoring cost and fixed entry cost, respectively
τ, α_τ	Per-unit transport cost and emissions intensity, respectively
$c_d(\varepsilon)$, c_f	Total unit cost of domestic and foreign firms' preferred technology
γ_d, γ_f	Domestic and foreign firms' production and capital recovery cost
α_d, α_f	Emissions intensity of domestic and foreign firms' preferred technology

Table 2 Cost and emissions parameters in setting without border adjustment

Preferred technologies Foreign firms select technology k to minimize offshore operating cost $\delta\gamma_k + \tau$. By Assumption 3, this implies that foreign firms operate technology 1, with $c_f = \delta\gamma_1 + \tau$.

If domestic firms operate in the regulated region (i.e., if $l = r$), they prefer technology k that minimizes domestic operating costs $\gamma_k + \alpha_k\varepsilon$, with $\varepsilon_2^d = (\gamma_2 - \gamma_1) / (\alpha_1 - \alpha_2)$ representing the break-even emissions price between technology 1 and 2 in the regulated region. However, if domestic firms offshore (i.e., if $l = o$) then, without border adjustment, they prefer technology 1. Therefore,

$$c_d(\varepsilon) = \begin{cases} \gamma_1 + \alpha_1\varepsilon & \text{if } l = r \text{ and } \varepsilon < \varepsilon_2^d \\ \gamma_2 + \alpha_2\varepsilon & \text{if } l = r \text{ and } \varepsilon \geq \varepsilon_2^d \\ \delta\gamma_1 + \tau & \text{if } l = o. \end{cases}$$

These technology choices imply that, without a border adjustment, the regulator cannot incentivize clean technology adoption if domestic firms offshore or exit at a lower emissions price than they adopt clean technology. This has practical implications. The threshold at which cement firms would offshore from Europe, for example, is estimated to be significantly less than the adoption threshold for CCS cement kilns (US Energy Information Administration 2011, and Boston Consulting Group 2008), preempting the regulator's ability to incentivize clean technology adoption.

Objectives Each domestic firm produces x_l units with its preferred technology/location. Each foreign firm produces y units with its preferred technology. The market clears at price $P(n_d, n_f, x_l, y) = A - b(n_d x_l + n_f y)$, with $b > 0$ and $A > c_d(\varepsilon)$ to avoid cases with trivial outcomes.

Each domestic firm competing in the market maximizes operating profit by solving

$$\pi_d(n_d, n_f, y, \varepsilon) = \max_{x_l \geq 0} P(n_d, n_f, x_l, y)\, x_l - c_d(\varepsilon) x_l, \tag{1}$$

while each foreign competitor maximizes operating profit by solving

$$\pi_f(n_d, n_f, x_l) = \max_{y \geq 0} P(n_d, n_f, x_l, y)\, y - c_f y. \tag{2}$$

All proofs are provided in Appendix A, including the proofs for the joint concavity of (1) and (2) in x_l and y.

2.2. Equilibrium location, exit, and entry

The market structure that evolves in equilibrium is determined by three decisions—domestic firms' location decisions; domestic firms' exit decisions; and foreign firms' entry decisions. Four market structure thresholds, presented in Table 3 and described below, determine each of these decisions.

Threshold	**Description**
$\overline{F}_o$	Offshoring cost beyond which it is unprofitable for domestic firms to relocate
ε_o	Emissions price beyond which domestic firms offshore if $F_o < \overline{F}_o$
ε_{exit}	Emissions price beyond which domestic firms exit if $F_o \geq \overline{F}_o$
ε_{entry}	Emissions price beyond which foreign firms enter if $\varepsilon_{entry} < \varepsilon_o$

Table 3 Fixed offshoring and emissions price thresholds that co-determine equilibrium market structure

Star notation will be used to indicate equilibrium decisions. For brevity, star notation will also indicate dependency on emissions price, so that a^* implies $a^*(\varepsilon)$.

Domestic offshoring For domestic firms to offshore in equilibrium, ε must be sufficiently large and F_o sufficiently small that domestic firms can operate more profitably outside the regulated region than in it. Where $\pi_{d,r}(\cdot)$ is each domestic firm's operating profit when producing in the regulated region, and $\pi_{d,o}(\cdot)$ is its operating profit when producing offshore, domestic firms offshore at emissions prices greater than ε_o, where

$$\varepsilon_o = \{\varepsilon | \pi_{d,r}\left(N_d, n_f^*, y^*, \varepsilon\right) = \pi_{d,o}\left(N_d, n_f^*, y^*, \varepsilon\right) - F_o\}.$$

Relocation is cost prohibitive if fixed offshoring costs exceed the operating profit that each domestic firm can earn when operating outside the regulated region, i.e., if $F_o \geq \overline{F}_o$, where

$$\overline{F}_o = \{F_o | \pi_{d,o}\left(N_d, n_f^*, y^*, \varepsilon\right) - F_o = 0\}.$$

In equilibrium, domestic firms choose location $l^* = o$ if $\varepsilon \geq \varepsilon_o$ and $F_o < \overline{F}_o$, and $l^* = r$ otherwise.

Domestic exit If $F_o \geq \overline{F}_o$, domestic firms are no longer able to operate profitably within the domestic region and abandon the market at the emissions prices greater than ε_{exit}, where

$$\varepsilon_{exit} = \{\varepsilon | \pi_{d,r}\left(N_d, n_f^*, y^*, \varepsilon\right) = 0\}.$$

Therefore, $n_d^* = 0$ if $\varepsilon \geq \varepsilon_{exit}$ and $F_o \geq \overline{F}_o$, and $n_d^* = N_d$ otherwise.

Foreign entry Foreign firms compete operating profits down to the minimum level for entry such that $n_f^* = \{(n_f)^+ | \pi_f\left(n_d^*, n_f, x_l^*\right) = F_e\}$, which leads to the following lemma:

Lemma 1. *Without border adjustment, the equilibrium number of entrants is* $n_f^* = \left(h(\varepsilon)\right)^+$, *where*

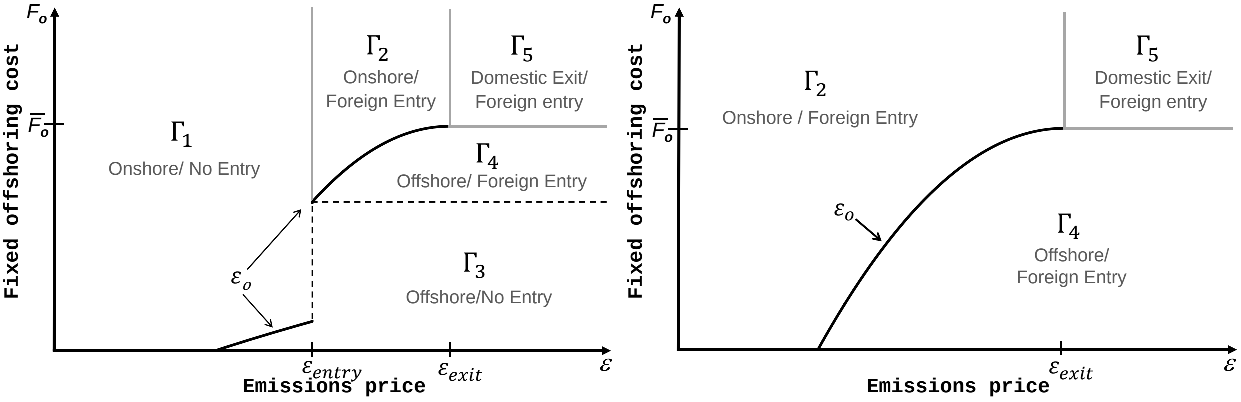
$$h(\varepsilon) = \frac{A - c_f - n_d^*\left(c_f - c_d(\varepsilon)\right)}{\sqrt{F_e b}} - n_d^* - 1. \tag{3}$$

With (3) strictly increasing in ε, the emissions price threshold above which foreign firms enter is

$$\varepsilon_{entry} = \{\varepsilon | h(\varepsilon) = 0\}.$$

Note that, without border adjustment, n_f^* is inelastic in ε if domestic firms offshore because $c_d(\varepsilon) = c_f$. Therefore, if domestic firms offshore at a lower emissions price than foreign firms would enter (i.e., if $F_o < \overline{F}_o$ and $\varepsilon_o \leq \varepsilon_{entry}$), then foreign entry is preempted and will not occur at any ε.

Equilibrium market structure Figures 3a and 3b illustrate how fixed offshoring cost and emissions price determine market structure. Figure 3a does so without foreign entry at $\varepsilon = 0$. This reflects the EU cement industry where less than 1.5% of revenues were generated by imports (European Commission 2009). Figure 3b depicts equilibrium market structures with foreign entry at $\varepsilon = 0$, reflecting the EU steel industry where imports served 20.4% of sales in 2004 (International Iron and Steel Institute 2006). Appendix B provides parameters for all numerical illustrations.



(a) $\varepsilon_{entry} > 0$ (b) $\varepsilon_{entry} \leq 0$

Figure 3 **Equilibrium market structure with no entry at $\varepsilon = 0$ (Figure 3a) and with entry at $\varepsilon = 0$ (Figure 3b)**

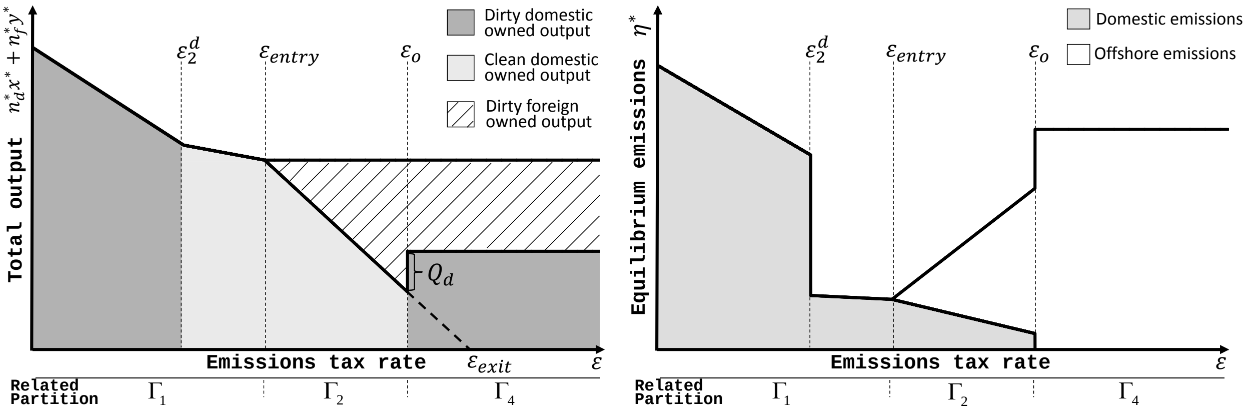
As illustrated in Figure 3a, if there is no foreign entry when $\varepsilon = 0$, then five equilibrium market structures can evolve, $\Gamma_m \in \{\Gamma_1, ..., \Gamma_5\}$. In Γ_1, emissions price is sufficiently low that domestic firms produce in the regulated region and foreign firms do not enter. In Γ_2, emissions price is sufficiently low and fixed offshoring cost sufficiently great that domestic firms produce in the regulated region. However, unlike in Γ_1, in region Γ_2 emissions price exceeds the entry threshold, $\varepsilon > \varepsilon_{entry}$, indicating foreign entry occurs. In Γ_3, emissions price exceeds the offshoring threshold, $\varepsilon > \varepsilon_o$, and the fixed offshoring cost is sufficiently low that domestic firms relocate. Entry does not arise in Γ_3, even when $\varepsilon > \varepsilon_{entry}$ because the offshoring threshold is less than the entry threshold, $\varepsilon_o \le \varepsilon_{entry}$, so domestic offshoring preempts foreign entry. In Γ_4, domestic firms relocate, however, unlike in Γ_3, $\varepsilon_{entry} < \varepsilon_o$ so foreign firms compete in the market. In Γ_5, offshoring is prohibitively costly with $F_o \ge \overline{F}_o$ and emissions price is sufficiently great, $\varepsilon \ge \varepsilon_{exit}$, that domestic firms exit while foreign firms compete ($\varepsilon > \varepsilon_{entry}$). If there is significant entry when $\varepsilon = 0$, the equilibrium market structures that can evolve are depicted in Figure 3b. Note that there is no partition Γ_1 because $\varepsilon_{entry} \le 0$ and there is no partition Γ_3 because the entry threshold is less than the offshoring threshold, $\varepsilon_{entry} < \varepsilon_o$, $\forall F_o$.

2.3. Equilibrium quantities and emissions

Emissions regulation is intended to abate the driver of anthropogenic climate change: global CO_2 emissions, η. Emissions from domestic output are generated by firms' production technology. Emissions from imports, on the other hand, are generated by offshore production as well as transport to the regulated region. Therefore, without border adjustment,

$$\eta = \underbrace{n_d x_r \alpha_d}_{\text{Domestic emissions}} + \underbrace{(n_d x_o + n_f y)(\alpha_1 + \alpha_\tau)}_{\text{Offshore emissions}}. \tag{4}$$

The effect of emissions price on quantity decisions and resulting emissions depends on equilibrium market structure. To demonstrate this, Figure 4a provides a preview of the quantity results described in this section, while Figure 4b provides a corresponding preview of emissions results.



