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# **Carbon Tariffs: Effects in Settings with Technology Choice and Foreign Comparative Advantage**

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# Carbon Tariffs: Effects in Settings with Technology Choice and Foreign Comparative Advantage

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Carbon regulation is intended to reduce global emissions, but there is growing concern that such regulation may simply shift production to unregulated regions and increase global emissions in the process. Carbon tariffs have emerged as a possible mechanism to address these concerns by imposing carbon costs on imports at the regulated region's border. I show that, when firms choose from discrete production technologies and offshore producers hold a comparative cost advantage, carbon leakage can result despite the implementation of a carbon tariff. In such a setting, foreign firms adopt clean technology at a lower emissions price than firms operating in the regulated region, with foreign entry increasing only over emissions price intervals within which foreign firms hold this technology advantage. Further, domestic firms are shown to conditionally offshore production despite the implementation of a carbon tariff, adopting cleaner technology when they do so. As a consequence, when carbon leakage does occur under a carbon tariff, it conditionally *decreases* global emissions. Three sources of potential welfare improvement realized through carbon tariffs require both foreign comparative advantage and endogenous technology choice, underscoring the importance of considering both in value assessments of such a policy.

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## 1. Introduction

With carbon regulation driving projected production cost increases in excess of 40% in some industries (Drake et al. 2010, Ryan 2012), such policies endow facilities located outside the regulated region with a windfall cost advantage, altering the competitive landscape. This cost advantage enables competitors outside the regulated region (i.e., “foreign” firms) to increase their penetration into the regulated (i.e., “domestic”) region. Further, such policies can 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 domestic production and its associated carbon emissions to offshore locations as a result of climate change policy – which has been shown to erode emissions improvements resulting from such policy.

Carbon leakage could potentially be mitigated by *border adjustments* – tariffs on the carbon content of imported goods that would incur carbon-costs if produced domestically. Proponents of border adjustments, including the authors of the Waxman-Markey bill that passed through the U.S. House of Representatives (U.S. Congress, House 2009), argue that such a measure would level the playing field by treating domestic and offshore production equivalently. Opponents, including

President Obama (Broder 2009, June 28), argue that border adjustments can be interpreted as a trade barrier and therefore risk sparking trade disputes. Such a policy is also debated in Europe and Australia where unilateral emissions regulation currently in place is perceived to threaten the regional economy (e.g., HeidelbergCement 2008, Carmody 2011, March 2).

It is well-established within the literature that, without a border adjustment, carbon leakage increases global emissions, offsetting some or all of the regulation's emission improvements (e.g., Babiker 2005, Demailly and Quirion 2006, Ponsard and Walker 2008, Di Maria and van der Werf 2008, Fowlie 2009). It is a widely held belief among policymakers and practitioners that the implementation of a symmetric border adjustment will eliminate the threat of leakage (e.g., Barry 2009, December 21; Barber 2010, April 15). Developing a model of imperfect competition between domestic and foreign firms that choose from discrete production technologies, I show that a symmetric border adjustment does not, in general, eliminate carbon leakage from foreign entry or offshoring. Rather, when foreign firms hold a comparative cost advantage, they adopt clean technology at a lower emissions price than domestic firms, and entry conditionally increases in emissions price intervals in which foreign firms hold this advantage. Further, conditions are established under which domestic firms shift production offshore despite a border adjustment, adopting cleaner technology when they do so. As a consequence, when carbon leakage does occur under a border adjustment, it conditionally *decreases* global emissions, in sharp contrast to the increased emissions resulting from leakage without a border adjustment.

A border adjustment is shown to increase welfare, providing greater advantage at higher social costs of carbon. Four conditional sources of welfare advantage are identified: 1) the preservation of domestic firm profits by reducing or limiting foreign entry; 2) cleaner entry due to the adoption of lower emissions technology by foreign firms; 3) cleaner domestic production in settings in which incentivizing the adoption of clean technology through emissions regulation is not possible without a border adjustment; and 4) cleaner offshoring by domestic firms. The latter two sources of welfare advantage are mutually exclusive. Only the first source is accounted for without technology choice, underscoring the importance of incorporating that choice into border adjustment welfare analysis.