(a) (b)

Figure 4 **Example of equilibrium quantities (Figure 4a) and emissions (Figure 4b) without border adjustment**

In Figure 4a, emissions price is sufficiently low that domestic firms produce in the regulated region without foreign entrants (partition Γ_1), with quantities decreasing in ε. At ε_2^d, domestic firms adopt clean technology, reducing the rate at which domestic quantities decrease in ε. Foreign firms enter at ε_{entry}, shifting the market structure to Γ_2. Over this market structure, domestic quantities decrease, foreign entry increases, and total output remains unchanged in ε. In this example $F_o < \overline{F}_o$, so domestic firms offshore at ε_o. Because fixed offshoring cost is non-zero ($F_o > 0$) in this example, domestic firms' production costs decrease with offshoring and their output increases (indicated by Q_d). With all firms operating outside of the regulated region (partition Γ_4), they are unaffected by further increases in ε. If, in this example, $F_o \geq \overline{F}_o$, offshoring would be cost-prohibitive and domestic firms would exit at ε_{exit} (partition Γ_5).

In Figure 4b, global and domestic emissions decrease with respect to emissions price over Γ_1 due to two factors: i) the decreasing output observed in Figure 4a; and ii) a step decrease due to the adoption of clean technology at ε_2^d. In this example, foreign firms use more emissions-intensive technology than domestic firms over Γ_2 and generate transport emissions. Therefore, despite total output remaining unchanged (as seen in Figure 4a), global emissions increase with emissions price over Γ_2 as foreign production displaces domestic production. Lastly, global emissions step increase as domestic firms offshore at ε_o.

Equilibrium quantities When location is non-central, x^* and y^* denote each domestic and foreign firm's equilibrium quantities, respectively. When location is central, x_l^* denotes domestic quantities.

LEMMA 2. *Without border adjustment, total equilibrium domestic output $n_d^* x^*$ and foreign output $n_f^* y^*$ depend on market structure and are characterized by the following table:*

Region	**Domestic decision**	**Entry decision**	**Total equilibrium quantities:**	
			Domestic, $n_d^* x^*$	**Foreign,** $n_f^* y^*$
Γ_1	Domestic production	No entry	$N_d\left(\frac{A-\gamma_d-\alpha_d\varepsilon}{b(N_d+1)}\right)$	0
Γ_2		Entry	$N_d\left(\sqrt{\frac{F_e}{b}}+\frac{\delta\gamma_1+\tau-\gamma_d-\alpha_d\varepsilon}{b}\right)$	$n_f^*\sqrt{\frac{F_e}{b}}$
Γ_3	Offshore production	No entry	$N_d\left(\frac{A-\delta\gamma_1-\tau}{b(N_d+1)}\right)$	0
Γ_4		Entry	$N_d\sqrt{\frac{F_e}{b}}$	$n_f^*\sqrt{\frac{F_e}{b}}$
Γ_5	Exit	Entry only	0	$n_f^*\sqrt{\frac{F_e}{b}}$

From Lemma 2, if domestic firms offshore or exit (partitions Γ_3, Γ_4, and Γ_5), then total domestic output is independent of emissions price. In each of these cases, domestic firms compete from outside the regulated region (i.e., $c_d(\varepsilon) = c_f$) or they no longer compete in the market (i.e., $n_d^* = 0$). Either way, they are beyond the umbrella of emissions regulation without border adjustment, making further changes in emissions price ineffective in influencing domestic firms' quantities. Similarly, when domestic firm decisions are unaffected by changes in emissions price due to offshoring or exit, no incremental opportunity for foreign entry is created in the market so total foreign entry $n_f^* y^*$ is also unchanged. This can be observed from Lemmas 1 and 2 when $c_d(\varepsilon) = c_f$ or $n_d^* = 0$.

On the other hand, per Lemma 2, domestic quantities clearly decrease with respect to emissions price when domestic firms produce in the regulated region (partitions Γ_1 and Γ_2). In these settings, domestic firms' production cost $c_d(\varepsilon)$ increases with emissions price, driving their production volumes down. In settings where domestic firms compete in the regulated region without foreign competition (partition Γ_1), this decrease in domestic output trivially results in decreased total output. However, if domestic firms produce in the regulated region and compete against foreign firms (partition Γ_2), reduced domestic output creates an opportunity for further foreign entry. In such a setting, foreign entry increases with emissions price as domestic firms are burdened by greater emissions costs. This is evident in Lemma 1 where the number of foreign entrants increases in ε when domestic firms operate in the regulated region. Total output remains unchanged in this setting, with total foreign entry increasing at a rate of $N_d \alpha_d / b$, the same rate at which domestic output decreases.

Notably, in the absence of border adjustment, total output only decreases with respect to emissions price if domestic firms compete in the regulated region without foreign competition (partition Γ_1). Total output is unaffected by changes in emissions price in all other settings. This has important emissions regulation implications for the US and EU steel industry where foreign firms compete even when emissions are costless. In these settings, without a border adjustment, carbon regulation (i.e., any $\varepsilon > 0$) would be unlikely to significantly affect the total output serving the region, but *is* likely to result in increased foreign entry relative to an unregulated ($\varepsilon = 0$) baseline.

In addition to changing continuously in emissions price as described above, total output can step-increases due to offshoring.

LEMMA 3. *Without border adjustment, offshoring strictly increases equilibrium total output if and only if no foreign entrants compete in the market when offshoring occurs* $h(\varepsilon_o) < 0$ *and fixed offshoring cost is positive* $F_o > 0$*. Otherwise, total output remains unchanged due to offshoring.*

If $F_o = 0$, domestic firms offshore at the emissions price at which operating costs in the regulated region $\gamma_d + \alpha_d \varepsilon$ are equivalent to operating costs offshore $\delta\gamma_1 + \tau$. If $F_o > 0$, however, operating costs in the offshore region are less than those in the regulated region at the threshold ε_o; i.e., relocating domestic firms require greater operating profit offshore to compensate for the fixed offshoring cost they incur. Therefore, when $F_o > 0$, domestic firms' operating costs decrease if they offshore in equilibrium and, consequently, total domestic-owned output increases. Total foreign entry decreases as a result of domestic firms' reduced operating costs (evident through Lemma 1). If foreign firms remain in the market when domestic firms offshore, then the decrease in total foreign entry fully offsets the increase in domestic output, leaving total output unchanged. Otherwise, total output increases. The magnitude of this conditional increase is characterized in the proof to Lemma 3.

Equilibrium emissions The regulator's ability to reduce global emissions without border adjustment is limited.

PROPOSITION 1. *Without border adjustment, equilibrium global emissions: a) <u>decrease</u> with respect to emissions price if domestic firms operate in the regulated region <u>without</u> foreign entrants,* $\Gamma_m = \Gamma_1$*; b) <u>increase</u> with emissions price if domestic firms operate in the regulated region <u>with</u> foreign entrants,* $\Gamma_m = \Gamma_2$*; c) are unaffected by changes in emissions price if domestic firms operate offshore or exit,* $\Gamma_m \in \{\Gamma_3, \Gamma_4, \Gamma_5\}$*; and d) step increase if domestic firms offshore.*

Regarding Propositions 1a-c, when domestic firms produce in the regulated region without foreign competition (partition Γ_1), total output decreases with respect to emissions price as described above. Without foreign competition, there is no shift in domestic versus foreign market share, so changes in global emissions due to increases in emissions price are driven solely by changes in total output. Therefore, global emissions also decrease with respect to emissions price in cases of a domestic oligopoly. When domestic firms produce in the regulated region and foreign firms compete (partition Γ_2), increases in emissions price result in carbon leakage due to entry. Total output does not change due to changes emissions price under these conditions—increases in foreign entry are offset by decreases in domestic production. However, each unit of domestic production displaced by foreign entry increases emissions by $\alpha_1 + \alpha_\tau - \alpha_d$. As a consequence, increasing emissions price *increases* global emissions in this setting (as seen in Figure 4b over partition Γ_2). Under domestic offshoring (partitions Γ_3 and Γ_4) or exit (partition Γ_5), the market is served only by offshore facilities. Therefore, without border adjustment, further increases in emissions price do not affect global emissions if domestic firms operate offshore or exit. Table C.1 in Appendix C characterizes these comparative static effects.

Proposition 1d states that carbon leakage due to offshoring, which occurs at the offshoring threshold ε_o if $F_o < \overline{F}_o$, increases global emissions in the absence of a border adjustment. As with foreign entry, emissions intensity increases by $\alpha_1 + \alpha_\tau - \alpha_d$ for every unit of domestic production offshored. Due to emissions from transport, this results in strictly greater global emissions even if total output remains unchanged. If total output increases due to offshoring, per Lemma 3, increases in volume and emissions intensity combine to drive greater global emissions. The issue of an industry offshoring *en masse* without border adjustment is of practical concern. Studies of the EU cement sector suggest that all production in Italy, Greece, Poland, and the UK would offshore at an emissions price of 25 euro per tonne of CO_2, increasing global emissions by an estimated minimum of 7 million tonnes of CO_2 annually (Boston Consulting Group 2008).

In short, without border adjustment, the regulator's ability to reduce global emissions through emissions regulation is limited—it is only possible in cases of a domestic oligopoly (partition Γ_1) or by incentivizing the adoption of clean technology. The regulator can only achieve the latter if the clean technology adoption threshold is less than the offshoring or exit threshold (whichever is applicable given fixed offshoring costs). Further, the regulator can inadvertently *increase* global emissions through leakage by: i) imposing emissions regulation on sectors where domestic firms produce in the regulated region and compete against foreign entrants (partition Γ_2); or ii) imposing emissions regulation that results in offshoring (partitions Γ_3 and Γ_4).

3. Firm Decisions and Performance *with* Border Adjustment

Much debate related to emissions regulation has centered on border adjustments as a possible means to prevent the adverse effects of carbon leakage. This section focuses on how results with border adjustment differ from results without border adjustment or from conventional wisdom.

3.1. Model development

The model here resembles that in Section 2 except imports incur border adjustment $\beta_k(\varepsilon) = \alpha_k\varepsilon, \forall k \in \{1,2\}$. A symmetric border adjustment such as this is consistent with what Grubb and Neuhoff (2006) propose would be allowable under WTO law, and with the ruling in the case of Outokumpu Oy (Court of Justice of the European Union 1998). Hat notation distinguishes objectives, decisions, and thresholds with border adjustment from those without it, with $\hat{c}_d(\varepsilon)$ and $\hat{c}_f(\varepsilon)$ representing the operating cost of domestic and foreign firms' preferred technology, respectively. Therefore, with a border adjustment, domestic firms maximize operating profit by solving

$$\hat{\pi}_d\left(\hat{n}_d, \hat{n}_f, \hat{y}, \varepsilon\right) = \max_{\hat{x}_l \geq 0} P\left(\hat{n}_d, \hat{n}_f, \hat{x}_l, \hat{y}\right)\hat{x}_l - \hat{c}_d(\varepsilon)\hat{x}_l. \tag{5}$$

Each foreign competitor maximizes operating profit by solving

$$\hat{\pi}_f\left(\hat{n}_d, \hat{n}_f, \hat{x}_l, \varepsilon\right) = \max_{\hat{y} \geq 0} P\left(\hat{n}_d, \hat{n}_f, \hat{x}_l, \hat{y}\right)\hat{y} - \hat{c}_f(\varepsilon)\hat{y}.$$

3.2. Equilibrium technology choice

Unlike in settings without border adjustment, with a border adjustment the regulator can incentivize any firm serving the regulated market—domestic or foreign; operating in the regulated region or offshore—to adopt clean technology at some emissions price. Counterintuitively, foreign firms' technology choices are more sensitive than domestic firms' to emissions price.