While border adjustment provides clear advantages, it also raises issues. The welfare-maximizing emissions price in some settings results in the adoption of clean technology by foreign firms, but not by domestic firms. In other settings, the welfare-maximizing emissions price under border adjustment, in equilibrium, eliminates foreign entry that would exist if emissions were unregulated. Both of these outcomes lend credence to claims that a border adjustment could prove anticompetitive.

## 2. Relation to the Literature

Within the Policy literature, leakage is largely taken as a foregone outcome of the current plans for the EU-ETS post-2012, when the free allocation of emissions allowances expires (e.g., van Asselt

and Brewer 2010, Kuik and Hofkes 2010, Monjon and Quirion 2010). Therefore, a key issue in this literature relates to the legality of border adjustments as a leakage-mitigating mechanism under WTO and the General Agreement on Tariffs and Trade (GATT) law (e.g., Grubb and Neuhoff 2006, van Asselt and Biermann 2007, de Cendra 2006). Most conclude that border adjustments are legal, conditional on the elimination of the free allocation of allowances (Grubb and Neuhoff 2006, de Cendra 2006). Others conclude that border adjustments may only be legal for inputs directly incorporated into finished goods, such as clinker into cement (Biermann and Brohm 2005, van Asselt and Biermann 2007). In terms of border adjustment design, Grubb and Neuhoff (2006) propose a symmetric tariff so that imports would incur the same carbon cost that they would have incurred had they been produced domestically. Ismer and Neuhoff (2007), on the other hand, propose a flat carbon cost based on the emissions intensity of the “best available technology.”

Also within the Policy literature, Demailly and Quirion (2006) simulate the impact of cap-and-trade emissions allowance allocation methods on the EU cement sector to determine leakage effects. Similarly, Ponsard and Walker (2008) numerically estimate leakage within EU cement under full cap-and-trade allowance auctioning. While both studies are based on Cournot competition (the method employed in the present paper), neither addresses the issues of border adjustment, technology choice or the potential for EU firms to shift production offshore. Lockwood and Whalley (2010) note that, within the Policy literature, the border adjustment debate has centered primarily on the legality issues related to WTO and GATT, with little work focusing on the policy’s impact.

Technology innovation and adoption in response to environmental regulation has been a focal interest in Environmental Economics, with Jaffe et al. (2002) and Popp et al. (2009) providing thorough reviews. However, the studies reviewed and the majority of the technology innovation and adoption literature in Environmental Economics do not address carbon leakage or border adjustment, which are of primary interest here. Requate (2006) reviews the literature pertaining to environmental policy under imperfect competition, with the vast majority of the studies considering homogeneously regulated firms without technology choice. Of the exceptions, Bayindir-Upmann (2004) considers imperfect competition under an environmental tax imposed on a fixed number of exogenously dirty firms, but does not consider border adjustment or technology choice.

Within the Economics literature that studies carbon leakage, most focuses on leakage due only to foreign entry (e.g., Di Maria and van der Werf 2008, Fowlie 2009). Di Maria and van der Werf (2008) study leakage through an analytical model of imperfect competition between two asymmetrically regulated regions, showing that a regulated region’s ability to change technology attenuates leakage effects. Fowlie (2009) studies leakage under imperfect competition when firms operate different but exogenous technologies, finding that leakage eliminates two-thirds of the emissions reduction that could be obtained by a uniform policy. Babiker (2005) considers leakage in terms of both entry

and offshoring in a numerical study, finding that asymmetric emissions regulation *increases* global emissions by 30% as a result of leakage. Of these studies, none consider border adjustments or endogenize the number of foreign entrants and only Di Maria and van der Werf (2008) allow for technology choice. Also in the economics literature, Ryan (2012) studies emissions regulation as it relates to the U.S. cement industry, estimating a structural model that endogenizes firm entry, exit, and capacity decisions with a given technology. However, Ryan (2012) does not explore leakage, border adjustment, or technology choice – all of which are central to the present paper.

Within the Operations Management (OM) literature, Krass et al. (2010) and Drake et al. (2012) both consider technology choice under emissions regulation in noncompetitive settings. Zhao et al. (2010) explores the impact of allowance allocation schemes on technology choice in electric power markets, assuming a fixed number of competitors facing a uniform regulatory environment. Islegen and Reichelstein (2011) estimate break-even points for the adoption of carbon capture and storage in power generation. However, foreign entry, offshoring and asymmetric emissions regulation, which are of primary interest in the present paper, are not considered (or pertinent) in their context.