PROPOSITION 2. *With a border adjustment, foreign firms serving the regulated region adopt clean technology at a lower emissions price than domestic-owned firms.*

Foreign firms adopt clean technology at their break-even emissions price for technology 1 and 2,

$$\hat{\varepsilon}_2^f = \delta\left(\gamma_2 - \gamma_1\right) / \left(\alpha_1 - \alpha_2\right). \tag{6}$$

The domestic clean technology adoption threshold is identical to that without a border adjustment,

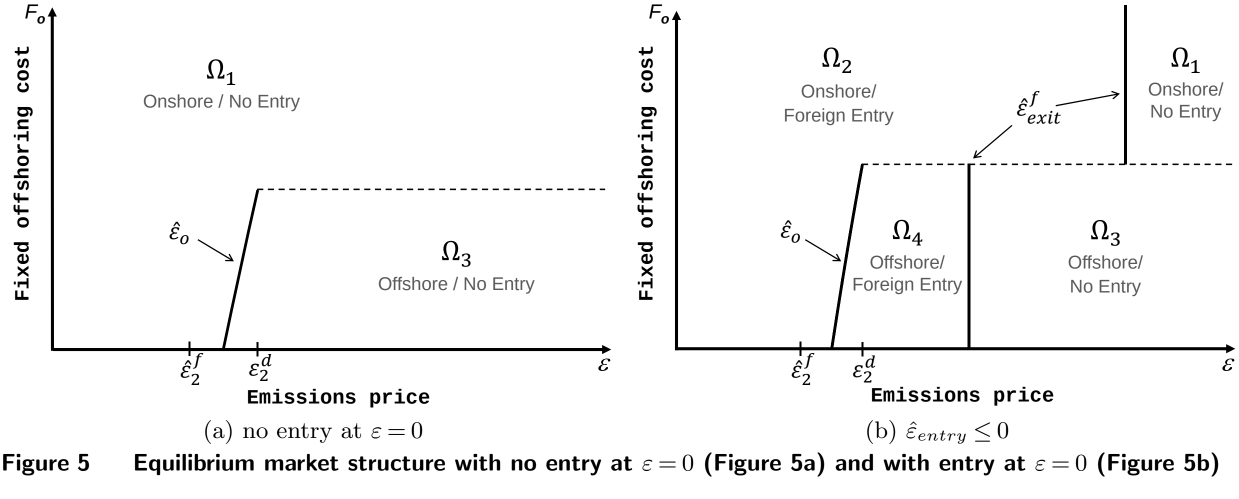
$$\varepsilon_2^d = \left(\gamma_2 - \gamma_1\right) / \left(\alpha_1 - \alpha_2\right). \tag{7}$$

Conditional upon entry, foreign firms therefore adopt clean technology at a lower emissions price than locally-producing domestic firms, with foreign firms operating cleaner technology than locally-producing domestic firms when $\varepsilon \in \left[\hat{\varepsilon}_2^f, \varepsilon_2^d\right)$. Further, (as described below in Section 3.3), if domestic firms offshore in equilibrium, they do so at a threshold greater than foreign firms' clean technology adoption threshold. This implies that domestic firms adopt clean technology, whether they do so in the domestic region or offshore, at a greater emissions price than foreign firms.

A comparison of the offshore and domestic clean technology adoption thresholds in (6) and (7) reveals the centrality of Assumption 1 to the result. This assumed foreign production cost advantage $\delta \in (0,1)$ therefore warrants revisiting. It should be reiterated that industry and governmental reports support this assumption. Foreign production costs are estimated to be significantly less in offshore regions than emissions-regulated regions for both established carbon-intensive technology (Boston Consulting Group 2008), and for nascent clean technology (IEA Greenhouse Gas Programme 2008). However, if Assumption 1 did not hold in a given context, then Proposition 2 and results that follow would also not hold for that specific context.

3.3. Equilibrium offshoring, exit, and entry

With border adjustment, four equilibrium market structures are of interest, $\Omega_1, ..., \Omega_4$. Figures 5a and 5b, the former without entry at $\varepsilon = 0$ and latter with entry at $\varepsilon = 0$, illustrate how these market structures evolve with respect to emissions price and fixed offshoring cost.



(a) no entry at $\varepsilon = 0$ (b) $\hat{\varepsilon}_{entry} \leq 0$

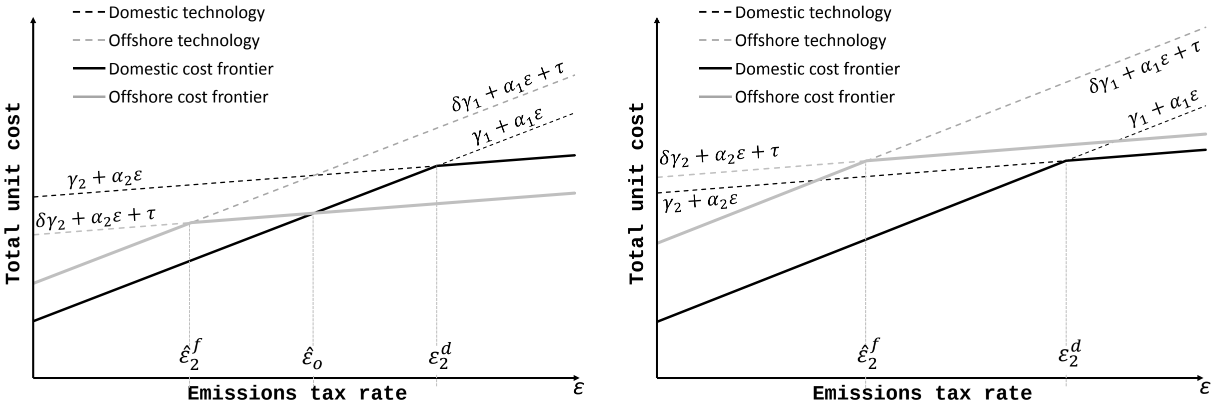
Figure 5 Equilibrium market structure with no entry at $\varepsilon = 0$ (Figure 5a) and with entry at $\varepsilon = 0$ (Figure 5b)

Three observations arise from Figures 5a and 5b that contradict conventional wisdom or settings without border adjustment. First, when fixed offshoring cost F_o is sufficiently small, domestic firms relocate at emissions prices greater than $\hat{\varepsilon}_o$ despite border adjustment (partitions Ω_3 and Ω_4). This contradicts the conventional wisdom that border adjustment eliminates carbon leakage. Second, the absence of an Ω_5 partition in both figures is notable—unlike settings without order adjustment, domestic exit due to increases in emissions price is impractical with border adjustment. Third, foreign entry increased with emissions price or was unaffected by changes in emissions price without border adjustment. However, with border adjustment, foreign entry can decrease with respect to emissions price—to the point that foreign firms exit the market at the threshold $\hat{\varepsilon}^f_{exit}$ (partitions Ω_1 and Ω_3 in Figure 5b). The intuition underlying these observations is developed below.

Domestic offshoring Conventional wisdom holds that a border adjustment will eliminate carbon leakage, including offshoring (e.g., Barry 2009, Barber 2010). However, results here indicate that domestic firms offshore under some conditions despite incurring a symmetric border adjustment.

PROPOSITION 3. *With a border adjustment, domestic firms offshore and adopt clean technology at the offshoring threshold* $\hat{\varepsilon}_o$ *if and only if* $\hat{\varepsilon}_o$ *is less than the clean technology adoption threshold in the regulated region* $\hat{\varepsilon}_o < \varepsilon^d_2$. *Otherwise, domestic firms do not offshore at any emissions price.*

Figures 6a and 6b depict the domestic (solid black line) and offshore (solid gray line) operating cost frontiers with respect to emissions price, and help develop the intuition behind Proposition 3.



(a) With offshoring and $F_o = 0$ (b) No offshoring

Figure 6 Operating cost frontiers when technologies are deployed domestically (black) and offshore (gray)

The gap between the cost frontiers in Figures 6a and 6b is the per-unit operating cost difference between locations. Over intervals in which domestic and offshore facilities prefer the same technology, $\varepsilon \in [0, \hat{\varepsilon}^f_2)$ or $\varepsilon \geq \varepsilon^d_2$, the frontiers are parallel; both regions have the same production emissions intensity and therefore equivalent per-unit carbon costs. In emissions price intervals where offshore facilities operate cleaner technology than facilities in the regulated region, $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$, offshore carbon costs increase at a slower rate with respect to emissions price than domestic carbon costs.

Offshore operating costs only improve relative to operating costs in the regulated region over emissions prices between the foreign and domestic clean technology adoption thresholds, $\hat{\varepsilon}_2^f$ and ε_2^d respectively. Therefore the threshold $\hat{\varepsilon}_o$ must fall within the interval $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ when it exists. For example, if $F_o = 0$, then offshoring threshold $\hat{\varepsilon}_o$ is determined by the emissions price at which domestic and offshore operating costs are equal, represented by the intersection of the cost frontiers in Figure 6a. When the threshold $\hat{\varepsilon}_o$ exists, then the operating profit improvement that domestic firms realize by relocating exceeds fixed offshoring cost F_o at any emissions price greater than $\hat{\varepsilon}_o$. In such cases, domestic firms offshore at $\hat{\varepsilon}_o$ despite the implementation of a border adjustment. Offshoring under border adjustment therefore implies domestic firms adopt cleaner technology when they relocate than they operated in the regulated region. As a consequence, domestic firms adopt clean technology at some emissions price $\hat{e}_2^d > \varepsilon_2^f$, where

$$\hat{e}_2^d = \begin{cases} \hat{\varepsilon}_o & \text{if } \varepsilon_2^d > \hat{\varepsilon}_o \\ \varepsilon_2^d & \text{otherwise.} \end{cases}$$

If technologies were more emissions-intensive when operated offshore, potentially due to the use of different inputs, then the slopes illustrated in Figures 6a and 6b would not be parallel. In such a case, provided that cost frontiers intersect when applying region-specific emissions intensities (as in Figure 6a), Proposition 3 and all other results would continue to hold. If domestic and offshore cost frontiers do not intersect (for any reason), then domestic firms would not offshore under border adjustment. In such a case, all results except Propositions 3, 5b, and 6e would still hold.

Domestic exit Under a border adjustment, it is straightforward to show that domestic firm profits are independent of emissions price when foreign firms compete in the market and operate the same technology as foreign firms. Therefore, given that foreign firms adopt clean technology at a lower emissions price than domestic firms with a border adjustment (per Proposition 2), $\hat{\varepsilon}_{exit} < \varepsilon_2^d$ is a necessary condition for domestic firm exit. This relationship holds only if offshore production costs are unrealistically small relative to domestic production costs; i.e., if $\delta < 1 - (\sqrt{F_e b} + \tau)/\gamma_2$. Such a condition is unlikely to be met in practice given the substantial transport costs for leakage-threatened goods. In cement, for example, transport costs are greater than production costs in four of the five offshore regions in Figure 2, which would require $\delta < 0$ for domestic exit. Therefore, given the impracticality of such outcomes, it is assumed that $\hat{n}_d^* = N_d$ in the discussion that follows.

Foreign entry and exit Without border adjustment, the number of foreign entrants increased with emissions price if domestic firms operated in the regulated region with foreign competitors in the market. The number of entrants was unaffected by emissions price in all other settings.

However, with border adjustment, the equilibrium number of entrants can be non-monotonic. Entry can increase over intervals in which foreign firms operate cleaner technology than domestic firms, but entry decreases if domestic and foreign firms operate identical technology.

The characterization of the number of foreign entrants under border adjustment, $\hat{n}_f^*$, resembles the characterization of n_f^* in Lemma 1 (and the proof is symmetric), with

$$\hat{n}_f^* = (\hat{h}(\varepsilon))^+, \quad \text{where} \quad \hat{h}(\varepsilon) = \frac{A - \hat{c}_f(\varepsilon) - \hat{n}_d^*(\hat{c}_f(\varepsilon) - \hat{c}_d(\varepsilon))}{\sqrt{F_e b}} - \hat{n}_d^* - 1. \tag{8}$$

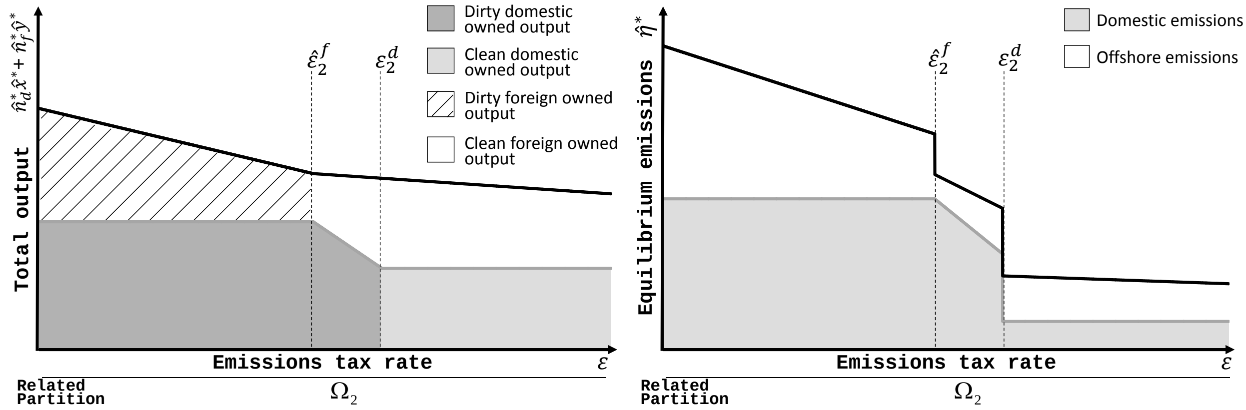
If foreign firms operate cleaner technology than domestic firms, it is straightforward to show that (8) increases with respect to emissions price if and only if the following inequality holds

$$\alpha_1 > \alpha_2(1 + 1/N_d). \tag{9}$$

In contexts where (9) holds,[1] clean technology offers a sufficient emissions intensity improvement relative to dirty technology that the number of foreign entrants increases with respect to emissions price over intervals where foreign firms operate cleaner technology than domestic firms. In such cases, foreign firms enter the market at $\hat{\varepsilon}_{entry} = \{\varepsilon | \hat{h}(\varepsilon) = 0,\ \varepsilon \in [\hat{\varepsilon}_2^f, \hat{e}_2^d)\}$ and they exit at $\hat{\varepsilon}_{exit}^f = \{\varepsilon | \hat{h}(\varepsilon) = 0,\ \varepsilon \notin [\hat{\varepsilon}_2^f, \hat{e}_2^d)\}$. However, if (9) does not hold, then the number of foreign entrants decreases monotonically with respect to emissions price. In such a case, there is no entry threshold and foreign firms that competed in the market at $\varepsilon = 0$ would exit at $\hat{\varepsilon}_{exit}^f = \{\varepsilon | \hat{h}(\varepsilon) = 0\}$.

3.4. Equilibrium quantities and emissions

Figures 7a and 7b provide a preview of the effect emissions price has on quantities and emissions, respectively, in settings where a border adjustment has been implemented.



(a) (b)

Figure 7 **Example of equilibrium quantities (Figure 7a) and emissions (Figure 7b) with border adjustment**

---

[1] For example, in cement, CCS technology is expected to eliminate more than 90% of emissions relative to standard precalciner kilns, i.e., $\alpha_2 \leq .10\alpha_1$ (European Cement Research Academy 2009). Therefore, $\alpha_1 > \alpha_2(1 + 1/N_d)$ holds, requiring only $N_d > 1/9$ (while $N_d \geq 1$ can be assumed in an emissions regulated setting with border adjustment).

Three differences in the figures above, relative to their counterparts without border adjustment (Figures 4a and 4b) or conventional wisdom, are central to the discussion that follows. First, in Figure 7a, total foreign entry increases with emissions prices over intervals between the foreign and domestic clean technology adoption thresholds, $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$, which contradicts the conventional wisdom that border adjustment will eliminate carbon leakage. Second, total output strictly decreases with respect to emissions price in Figure 7a, which differs from the setting without border adjustment where total output was unaffected by changes in emissions price in the comparable market structure (partition Γ_2). Third, global emissions strictly decrease with respect to emissions price in Figure 7b, differing from the setting without border adjustment where global emissions decreased with respect to emissions price only in cases of domestic oligopoly, and strictly increased with emissions price when domestic firms operated in the regulated region with foreign entry.

Equilibrium quantities As in the setting without border adjustment, $\hat{x}^*$ and $\hat{y}^*$ denote each domestic and foreign firm's equilibrium quantity when location is clear and non-central, and $\hat{x}_l^*$ denotes each domestic firm's production when location is otherwise unclear or central.

LEMMA 4. *With border adjustment, equilibrium total domestic output $\hat{n}_d^* \hat{x}^*$ and foreign output $\hat{n}_f^* \hat{y}^*$ depend on market structure and are characterized by the following table:*

Region	**Domestic decision**	**Entry decision**	**Total equilibrium quantities:** **Domestic, $\hat{n}_d^* \hat{x}^*$**	 **Foreign, $\hat{n}_f^* \hat{y}^*$**
Ω_1	Domestic production	No entry	$N_d \left(\frac{A - \hat{\gamma}_d - \hat{\alpha}_d \varepsilon}{b(N_d+1)} \right)$	0
Ω_2		Entry	$N_d \left(\sqrt{\frac{F_e}{b}} + \frac{\delta \hat{\gamma}_f + \hat{\alpha}_f \varepsilon + \tau - \hat{\gamma}_d - \hat{\alpha}_d \varepsilon}{b} \right)$	$\hat{n}_f^* \sqrt{\frac{F_e}{b}}$
Ω_3	Offshore production	No entry	$N_d \left(\frac{A - \delta \gamma_2 - \alpha_2 \varepsilon - \tau}{b(N_d+1)} \right)$	0
Ω_4		Entry	$N_d \left(\sqrt{\frac{F_e}{b}} \right)$	$\hat{n}_f^* \sqrt{\frac{F_e}{b}}$

The number of foreign entrants, given by (8), and firms' production quantities, presented in Lemma 4, provide insights related to total output and the potential for carbon leakage in settings with a border adjustment.

PROPOSITION 4. *With border adjustment: a) equilibrium total output strictly decreases with respect to emissions price; and b) equilibrium total foreign entry increases with emissions price if and only if (9) holds and foreign firms operate cleaner technology than domestic firms, $\varepsilon \in [\hat{\varepsilon}_f^2, \hat{e}_2^d)$. Otherwise, total foreign entry decreases with respect to emissions price.*

With border adjustment, as emissions price increases, operating costs for all participants in the market increase regardless of equilibrium market structure. This leads to Proposition 4a, the equilibrium total output serving the market decreases with respect to emissions price regardless of equilibrium market structure. This sharply differs from the setting without border adjustment where total output only decreased in the case of a domestic oligopoly (partition Γ_1).

Regarding Proposition 4b, if domestic and foreign firms operate identical technology, then they are equally exposed to changes in emissions price. In such cases, the reduced market size (decreased total output) resulting from an increase in emissions price leaves less opportunity for foreign entry, and the number of entrants decreases. This is evident from (8) if domestic and foreign firms operate identical technology, $\hat{c}_f(\varepsilon) = \hat{c}_d(\varepsilon)$. However, over intervals where foreign firms operate cleaner technology than domestic firms, they are relatively less exposed to emissions price. In such cases, their operating cost increases with emissions price at a slower rate than domestic firms' operating cost. As a consequence, if emissions price falls in the interval between foreign and domestic firms' clean technology adoption thresholds, $\varepsilon \in [\hat{\varepsilon}_2^f, \hat{e}_2^d)$, total foreign entry can increase with emissions price. This occurs if clean technology offers a sufficient emissions improvement relative to the dirty technology, i.e., if (9) holds. As described in footnote 1 above, this inequality holds trivially in cement, requiring only $N_d > 0.11$. This contradicts the conventional wisdom that border adjustment will eliminate the threat of carbon leakage (Barry 2009, Barber 2010, Ponssard and Walker 2008, Fowlie et al. 2016). Carbon leakage due to entry can arise despite border adjustment.

Similar to the setting without border adjustment, when a border adjustment has been implemented, total output potentially step-increases due to domestic offshoring.

LEMMA 5. *With border adjustment, offshoring increases equilibrium total output by* $\hat{Q}_o > 0$ *if and only if no foreign entrants compete when offshoring occurs* $\hat{h}(\hat{\varepsilon}_o) < 0$ *and fixed offshoring cost is positive* $F_o > 0$*. Otherwise, total output remains unchanged due to offshoring,* $\hat{Q}_o = 0$*.*

As described in the setting without border adjustment, if $F_o > 0$ total domestic-owned output increases with offshoring. This results because, at the offshoring threshold $\hat{\varepsilon}_o$, unit operating cost in the regulated region is greater than it is offshore if $F_o > 0$. As in the setting without border adjustment, if $F_o > 0$, foreign entry decreases when domestic firms offshore due to domestic firms' decreased operating cost (and consequently increased output). If foreign firms remain in the market despite domestic offshoring, i.e., if $\hat{h}(\hat{\varepsilon}_o) > 0$, then the decrease in foreign entry fully offsets the increase in domestic output, leaving total output unchanged as a consequence of offshoring. Otherwise, total output increases by $\hat{Q}_o > 0$, where $\hat{Q}_o$ is characterized in the proof to Lemma 5.

Equilibrium emissions Border adjustment improves the effectiveness of emissions price as a mechanism to reduce global emissions.

PROPOSITION 5. *With border adjustment: a) global emissions decrease monotonically with respect to emissions price if and only if no foreign firms compete in the market,* $\hat{n}_f^* = 0$*, and/or*

$$N_d (\alpha_1 - \alpha_2 - \alpha_\tau)(\alpha_1 - \alpha_2) + \alpha_2 (\alpha_2 + \alpha_\tau) > 0, \tag{10}$$

otherwise global emissions increase with emissions price if foreign firms operate cleaner technology than domestic firms, $\varepsilon \in [\hat{\varepsilon}_2^f, \hat{e}_2^d)$*, and decrease if foreign and domestic firms operate identical technology,* $\varepsilon \notin [\hat{\varepsilon}_2^f, \hat{e}_2^d)$*; and b) global emissions decrease due to offshoring if and only if*

$$\alpha_1 / (\alpha_2 + \alpha_\tau) > 1 + \hat{Q}_o / N_d \hat{x}_r^* (\hat{\varepsilon}_o) \tag{11}$$

but otherwise increase due to offshoring.

When domestic firms compete alone in the market, increases in emissions price reduce their output, per Proposition 4, and therefore reduce global emissions. Unlike the setting without border adjustment, this is true whether domestic firms operate alone in the regulated region (partition Ω_1) or offshore (partition Ω_3). When domestic firms compete against foreign firms and operate identical technology (partition Ω_2 when $\varepsilon \notin [\hat{\varepsilon}_2^f, \hat{e}_2^d)$ and partition Ω_4), total foreign entry decreases with respect to emissions price, per Proposition 4, and domestic-owned output is unchanged by changes in emissions price (which is evident through Lemma 4). Global emissions again decrease as a result, which also differs from the setting without border adjustment where global emissions are unchanged or increasing with respect to emissions price when foreign firms compete.

If domestic firms operate in the regulated region and foreign firms compete with cleaner technology (partition Ω_2 with $\varepsilon \in [\hat{\varepsilon}_2^f, \hat{e}_2^d)$), increases in emissions price decrease total output but increase carbon leakage due to entry, per Proposition 4. In contrast to the setting without border adjustment, when a border adjustment is implemented, each unit of leakage reduces emissions intensity if $\alpha_1 - \alpha_2 - \alpha_\tau > 0$; each unit of carbon leakage replaces a unit of dirty production in the regulated region with a unit of clean production and international transport. Further, one must also account for changes in total output, which decreases with respect to emissions price. Therefore, when accounting for both the change in per unit emissions intensity and the change in total output, global emissions decrease as foreign entry increases if and only if (10) holds. This inequality holds under the sufficient condition that per-unit transport emissions are less than the emissions intensity improvement achieved by adopting clean technology. This holds in cement, where per ton transport emissions $\alpha_\tau \approx 0.07$ for a shipment from China to Western Europe (Log-net.com 2014, assuming 22 tonnes of cement per 20 foot container) are nearly an order of magnitude less than the estimated emissions intensity improvement achieved by adopting clean technology $(\alpha_1 - \alpha_2) \approx 0.64$ (Cement Sustainability Initiative 2009). Table C.2 in Appendix C characterizes these effects.

Regarding Proposition 5b, there is an intensity and volume effect to consider. The emissions intensity of production decreases by $\alpha_1 - \alpha_2$ for each unit of production moved offshore (per Proposition 3). However, α_τ transport emissions are also generated for each unit imported into the regulated region. Therefore, the emissions intensity of the $N_d \hat{x}_r^*(\hat{\varepsilon}_o)$ units moved offshore decreases if $\alpha_1 - \alpha_2 - \alpha_\tau > 0$. However, per Lemma 5, total output can increase due to offshoring. Therefore, total global emissions decrease due to offshoring only if emissions intensity decreases sufficiently to offset the $\alpha_2 + \alpha_\tau$ emissions generated per unit of additional output, $\hat{Q}_o$, potentially produced due to offshoring. This gives rise to condition (11). Returning to cement as an example, recall that α_2 and α_τ are each approximately 10% of α_1 (Cement Sustainability Initiative 2009, and Log-net.com 2014). Therefore, by condition (11), global emissions would decrease due to offshoring unless total output were to increase by more than 400% of pre-offshoring domestic production.

In short, border adjustment provides the regulator with greater ability to use emissions price as a mechanism to reduce global emissions. With a border adjustment: i) total output strictly decreases with respect to emissions price, rather than decreasing only if domestic firms produce in the regulated region without foreign competition; ii) carbon leakage from both offshoring and entry decrease emissions under some conditions, rather than strictly increasing emissions; and, iii) the regulator can incentivize the adoption of clean technology by both domestic and foreign firms, rather than only being able to incentivize such adoption among domestic firms, and only if the adoption threshold is less than the offshoring or exit threshold (whichever is applicable given F_o).

4. Effects on Emissions Regulation Efficacy and Welfare Performance

This section explores how the decision whether or not to implement a border adjustment affects emissions regulation efficacy and social welfare. Throughout this section, border adjustment costs per unit are β_k, where $\beta_k = 0$ without border adjustment and $\beta_k = \alpha_k \varepsilon$ with border adjustment. Superscript w denotes parameters and equilibrium decisions given the regulator's decision whether or not to implement a border adjustment. For example, equilibrium domestic quantities are:

$$x^w = \begin{cases} x^* & \text{if } \beta_k = 0 \\ \hat{x}^* & \text{if } \beta_k = \alpha_k \varepsilon. \end{cases}$$

4.1. The effect of border adjustment on emissions regulation efficacy

Emissions regulation is intended to reduce equilibrium global emissions, $\eta^w = n_d^w x_r^w \alpha_d^w + \left(n_d^w x_o^w + n_f^w y^w\right)\left(\alpha_f^w + \alpha_\tau\right)$. If, in the absence of border adjustment, foreign firms would compete in the market or domestic firms would offshore, then a border adjustment improves the regulator's ability to deliver on this intent.

Proposition 6. *Border adjustment strictly decreases global emissions if, without border adjustment, foreign firms compete in the market and/or domestic firms offshore, $\Gamma_m \in \{\Gamma_2, ..., \Gamma_5\}$. Border adjustment decreases emissions through five mechanisms: a) reduced total output; b) reduced transport emissions; c) clean foreign-owned production if $\varepsilon \geq \hat{\varepsilon}_2^f$ and foreign firms compete in the market under border adjustment, $\Omega_m \in \{\Omega_2, \Omega_4\}$; d) clean domestic production if $\varepsilon \geq \varepsilon_2^d$ and border adjustment prevents offshoring, $\Gamma_m \in \{\Gamma_3, \Gamma_4\}$ and $\Omega_m \in \{\Omega_1, \Omega_2\}$; and e) clean offshoring if domestic firms offshore despite border adjustment, $\Omega_m \in \{\Omega_3, \Omega_4\}$.*

Proposition 6 states that border adjustment reduces global emissions if, without such a mechanism, foreign firms compete and/or domestic firms offshore. In such settings, border adjustment improves the regulator's control over both the total output serving the market and the emissions intensity of production. Thus, border adjustment enables greater control over global emissions.

Without border adjustment, total output $n_d^* x^* + n_f^* y^*$ decreases with respect to emissions price only in the case of domestic oligopoly, partition Γ_1 (per Section 2.3). However, with border adjustment, total output decreases with respect to emissions price across all market structure equilibria per Proposition 4. As a consequence, total output is less under a border adjustment if foreign firms compete and/or domestic firms offshore without a border adjustment. Further, without border adjustment, offshore facilities produce with dirty technology. However, if foreign firms compete in the market under border adjustment, they adopt clean technology if $\varepsilon \geq \hat{\varepsilon}_2^f$, reducing the emissions intensity of foreign-owned production vis-à-vis the setting without border adjustment.

Border adjustment can also enable reduced emissions intensity if offshoring would occur without such a mechanism. The emissions price at which domestic firms offshore is greater with border adjustment than without it, $\hat{\varepsilon}_o \geq \varepsilon_o$. Border adjustment can therefore deter offshoring. Such deterrence has two benefits with respect to global emissions. First, by preventing domestic firms from offshoring and then importing into the regulated region, border adjustment contributes to decreased transport emissions. Second, offshoring deterrence can improve the regulator's ability to incentivize clean technology adoption by domestic-owned firms. Domestic firms operate dirty technology if they offshore in the absence of border adjustment. However, if border adjustment deters offshoring, the regulator incentivizes clean technology adoption by those firms if emissions price is at least as great as the domestic clean technology adoption threshold, $\varepsilon \geq \varepsilon_2^d$. On the other hand, if domestic firms offshore despite border adjustment, they adopt clean technology when doing so, per Proposition 3. In either case, border adjustment enables the adoption of clean technology among domestic-owned firms in settings in which they would operate dirty technology without border adjustment. Consequently, border adjustment improves the regulator's ability to reduce the emissions intensity of domestic-owned production.

In short, in any setting in which it would have an effect, a border adjustment improves the regulator's ability to use emissions price as a lever to reduce total output and, in some scenarios, to reduce emissions from transportation and/or to incentivize the adoption of clean technology.

4.2. The effect of border adjustment on welfare

When choosing whether or not to implement a border adjustment, the domestic regulator must consider traditional welfare drivers as well as emissions revenues and emissions-driven social costs. Total domestic firm profits in equilibrium are $\Pi^w = n_d^w \pi_d^w - I_o n_d^w F_o$, where I_o is 1 if domestic firms offshore and zero otherwise. Given the demand curve in Sections 2 and 3, equilibrium consumer surplus is $\psi^w = (1/2)b\left(n_d^w x^w + n_f^w y^w\right)^2$.

Since domestic and foreign firms use identical technology when producing offshore, imports to the region incur border adjustment β_f when produced by either type of firm. The domestic regulator therefore earns equilibrium emissions revenues, $\rho^w = n_d^w x_r^w \alpha_d^w \varepsilon + \left(n_d^w x_o^w + n_f^w y^w\right)\beta_f$.

The per-ton social cost of emissions, $\varepsilon_s \geq 0$, is the monetized climate change damage done by each ton of carbon dioxide equivalent emissions. These costs have been estimated as beginning at \$21.40 in 2010 and increasing to \$44.90 by 2050, with both figures based on 2007 dollars (Greenstone et al. 2011). These social costs are included in the welfare problem as $\xi^w = \eta^w \varepsilon_s$.

The domestic regulator maximizes equilibrium welfare, W, through the following objective:

$$W = \max_{\beta_f \in \{0, \hat{\alpha}_f \varepsilon\}} \Pi^w + \psi^w + \rho^w - \xi^w.$$

Border adjustment affects welfare drivers in opposing directions and can therefore increase or decrease welfare. Where $\Delta a = \hat{a} - a$, a border adjustment improves welfare if and only if

$$\Delta\xi < \Delta\Pi + \Delta\psi + \Delta\rho. \tag{12}$$

As demonstrated by Proposition 6 and its related discussion, border adjustment decreases global emissions, and therefore the social cost of carbon, in any setting in which it would apply (i.e., $\Delta\xi$ is negative). Further, it is straightforward to demonstrate that border adjustment increases emissions revenues (i.e., $\Delta\rho$ is positive); unsurprising given that the regulator collects revenues from both domestic and offshore production under border adjustment and from only domestic production without such a mechanism. Both of these effects increase welfare and contribute to (12) holding. However, consumer surplus works in the opposite direction. As discussed above, total output decreases with border adjustment. Consequently, consumer surplus also decreases (i.e., $\Delta\psi$ is negative). As a result, the effect border adjustment has on welfare is ambiguous. For example, define T as total output without border adjustment, $n_d^* x^* + n_f^* y^*$, and $\hat{T}$ as total output with border adjustment, $\hat{n}_d^* \hat{x}^* + \hat{n}_f^* \hat{y}^*$. If domestic firms offshore and face foreign competition with and without border adjustment, the inequality in (12) equates to

$$\left[\hat{T}\left(\alpha_2 + \alpha_\tau\right) - T\left(\alpha_1 + \alpha_\tau\right)\right]\varepsilon_s < \left(\hat{T}^2 - T^2\right) b/2 + \hat{T}\alpha_2\varepsilon. \tag{13}$$

The LHS of (13) is negative as $\hat{T} < T$ and $\alpha_2 < \alpha_1$. However, the RHS can be positive or negative as the first term of the RHS is strictly negative, while the second term of the RHS is strictly positive. Whether (13) holds depends, in part, on the per-unit social cost of carbon (ε_s), the magnitude of change in total output ($\hat{T} - T$), and the emissions intensity of firms' preferred technologies with and without border adjustment (α_2 and α_1, respectively).

Irrespective of these ambiguous overall welfare effects, in order to contribute to the debate as to whether border adjustments are protectionist measures or climate policy, it is important to understand how border adjustment affects domestic firm profits. In order for a border adjustment to be considered protectionist, domestic firms, at a minimum, should be no worse off as a consequence of the mechanism. However, the effect border adjustment has on domestic firms' profits, $\Delta\Pi$ from (12), can be positive, negative, or zero.

PROPOSITION 7. *Total domestic firms' profit can increase, decrease, or remain unchanged due to the implementation of a border adjustment.*

A border adjustment increases domestic firm profits if, in the absence of such a mechanism, domestic firms operate in the regulated region with foreign entry. In this case, border adjustment reduces total foreign entry and domestic firms' profit benefits. However, if domestic firms would offshore without a border adjustment, then the mechanism can reduce their profits. In this case, domestic firms incur greater emissions costs due to border adjustment—either directly through the border adjustment while operating offshore, or by continuing to operate in the regulated region if offshoring is deterred by border adjustment. Lastly, if domestic firms offshore and foreign firms participate in the market with and without border adjustment, foreign entry competes operating profit down to F_e for all participants, domestic firms included. As a consequence, domestic firms earn equivalent profit with and without border adjustment.

Considered together, Propositions 6 and 7 suggest that the general benefit of a border adjustment is *not* to protect domestic firms' profits as some have argued (e.g., Beattie and Hill 2009, The Economist 2007). Proposition 7 states that, if foreign entry and/or domestic offshoring would occur in the absence of a border adjustment, domestic firm profits could benefit or could be harmed by the implementation of such a mechanism. Proposition 6, on the other hand, states that global emissions strictly decrease with the implementation of a border adjustment under identical conditions. These results suggest that border adjustments are good climate policy rather than protectionism. Border adjustments improve the efficacy of emissions regulation by eliminating adverse outcomes from carbon leakage and by enabling emissions price to be used to reduce global emissions in all settings.

5. Implications and Conclusions

There are two widely held beliefs related to carbon leakage—that carbon leakage increases global emissions; and that a border adjustment eliminates the threat of carbon leakage. However, this paper suggest that neither of these beliefs necessarily holds if: i) firms can choose production technologies; and ii) offshore producers have a production cost advantage. In such settings it is shown here that foreign firms adopt clean technology at a lower emissions price than domestic firms (Proposition 2), with foreign entry potentially increasing with emissions price over intervals in which foreign firms hold this advantage (Proposition 4). It is also shown that domestic firms may still offshore despite a border adjustment, but doing so implies the adoption of cleaner technology (Proposition 3). In short, carbon leakage can still occur under border adjustment. However, if it does arise, it *decreases* global emissions in practical settings (Proposition 5), which differs from the strict increase in global emissions that results from carbon leakage in the absence of border adjustment (Proposition 1).

In any setting in which domestic firms would offshore or foreign firms would compete in the absence of a border adjustment, the implementation of a border adjustment provides five potential sources of emissions improvement relative to emissions regulation without border adjustment (Proposition 6). First, it reduces total output relative to emissions-regulated settings without border adjustment. Second, it reduces emissions from transport to the regulated region. Third, it potentially enables the regulator to incentivize clean production in the regulated region. Fourth, it potentially enables the regulator to incentivize clean production by foreign entrants. Fifth and finally, it results in “clean” leakage due to offshoring by domestic firms in any setting in which offshoring arises despite the border adjustment. The latter three sources of benefit require technology choice, highlighting the importance of accounting for firms’ technology decisions when assessing the effects of border adjustment policy.

Domestic firm profits can increase or decrease due to border adjustment (Proposition 7). However, a border adjustment strictly decreases global emissions in any setting in which it would have an effect (Proposition 6). Together, these results suggest that a border adjustment is not inherently protectionist as some argue, but rather that it enables carbon regulation to deliver on its intended purpose: the reduction of global emissions.

References

Babiker, M. 2005. Climate change policy, market structure, and carbon leakage. *Journal of International Economics* **65**(2) 421–445.

Barber, J. 2010. US Senate Democrats want manufacturing incentives in climate bill. *Platts Commodity News* (April 15).

Barry, C. 2009. California advisers push ‘border adjustments’ to address GHG leakage. *Carbon Control News* **3**(51).

Beattie, A., K. Hill. 2009. China joins carbon tax protest. *Financial Times* (July 3), http://www.ft.com/content/76f0e4b0–67fc–11de–848a–00144feabdc0.

Boston Consulting Group. 2008. Assessment of the impact of the 2013-2020 ETS proposal on the European cement industry. Project report with Cembureau.

Broder, J. M. 2009. Obama opposes trade sanctions in climate bill. *The New York Times (June 28), http://www.nytimes.com/2009/06/29/us/politics/29climate.html?_r=0.*

Cement Association of Canada. 2015. Re: Discussion paper—BC climate leadership plan, July 2015. August 10, 2015 correspondence to the British Columbia Climate Action Secretariat, https://engage.gov.bc.ca/climateleadership/files/2015/12/063_-Cement-Association-of-Canada.pdf.

Cement Sustainability Initiative. 2009. Development of state-of-the-art techniques in cement manufacturing: Trying to look ahead. Working paper, Cement Sustainability Initiative.

Condon, M., A. Ignaciuk. 2013. Border carbon adjustment and international trade: A literature review. OECD Trade and Environment Working Paper.

Court of Justice of the European Union. 1998. Judgment of the Court of 2 April 1998. Outokumpu Oy. Reference for a preliminary ruling: Uudenmaan lääninoikeus - Finland, http://publications.europa.eu/en/publication-detail/-/publication/550a7cb8-5f23-4802-bd2f-015da4b13270/language-en.

Demailly, D., P. Quirion. 2006. CO_2 abatement, competitiveness and leakage in the European cement industry under the EU-ETS: Grandfathering versus output-based allocation. *Climate Policy* **6**(1) 93–113.

Di Maria, C., E. van der Werf. 2008. Carbon leakage revisited: Unilateral climate policy with directed technical change. *Environmental and Resource Economics* **39**(2) 55–74.

Drake, D., P. K. Kleindorfer, L. N. Van Wassenhove. 2010. Heidelbergcement: Technology choice under emissions regulation. Case 610-014-1, European Case Clearing House.

Drake, D., P. K. Kleindorfer, L. N. Van Wassenhove. 2016. Technology choice and capacity portfolios under emissions regulation. *Production and Operations Management* **25**(6) 1006–1025.

European Cement Research Academy. 2009. Technology paper number 31: Post combustion capture using absorption technologies. Cement Sustainability Initiative, http://www.wbcsdcement.org/pdf/technology/Technology%20papers.pdf.

European Cement Research Academy. 2012. Technical report – ECRA CCS project—Report on Phase III, https://www.ecra-online.org/fileadmin/redaktion/files/pdf/ECRA_Technical_Report_CCS_Phase_III.pdf.

European Commission. 2009. Glass, ceramic, clay and cement production statistics - NACE Rev. 1.1, http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glass,_ceramic,_clay_and_cement_production_statistics_-_NACE_Rev._1.1.

Fowlie, M. 2009. Incomplete environmental regulation, imperfect competition, and emissions leakage. *American Economic Journal: Economic Policy* **1**(2) 72–112.

Fowlie, M., M. Reguant, S. P. Ryan. 2016. Market-based emissions regulation and industry dynamics. *Journal of Politcal Economy* **124**(1) 249–302.

Greenstone, M., E. Kopits, A. Wolverton. 2011. Estimating the social cost of carbon for use in US federal rulemakings: A summary and interpretation. Working paper, NBER Working Paper Series.

Grubb, M., K. Neuhoff. 2006. Allocation and competitiveness in the EU Emissions Trading Scheme: Policy overview. *Climate Policy* **6**(1) 7–30.

Holmes, P., T. Reilly, J. Rollo. 2011. Border carbon adjustments and the potential for protectionism. *Climate Policy* **11**(2) 883.

İşlegen, Ö., E. L. Plambeck, T. Taylor. 2016. Variability in emissions cost: Implications for facility location, production and shipping. A. Atasu, ed., *Environmentally Responsible Supply Chains*. Springer, New York, NY.

İşlegen, Ö., S. J. Reichelstein. 2011. Carbon capture by fossil fuel power plants: An economic analysis. *Management Science* **57**(1) 21–39.

IEA Greenhouse Gas Programme. 2008. CO_2 capture in the cement industry. Technical study report number 2008/3, http://www.ieaghg.org/docs/General_Docs/Reports/2008-3.pdf.

International Iron and Steel Institute. 2006. World Steel in Figures 2006.

Krass, D., T. Nedorezov, A. Ovchinnikov. 2013. Environmental taxes and the choice of green technology. *Production and Operations Management* **22**(5) 1035–1055.

Krugman, P. 2009. Climate, trade, Obama. *New York Times* blog: The Opinion Pages—The Conscience of a liberal (June 29), http://krugman.blogs.nytimes.com/2009/06/29/climate-trade-obama/comment-page-2/?_r=0.

Log-net.com. 2014. Log-net carbon calculator, http://www.log-net.com/sustainability/.

Ponssard, J. P., N. Walker. 2008. EU emissions trading and the cement sector: A spatial competition analysis. *Climate Policy* **8**(5) 467–493.

Popp, D., R. G. Newell, A. B. Jaffe. 2009. Energy, the environment, and technological change. NBER Working Paper Series.

Ryan, S. P. 2012. The costs of environmental regulation in a concentrated industry. *Econometrica* **80**(3) 1019–1061.

Sunar, N., E. Plambeck. 2016. Allocating emissions among co-products: Implications for procurement and climate policy. *Manufacturing & Service Operations Management.* Forthcoming.

The Economist. 2007. Climate change: Green protectionism. *The Economist* (November 15), http://www.economist.com/node/10134052.

US Congress, House. 2009. American Clean Energy and Security Act of 2009, HR 2454, 111th US Congress, 1st Session.

US Energy Information Administration. 2011. Assumptions to the Annual Energy Outlook 2011. Available at http://pbadupws.nrc.gov/docs/ML1209/ML12090A838.pdf. Accessed June 13, 2014.

A. Technical Appendix—Proofs

Proof of joint concavity of firm objectives. FOCs for each firm $i \in \mathcal{N}_d$ and firm $j \in \mathcal{N}_f$ are

$$\frac{\partial \pi_i\left(n_d, n_f, l, y, \varepsilon\right)}{\partial x_{i,l}} = A - b(x_{i,l} + (n_d - 1)x_{-i,l} + n_f y) - b x_{i,l} - c_d(\varepsilon) = 0, \quad \forall i \in \mathcal{N}_d, \tag{14}$$

and

$$\frac{\partial \pi_f\left(n_d, n_f, x_l\right)}{\partial y_j} = A - b(n_d x_l + (n_f - 1)y_{-j} + y_j) - b y_j - \delta\gamma_f - \tau = 0, \quad \forall j \in \mathcal{N}_f. \tag{15}$$

The joint concavity of firm objectives can be proven directly through the Hessian. Based on the FOCs in Equations (14) and (15), the second derivative of domestic and offshore objectives are

$$\frac{\partial^2 \pi_i(\cdot)}{\partial x_{i,l}^2} = -2b, \quad \forall i \in \mathcal{N}_d, \qquad \text{and} \qquad \frac{\partial^2 \pi_j(\cdot)}{\partial y_j^2} = -2b, \quad \forall j \in \mathcal{N}_f,$$

while the cross-partials are

$$\frac{\partial^2 \pi_i(\cdot)}{\partial x_{i,l}\partial y} = -b, \qquad \text{and} \qquad \frac{\partial^2 \pi_j(\cdot)}{\partial y_j \partial x_l} = -b, \quad \forall i \in \mathcal{N}_d, \quad \forall j \in \mathcal{N}_f.$$

Elements composing the main diagonal of the Hessian are equal to $-2b$ while all other elements are equal to $-b$. As a consequence, all odd-ordered leading principal minors are strictly negative and all even-ordered leading principal minors are positive, thereby implying strict concavity. □

Proof of Lemma 1. The following equilibrium quantities are required to prove Lemma 1:

LEMMA 6. *With the number of domestic and foreign competitors fixed at* n_d *and* $n_f > 0$*, domestic and foreign firms, respectively, produce at equilibrium quantities*

$$x_l^* = \frac{A - c_d\left(l, \varepsilon\right)}{b\left(n_d + n_f + 1\right)} + \frac{n_f\left(c_f - c_d\left(l, \varepsilon\right)\right)}{b\left(n_d + n_f + 1\right)}, \qquad \text{and} \qquad y^* = \frac{A - c_f}{b\left(n_d + n_f + 1\right)} - \frac{n_d\left(c_f - c_d\left(l, \varepsilon\right)\right)}{b\left(n_d + n_f + 1\right)}.$$

Proof of Lemma 6. Since the problem is symmetric for all domestic firms and is likewise symmetric for all foreign firms, solving (15) for y^* yields

$$y^* = \frac{A - c_f - b n_d x_l}{b(n_f + 1)}, \quad \forall j \in \mathcal{N}_f. \tag{16}$$

Substituting (16) into (14) and then solving for x_l yields

$$x_l^* = \frac{A - c_d\left(l, \varepsilon\right)}{b\left(n_d + n_f + 1\right)} + \frac{n_f\left(c_f - c_d\left(l, \varepsilon\right)\right)}{b\left(n_d + n_f + 1\right)}, \quad \forall i \in \mathcal{N}_d, \tag{17}$$

which, by substituting into (16) yields

$$y^* = \frac{A - c_f}{b\left(n_d + n_f + 1\right)} - \frac{n_d\left(c_f - c_d\left(l, \varepsilon\right)\right)}{b\left(n_d + n_f + 1\right)}, \quad \forall j \in \mathcal{N}_f. \qquad \blacksquare \tag{18}$$

The number of offshore entrants follows directly from its definition,

$$\max_y \pi_f\left(n_d, n_f, x_l\right) = \max_y \left[P\left(n_d, n_f, x_l, y\right) y - c_f y\right] = F_e, \quad \forall j \in \mathcal{N}_f.$$

$$\Rightarrow [A - b(n_d x_l + n_f y)]\, y - c_f y = F_e, \quad \forall j \in \mathcal{N}_f.$$

The result follows from the quantities in Equations (17) and (18), and the constraint that $n_f \geq 0$.

$$n_f^* = \max\left\{0, \frac{A - c_f - n_d(c_f - c_d(l,\varepsilon))}{\sqrt{F_e b}} - n_d - 1\right\}. \quad \square \tag{19}$$

Proof of Lemma 2 When domestic firms produce in the regulated region $c_d(\varepsilon) = \gamma_d + \alpha_d \varepsilon$, and when domestic firms produce offshore $c_d(\varepsilon) = \delta\gamma_1 + \tau$. Domestic quantity solutions for Γ_1 follow from (17) when $c_d(\varepsilon) = \delta\gamma_1 + \tau$, $n_d^* = N_d$, and $n_f^* = 0$. Similarly, domestic quantity solutions for Γ_3 follow from (17) when $c_d(\varepsilon) = \delta\gamma_1 + \tau$, $n_d^* = N_d$ and $n_f^* = 0$. For Γ_2 and Γ_4, $n_f^* > 0$, and therefore is equal to the righthand argument of the maximum statement given in (19), and $c_f = \delta\gamma_1 + \tau$. Domestic quantities then follow directly from (17) and foreign quantities follow from (18). For Γ_5, foreign quantities are determined directly from (18) when n_f^* is again equal to the righthand argument of (19) and $n_d^* = 0$. $\square$

Proof of Lemma 3 Define Q_o as the change in total output due to offshoring. Where $F_o \leq \overline{F}_o$,

$$Q_o = n_d^* x_r^*(\varepsilon_o) + n_f^* y^*(\varepsilon_o) - \left[\lim_{\varepsilon \to \varepsilon_o^-} \left(n_d^* x_r^*(\varepsilon) + n_f^* y^*(\varepsilon)\right)\right].$$

If $F_o \leq \overline{F}_o$, then without entry (i.e., when $n_f^* = y^* = 0$), the unique solution to ε_o is

$$\varepsilon_o = \frac{c_f - \gamma_d}{\alpha_d} + \frac{A - c_f - \sqrt{(A - c_f)^2 - F_o b (N_d + 1)^2}}{\alpha_d}, \tag{20}$$

while, with entry (i.e., $n_f^* > 0$), the unique solution is

$$\varepsilon_o = \frac{c_f - \gamma_d}{\alpha_d} + \frac{\sqrt{b}(\sqrt{F_e} - \sqrt{F_e - F_o})}{\alpha_d}. \tag{21}$$

If $F_o = 0$, then $\lim_{\varepsilon \to \varepsilon_o^-} c_d(\varepsilon) = c_f$. Wrt F_o, $c_d'(r,\varepsilon) > 0$. Therefore, if $0 < F_o \leq \overline{F}_o$, then $h(\varepsilon_o) < \lim_{\varepsilon \to \varepsilon_o^-} h(\varepsilon)$ because $c_f = c_d(\varepsilon_o) < \lim_{\varepsilon \to \varepsilon_o^-} c_d(\varepsilon)$. Substituting the appropriate values of x_l^* and y^* from Lemma 2, n_f^* from Lemma 1, and ε_o from (20) and (21),

$$Q_o = \begin{cases} \frac{N_d(A - c_f - \sqrt{(A - c_f)^2 - F_o b(N_d + 1)^2})}{b(N_d + 1)} & \text{if } \lim_{\varepsilon \to \varepsilon_o^-} h(\varepsilon) \leq 0 \\ \frac{((N_d + 1)\sqrt{F_e b} - A + c_f)}{b} & \text{if } h(\varepsilon_o) < 0 < \lim_{\varepsilon \to \varepsilon_o^-} h(\varepsilon) \\ 0 & \text{if } h(\varepsilon_o) \geq 0. \end{cases} \tag{22}$$

By Lemma 1, $h(\varepsilon_o) < 0 \Leftrightarrow ((N_d + 1)\sqrt{F_e b} - A + c_f)/b > 0$. Therefore, when $0 < F_o \leq \overline{F}_o$, $Q_o > 0$ iff $h(\varepsilon_o) < 0$, and $Q_o = 0$ otherwise. If $F_o = 0$, then $h(\varepsilon_o) = \lim_{\varepsilon \to \varepsilon_o^-} h(\varepsilon)$ with both equal to $(A - c_f)/\sqrt{F_e b} - N_d - 1$ per Lemma 1. Consequently, per (22), if $F_o = 0$ the interval $(h(\varepsilon_o), \lim_{\varepsilon \to \varepsilon_o^-} h(\varepsilon))$ is empty and $Q_o = 0$. $\square$

Proof of Proposition 1 From (4) and Lemma 2, $\partial\eta^*/\partial\varepsilon = -\alpha_d^2 N_d/b(N_d+1)$ when $l^* = r$ and $n_f^* = 0$. When $l^* = r$ and $n_f^* > 0$, $\partial n_d^* x_r^* \alpha_d/\partial\varepsilon = -\alpha_d^2 N_d/b$, while $\partial n_f^* y^*(\alpha_1 + \alpha_\tau)/\partial\varepsilon = \alpha_d N_d(\alpha_1 + \alpha_\tau)/b$ through Lemma 1 and Lemma 2; therefore $\partial\eta^*/\partial\varepsilon = (\alpha_1 + \alpha_\tau - \alpha_d)(\alpha_d N_d/b)$. If domestic firms offshore or exit, $\partial\eta^*/\partial\varepsilon = 0$ because $c_d(\varepsilon) = \delta\gamma_1 + \tau = c_f$ or $n_d^* = 0$, respectively. Related to Proposition 1d, the change in global emissions due to offshoring is $\varepsilon^\Delta\left(n_d^*\left[\lim_{\varepsilon\to\varepsilon_o^-} x_r^*(\varepsilon)\right]\right) + Q_o(\alpha_1 + \alpha_\tau)$, where ε^Δ is the change in emissions intensity due to offshoring, and Q_o is the change in total output due to offshoring defined in Lemma 3's proof. Emissions intensity increases due to offshoring by at least α_t and, per Lemma 3, total output is non-decreasing due to offshoring. $\square$

Proof of Proposition 2 Offshore firms prefer type 2 if $\delta\gamma_2 + \alpha_2\varepsilon + \tau \le \delta\gamma_1 + \alpha_1\varepsilon + \tau$. Therefore the offshore adoption threshold is $\hat{\varepsilon}_2^f = \delta(\gamma_2 - \gamma_1)/(\alpha_1 - \alpha_2)$. Symmetrically, the clean technology adoption threshold in the regulated region is $\varepsilon_2^d = (\gamma_2 - \gamma_1)/(\alpha_1 - \alpha_2)$. $\delta \in (0,1)$ implies $\hat{\varepsilon}_2^f < \varepsilon_2^d$. Further, if domestic firms offshore, they only do so at an emissions price greater than $\hat{\varepsilon}_2^f$, which follows directly from the proof of Proposition 3. The result follows. $\square$

Proof of Proposition 3 Where $\hat{\alpha}_r$ and $\hat{\alpha}_o$ are the emissions intensity of domestic firms' preferred type within and outside the regulated region, without entry, the solution to $\hat{\varepsilon}_o$ is

$$\hat{\varepsilon}_o = \frac{(A - \hat{\gamma}_r)\hat{\alpha}_r - (A - \delta\hat{\gamma}_o - \tau)\hat{\alpha}_o}{\hat{\alpha}_r^2 - \hat{\alpha}_o^2} - \frac{\sqrt{((A - \delta\hat{\gamma}_o - \tau)\hat{\alpha}_r - (A - \hat{\gamma}_r)\hat{\alpha}_o)^2 - F_o b(N_d+1)^2(\hat{\alpha}_r^2 - \hat{\alpha}_o^2)}}{\hat{\alpha}_r^2 - \hat{\alpha}_o^2}, \tag{23}$$

while the solution with entry is

$$\hat{\varepsilon}_o = \frac{\delta\hat{\gamma}_o + \tau - \hat{\gamma}_r}{\hat{\alpha}_r - \hat{\alpha}_o} + \frac{\sqrt{b}(\sqrt{F_e} - \sqrt{F_e - F_o})}{\hat{\alpha}_r - \hat{\alpha}_o}. \tag{24}$$

Assume $\hat{\alpha}_r > \hat{\alpha}_o$ and $F_o = 0$. Then per (23) and (24), $\hat{\varepsilon}_o = (\delta\gamma_2 + \tau - \gamma_1)/(\alpha_1 - \alpha_2)$. $\hat{\alpha}_r < \hat{\alpha}_o$ is not feasible per the discussion in the proof of Proposition 2. Likewise, $\hat{\alpha}_r = \hat{\alpha}_o$ is infeasible through (23) and (24). Further, without and with entry, respectively, $\hat{\pi}_{d,o}(\cdot)$ is

$$\hat{\pi}_{d,o}(\cdot) = \frac{(A - (\delta\hat{\gamma}_o + \tau + \hat{\alpha}_o\varepsilon))^2}{(N_d+1)^2 b}, \qquad \text{and} \qquad \hat{\pi}_{d,o}(\cdot) = F_e.$$

If $F_o > \hat{\bar{F}}_o = \hat{\pi}_{d,o}(\cdot)$, then $\hat{\varepsilon}_o$ is infeasible through (23) and (24). (In the case without entry, $\hat{\varepsilon}_o$ is infeasible because (23) simplifies to $\hat{\varepsilon}_o > (A - \hat{\gamma}_r)/\hat{\alpha}_r$ when $F_o > \hat{\bar{F}}_o = \hat{\pi}_{d,o}(\cdot)$, implying $A - \hat{\gamma}_r - \hat{\alpha}_r\hat{\varepsilon}_o < 0$, which violates the profitability condition $A - \hat{\gamma}_r - \hat{\alpha}_r\varepsilon \ge 0$). Therefore, there exits a unique solution to $\hat{\varepsilon}_o$ iff $\hat{\varepsilon}_o \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ and $F_o \le \hat{\bar{F}}_o$, otherwise $\hat{\varepsilon}_o$ is infeasible. $\square$

Proof of Lemma 4 The proof for Lemma 4 is symmetric to that of Lemma 2 except that $\hat{c}_d(\varepsilon) = \hat{\gamma}_d + \hat{\alpha}_d\varepsilon$ when domestic firms produce in the regulated region, $\hat{c}_d(\varepsilon) = \delta\hat{\gamma}_d + \hat{\alpha}_d\varepsilon + \tau$ when they produce offshore, and $\hat{c}_f(\varepsilon) = \delta\hat{\gamma}_f + \hat{\alpha}_f\varepsilon + \tau$. $\square$

Region	$\hat{n}_d^*\hat{x}^*/\partial\varepsilon$	$\partial\hat{n}_f^*\hat{y}^*/\partial\varepsilon$	$\partial(\hat{n}_d^*\hat{x}^*+\hat{n}_f^*\hat{y}^*)/\partial\varepsilon$
Ω_1	$-\hat{\alpha}_d N_d/b(N_d+1)$	—	$-\hat{\alpha}_d N_d/b(N_d+1)$
$\Omega_2,\ \varepsilon\in[\hat{\varepsilon}_2^f,\hat{e}_2^d)$	$-(\alpha_1-\alpha_2)N_d/b$	$[(\alpha_1-\alpha_2)N_d-\alpha_2]/b$	$-\alpha_2/b$
$\Omega_2,\ \varepsilon\notin[\hat{\varepsilon}_2^f,\hat{e}_2^d)$	0	$-\hat{\alpha}_f/b$	$-\hat{\alpha}_f/b$
Ω_3	$-\alpha_2 N_d/b(N_d+1)$	—	$-\alpha_2 N_d/b(N_d+1)$
Ω_4	0	$-\alpha_2/b$	$-\alpha_2/b$

Proof of Proposition 4 Regarding Proposition 4a, per Lemma 4 and (8), $\hat{n}_d^*\hat{x}^*/\partial\varepsilon$, $\partial\hat{n}_f^*\hat{y}^*/\partial\varepsilon$, and $\partial(\hat{n}_d^*\hat{x}^*+\hat{n}_f^*\hat{y}^*)/\partial\varepsilon$ are characterized by market structure in the following table:

From the last column, $\partial(\hat{n}_d^*\hat{x}^*+\hat{n}_f^*\hat{y}^*)/\partial\varepsilon<0$ in each market structure. Proposition 4a follows.

Regarding Proposition 4b, $\partial\hat{y}^*/\partial\varepsilon=0$ under all market structures, which is made obvious through Lemma 4. Changes in total entry $\hat{n}_f^*\hat{y}^*$ wrt ε are therefore driven through changes in $\hat{n}_f^*$. By (8), $\partial\hat{n}_f^*/\partial\varepsilon=-\alpha_f/\sqrt{F_e b}$ if foreign and domestic firms operate identical technology. When foreign firms operate type 2 technology and domestic firms operate type 1, $\partial\hat{n}_f^*/\partial\varepsilon=[N_d\alpha_1-(N_d+1)\alpha_2]/\sqrt{F_e b}$, which is positive iff $\alpha_1>\alpha_2(1+1/N_d)$. $\square$

Proof of Lemma 5 The proof to Lemma 5 is symmetric to that of Lemma 3 except that the unique solution to $\hat{\varepsilon}_o$ without entry is given by (23), while it is given by (24) with entry, and where $\Delta=(A-\delta\gamma_2-\tau)\alpha_1-(A-\gamma_1)\alpha_2$,

$$\hat{Q}_o=\begin{cases}\frac{N_d(\Delta-\sqrt{\Delta^2-F_o b(N_d+1)^2(\alpha_1^2-\alpha_2^2)})}{(N_d+1)(\alpha_1+\alpha_2)b} & \text{if } \lim_{\varepsilon\to\hat{\varepsilon}_o^-} h(\varepsilon)\le 0\\ \frac{((N_d+1)\alpha_1-N_d\alpha_2)\sqrt{F_e b}-\alpha_2\sqrt{(F_e-F_o)b}-\Delta}{(\alpha_1-\alpha_2)b} & \text{if } h(\hat{\varepsilon}_o)<0<\lim_{\varepsilon\to\hat{\varepsilon}_o^-} h(\varepsilon)\\ 0 & \text{if } h(\hat{\varepsilon}_o)\ge 0.\end{cases}\qquad\square$$

Proof of Proposition 5 Per Lemma 4 and (8), the change in domestic and offshore emissions in ε are summarized in the following table:

Region	$\partial\hat{n}_d^*\hat{x}_r^*\hat{\alpha}_d/\partial\varepsilon$	$\partial(\hat{n}_d^*\hat{x}_o^*+\hat{n}_f^*\hat{y}^*)(\hat{\alpha}_f+\alpha_\tau)/\partial\varepsilon$
Ω_1	$-\hat{\alpha}_d^2 N_d/b(N_d+1)$	0
$\Omega_2,\ \varepsilon\in[\hat{\varepsilon}_2^f,\hat{e}_2^d)$	$-(\alpha_1-\alpha_2)N_d\alpha_1/b$	$((\alpha_1-\alpha_2)N_d-\alpha_2)(\alpha_2+\alpha_\tau)/b$
$\Omega_2,\ \varepsilon\notin[\hat{\varepsilon}_2^f,\hat{e}_2^d)$	0	$-\hat{\alpha}_f(\hat{\alpha}_f+\alpha_\tau)/b$
Ω_3	0	$-\alpha_2 N_d(\alpha_2+\alpha_\tau)/b(N_d+1)$
Ω_4	0	$-\alpha_2(\alpha_2+\alpha_\tau)/b$

It is clear that $\hat{\eta}^*$ strictly decreases in ε in all cases except Ω_2 when $\varepsilon\in[\hat{\varepsilon}_2^f,\hat{e}_2^d)$ where $\hat{\eta}^*$ decreases iff $(\alpha_1-\alpha_2-\alpha_\tau)(\alpha_1-\alpha_2)N_d+\alpha_2(\alpha_2+\alpha_\tau)>0$. The change in global emissions due to offshoring is $\hat{\varepsilon}^{\Delta}\left(\hat{n}_d^*\left[\lim_{\varepsilon\to\hat{\varepsilon}_o^-}\hat{x}_r^*(\varepsilon)\right]\right)+\hat{Q}_o(\alpha_2+\alpha_\tau)$, where $\hat{\varepsilon}^{\Delta}$ is the change in emissions intensity due to offshoring which is $-(\alpha_1-\alpha_2-\alpha_\tau)$. The condition of Proposition 5b follows directly. $\square$

Proof of Proposition 6 $\eta>\hat{\eta}$ is equivalent to

$$\left(n_d^*x_r^*\right)\alpha_d+\left(n_d^*x_o^*+n_f^*y^*\right)\left(\alpha_f+\alpha_\tau\right)>\left(\hat{n}_d^*\hat{x}_r^*\right)\hat{\alpha}_d+\left(\hat{n}_d^*\hat{x}_o^*+\hat{n}_f^*\hat{y}^*\right)\left(\hat{\alpha}_f+\alpha_\tau\right)\tag{25}$$

The following two lemmas facilitate the proof that (25) holds if $\Gamma_m\in\{\Gamma_2,\Gamma_3,\Gamma_4,\Gamma_5\}$.

Lemma 7. *If $\varepsilon > \varepsilon_{entry}$ and/or $\varepsilon > \varepsilon_o$ and $F_o < \overline{F}_o$, then total output with a border adjustment $\hat{T} = \hat{n}_d^* \hat{x}^* + \hat{n}_f^* \hat{y}^*$ is less than total output without border adjustment $T = n_d^* x^* + n_f^* y^*$.*

Proof of Lemma 7 Per Lemmas 1 and 2,

$$T = \begin{cases} N_d(A - \delta\gamma_1 - \tau)/b(N_d+1) & \text{if } \varepsilon > \varepsilon_o,\ \varepsilon_o \le \varepsilon_{entry} \text{ and } F_o < \overline{F}_o \\ (A - \sqrt{F_e b} - \delta\gamma_1 - \tau)/b & \text{if } \varepsilon > \varepsilon_{entry} \text{ and either } \varepsilon_{entry} < \varepsilon_o \text{ or } F_o \ge \overline{F}_o. \end{cases} \tag{26}$$

Further, through (8) and Lemma 4,

$$\hat{T} = \begin{cases} N_d(A - \delta\gamma_2 - \alpha_2\varepsilon - \tau)/b(N_d+1) & \text{if } \varepsilon > \hat{\varepsilon}_o,\ \hat{\varepsilon}_o \le \hat{\varepsilon}_{entry} \text{ and } F_o < \hat{\overline{F}}_o \\ (A - \sqrt{F_e b} - \delta\hat{\gamma}_f - \hat{\alpha}_f\varepsilon - \tau)/b & \text{if } \varepsilon > \hat{\varepsilon}_{entry} \text{ and either } \hat{\varepsilon}_{entry} < \hat{\varepsilon}_o \text{ or } F_o \ge \hat{\overline{F}}_o. \end{cases} \tag{27}$$

Define T_z and $\hat{T}_z$, $z \in \{1,2\}$, as the z^{th} case of (26) and (27), respectively. By Assumption 3, $\delta\gamma_1 + \tau < \delta\hat{\gamma}_f + \hat{\alpha}_f\varepsilon + \tau$, $\forall \varepsilon > 0$, therefore $T_1 > \hat{T}_1$ and $T_2 > \hat{T}_2$. Further, $T_1 > T_2$ iff $(N_d+1)\sqrt{F_e b} > A - \delta\gamma_1 - \tau$, which holds iff the conditions for T_1 apply (in turn implying $n_f^* > 0$ per Lemma 1 and $l^* = o$). Therefore, if $T = T_1$, then $T_1 > T_2$, and $T > \hat{T}$ by transitivity whether $\hat{T} = \hat{T}_1$ or $\hat{T} = \hat{T}_2$. Likewise, if $T = T_2$, then $T_2 > T_1$, and $T > \hat{T}$ by transitivity whether $\hat{T} = \hat{T}_1$ or $\hat{T} = \hat{T}_2$. ■

Lemma 8. *If $\varepsilon > \varepsilon_{entry}$ and/or $\varepsilon > \varepsilon_o$ and $F_o < \overline{F}_o$, then transport emissions under a border adjustment $\left(\hat{n}_d^* \hat{x}_o^* + \hat{n}_f^* \hat{y}^*\right)(\hat{\alpha}_f + \alpha_\tau)$ are less than transport emissions without border adjustment $\left(n_d^* x_o^* + n_f^* y^*\right)(\alpha_f + \alpha_\tau)$.*

Proof of Lemma 8 If $\Gamma_m \in \{\Gamma_3, \Gamma_4\}$, then $x_r^* = 0$ and, by Lemma 7, $T > \hat{T}$. $x_r^* = 0$ and $T > \hat{T}$ implies $\left(n_d^* x_o^* + n_f^* y^*\right)\alpha_\tau > \left(\hat{n}_d^* \hat{x}_o^* + \hat{n}_f^* \hat{y}^*\right)\alpha_\tau$. The proof if $\Gamma_m \in \{\Gamma_2, \Gamma_5\}$ follows. It is evident from (21) and (23) that $\partial(\hat{\varepsilon}_o - \varepsilon_o)/\partial F_o = \alpha_o\sqrt{b}/2\sqrt{F_e - F_o}(\alpha_r - \hat{\alpha}_o)\alpha_r > 0$, $\forall F_o \in [0, \overline{F}_o]$, and that $\partial(\hat{\varepsilon}_o - \varepsilon_o)/\partial^2 F_o = \alpha_o\sqrt{b}/4(F_e - F_o)^{3/2}(\alpha_r - \hat{\alpha}_o)\alpha_r > 0$, $\forall F_o \in [0, \overline{F}_o]$.[2] Therefore, $\hat{\varepsilon}_o - \varepsilon_o$ is convex increasing in F_o. It is also evident from (21) and (23) that, if $F_o = 0$, then $\hat{\varepsilon}_o = \varepsilon_o$. Therefore, $\hat{\varepsilon}_o > \varepsilon_o$, $\forall F_o \in (0, \overline{F}_o]$ and $l^* = r$ implies $\hat{l}^* = r$; equivalently, $x_o = 0$ implies $\hat{x}_o = 0$. Since $\varepsilon_2^d = \hat{\varepsilon}_2^d$, $l^* = r$ also implies $c_d(\varepsilon) = \hat{c}_d(\varepsilon)$. Therefore, per Lemma 1, and (8), if $l^* = r$ and $n_d^* = N_d$, then $n_f^* > \hat{n}_f^*$ iff $(\delta\hat{\gamma}_f + \hat{\alpha}_f\varepsilon) - \delta\gamma_1 > 0$, which holds by Assumption 3. If $n_d^* = 0$, then $T = n_f^* y^*$. $T > \hat{T} = \hat{n}_d^* \hat{x}^* + \hat{n}_f^* \hat{y}^*$ per Lemma 7. Therefore, if $l^* = r$ and $n_d^* = 0$, $n_f^* y^* > \hat{n}_f^* \hat{y}^*$. Therefore, $l^* = r$ implies $n_f^* y^* > \hat{n}_f^* \hat{y}^*$. As a consequence, $l^* = r$ implies $(n_d^* x_o^* + n_f^* y^*)\alpha_\tau > (\hat{n}_d^* \hat{x}_o^* + \hat{n}_f^* \hat{y}^*)\alpha_\tau$. ■

Over $\varepsilon \in [0, \min\{\varepsilon_o, \varepsilon_2^d\})$, $\alpha_d = \hat{\alpha}_d = \alpha_1$, while if $\varepsilon_2^d < \varepsilon_o$ then over $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$, $\alpha_d = \hat{\alpha}_d = \alpha_2$. If $\varepsilon > \varepsilon_o$ and $F_o < \overline{F}_o$ then $\alpha_d = \alpha_1$. Per Proposition 3, $\hat{\alpha}_d = \alpha_2$ if domestic firms offshore under border adjustment. By Proposition 2, $\hat{\alpha}_d \ge \hat{\alpha}_f$. $\alpha_f = \alpha_1$ always. Therefore, $\alpha_f \ge \alpha_d \ge \hat{\alpha}_d \ge \hat{\alpha}_f$.

If $\Gamma_m \in \{\Gamma_2, \Gamma_3, \Gamma_4, \Gamma_5\}$, then $T > \hat{T}$ by Lemma 7, and $(n_d^* x_o^* + n_f^* y^*)\alpha_\tau > (\hat{n}_d^* \hat{x}_o^* + \hat{n}_f^* \hat{y}^*)\alpha_\tau$ by Lemma 8 and the ordering $\alpha_f \ge \alpha_d \ge \hat{\alpha}_d \ge \hat{\alpha}_f$. Therefore, inequality (25) holds, proving $\hat{\eta} < \eta$.

---

[2] Recall that subscript r and o in (21) and (23) denote domestic firms' technology choice in the regulated and offshore region, respectively. Also recall that $\varepsilon_2^d = \hat{\varepsilon}_2^d$, therefore $\alpha_r = \hat{\alpha}_r$.

Proposition 6a follows from (25) and Lemma 7. Proposition 6b follows from (25) and Lemma 8. Under the conditions of Proposition 6c, $\hat{n}_f > 0$ and $\hat{\alpha}_f = \alpha_2$. Under the conditions of Proposition 6d, $l^* = o$, $\hat{l}^* = r$, $\alpha_d = \alpha_1$, and $\hat{\alpha}_d = \alpha_2$. Under the conditions of Proposition 6e, $\hat{l}^* = o$ and, by Proposition 3, $\hat{\alpha}_f = \alpha_2$. With (25) demonstrated to hold, Propositions 6c-e follow. $\square$

Proof of Proposition 7 It is sufficient to prove that, under the conditions of the proposition, there exists an interval in ε in which $\hat{\Pi} > \Pi$, another in which $\hat{\Pi} < \Pi$, and another in which $\hat{\Pi} = \Pi$.

From Lemma 1 and (8), $\hat{\varepsilon}_{entry} > \varepsilon_{entry}$. As demonstrated in the proof of Lemma 8, $\hat{\varepsilon}_o > \varepsilon_o$. Assume $\hat{\varepsilon}_{entry} < \varepsilon < \varepsilon_o$, or $\hat{\varepsilon}_{entry} < \varepsilon < \varepsilon_{exit}$ and $F_o > \max\{\overline{F}_o, \hat{\overline{F}}_o\}$. Then $l^* = \hat{l} = r$, $n_f^* > 0$, and $\hat{n}_f^* > 0$. By Lemmas 1, 2 and 4 and Equations (1), (5), and (8),

$$\Pi = N_d(\sqrt{F_e b} + \delta\gamma_1 + \tau - \gamma_d - \alpha_d\varepsilon)^2/b \quad \text{while} \quad \hat{\Pi} = N_d(\sqrt{F_e b} + \delta\hat{\gamma}_f + \hat{\alpha}_f\varepsilon + \tau - \hat{\gamma}_d - \hat{\alpha}_d\varepsilon)^2/b.$$

Since $\varepsilon_2^d = \hat{\varepsilon}_2^d$, $\gamma_d + \alpha_d\varepsilon = \hat{\gamma}_d + \hat{\alpha}_d\varepsilon$. Therefore, for any $\varepsilon > 0$, $\hat{\Pi} > \Pi$ by Assumption 3 (i.e., $\gamma_2 > \gamma_1$).

Assume $\hat{\varepsilon}_o \leq \varepsilon \leq \varepsilon_{entry}$ and $F_o < \min\{\overline{F}_o, \hat{\overline{F}}_o\}$. Then $l^* = \hat{l}^* = o$ and $n_f^* = \hat{n}_f^* = 0$. By Lemmas 1, 2 and 4 and Equations (1), (5), and (8),

$$\Pi = \frac{N_d(A - \delta\gamma_1 - \tau)^2}{(N_d + 1)^2 b} - N_d F_o \quad \text{while} \quad \hat{\Pi} = \frac{N_d(A - \delta\gamma_2 - \alpha_2\varepsilon - \tau)^2}{(N_d + 1)^2 b} - N_d F_o.$$

Therefore, $\hat{\Pi} < \Pi$ by Assumption 3.

Assume $\hat{\varepsilon}_{etnry} < \hat{\varepsilon}_o \leq \varepsilon$ and $F_o < \min\{\overline{F}_o, \hat{\overline{F}}_o\}$. Then $l^* = \hat{l}^* = o$, $n_f^* > 0$, and $\hat{n}_f > 0$. By Lemmas 1, 2 and 4 and Equations (1), (5), and (8) $\Pi = \hat{\Pi} = N_d(F_e - F_o)$. $\square$

B. Parameters for Numerical Illustrations

Figure(s)	A	b	n_d	γ_1	α_1	γ_2	α_2	F_e	F_o	δ	τ	α_τ
Figure 3a	110	.02	6	75	.70	85	.20	1000	-	.80	30	.15
Figure 3b	110	.02	3	75	.70	85	.20	1000	-	.80	30	.15
Figures 4a and 4b	120	.01	4	75	.70	85	.20	1000	600	.85	30	.15
Figure 5a	100	.05	4	50	.70	65	.20	5000	-	.75	15	.15
Figure 5b	100	.01	3	55	.78	65	.28	5000	-	.75	15	.15
Figure 6a	-	-	-	50	1.0	70	.20	-	-	.75	15	-
Figure 6b	-	-	-	50	1.0	70	.20	-	-	.80	15	-
Figures 7a and 7b	120	.01	4	50	.70	65	.20	1000	600	.80	15	.15

Table B.1 Market, cost, and emissions parameters used in numerical illustrations.

C. Global Emissions Comparative Statics by Market Structure

Market	Change in global emissions wrt ε driven by:	
structure	Carbon leakage through entry	Total output
Γ_1	0	$-N_d\alpha_d^2/b(N_d+1)$
Γ_2	$N_d(\alpha_1+\alpha_\tau-\alpha_d)\alpha_d/b$	0
Γ_3	0	0
Γ_4	0	0
Γ_5	0	0

Table C.1 Change in global emissions wrt emissions price by source (without border adjustment)

Market	Change in global emissions wrt ε driven by	
structure	Carbon leakage through entry	Total output
Ω_1	0	$-N_d\hat{\alpha}_d^2/b(N_d+1)$
$\Omega_2,\ \varepsilon\in[\hat{\varepsilon}_2^f,\hat{e}_2^d)$	$-N_d(\alpha_1-\alpha_2-\alpha_\tau)(\alpha_1-\alpha_2)/b$	$-\alpha_2(\alpha_2+\alpha_\tau)/b$
$\Omega_2,\ \varepsilon\notin[\hat{\varepsilon}_2^f,\hat{e}_2^d)$	0	$-\hat{\alpha}_f(\hat{\alpha}_f+\alpha_\tau)/b$
Ω_3	0	$-N_d\alpha_2(\alpha_2+\alpha_\tau)/b(N_d+1)$
Ω_4	0	$-\alpha_2(\alpha_2+\alpha_\tau)/b$

Table C.2 Change in global emissions wrt emissions price by source (with border adjustment)