This paper makes significant contributions to the Sustainable OM and Environmental Economics literature by including technology choice and endogenous entry to explore the effects of emissions regulation with and without border adjustment. Incorporating these elements along with comparative advantage provides a number of important insights, including the centrality of technology choice in determining foreign entry and offshoring under a border adjustment. As a consequence of firms' technology-choice-driven entry and offshoring decisions, carbon leakage is shown to conditionally *decrease* global emissions, which contrasts the strict increase reported in the existing literature. Clean technology adoption is also shown to conditionally drive three sources of border adjustment welfare advantage, which are not accounted for without endogenous technology choice.

### 3. 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. While this section is framed for the setting with no border adjustment, the model explored here also supports a flat carbon tariff, such as a tariff based on the best available technology as proposed by Ismer and Neuhoff (2007). A flat carbon tariff is independent of the technology with which imports are produced with, and therefore does not incent technology change among foreign firms. Such a tariff could be incorporated into transport costs, with the results of this section holding.

#### 3.1. Model development

A regulator imposes an emissions price  $\varepsilon$  for each unit of emissions generated through domestic production. A set of domestic firms  $\mathcal{N}_d = \{1, \dots, n_d\}$  engages in Cournot competition with a set of

foreign firms  $\mathcal{N}_f = \{0, \dots, n_f\}$ .<sup>1</sup> Each domestic firm  $i \in \mathcal{N}_d$  chooses a production location,  $l \in \mathcal{L} = \{d, o\}$ , where  $d$  indicates domestic production and  $o$  indicates offshore production. The domestic market is assumed to be mature prior to the implementation of emissions regulation, which is the case for emissions-regulated sectors (e.g., cement, steel, glass, and pulp and paper), with the  $n_d$  firms strategically committed to serving the region. Foreign firm  $j \in \mathcal{N}_f$  enters the domestic market only if it can earn at least operating profit  $F > 0$ , where  $F$  represents a fixed entry cost. Each unit imported into the domestic market incurs transport cost  $\tau > 0$ .

Both domestic and foreign firms choose a production technology  $k \in \{1, 2\}$ , with unit production and capital recovery cost  $\gamma_k > 0$  and “Scope 1” emissions intensity  $\alpha_k \geq 0$ .<sup>2</sup> Wlog, technology 1 is assumed to be more emissions-intensive than technology 2,  $\alpha_1 > \alpha_2$ . Offshore production generates an additional  $\alpha_\tau > 0$  emissions per unit through transport. A discount factor  $\delta$  is the relative difference in production and capital recovery cost between offshore and domestic regions (due to differences in labor and other input costs).

Three assumptions are made with respect to technology costs:

*ASSUMPTION 1. The production and capital recovery cost for a given technology is less in exporting regions than in the domestic region;  $\delta \in (0, 1)$  so that  $\delta\gamma_i < \gamma_i, \forall i \in \{1, 2\}$ .*

This assumption follows from the significant labor cost advantage of exporting regions relative to importing regions of interest in emissions regulation contexts – e.g., the average hourly manufacturing labor cost in China is roughly 3-4% of U.S. and European levels (Banister and Cook 2011), and the equivalent cost in Mexico is less than 18% of U.S. and European levels (U.S. Bureau of Labor Statistics 2010).

*ASSUMPTION 2. The production and capital recovery cost of the dirty technology is less than the production and capital recovery cost of the clean technology;  $\gamma_1 < \gamma_2$ .*

If either type were dominated in both production and capital recovery cost as well as emissions intensity, firms’ would not consider it. The focus here is on settings where firms have a technology choice. Therefore, given  $\alpha_1 > \alpha_2$ , Assumption 2 ensures that technology 1 is not trivially discarded.

*ASSUMPTION 3. The domestic production cost of the dirty technology is less than the transport plus offshore production cost of the dirty technology;  $\gamma_1 < \delta\gamma_1 + \tau$ .*

<sup>1</sup> As Fowlie (2009) points out, empirical work suggests that firm behavior in emissions-intensive industries comports with static, oligopolistic competition in quantities.

<sup>2</sup> The Greenhouse Gas Protocol defines Scope 1 emissions as resulting from a firm’s direct activities. These exclude emissions from purchased electricity (Scope 2) and supplier activities (Scope 3). The emissions regulated under existing policy are Scope 1. Since power generation is a regulated sector under existing policy (e.g., European Parliament and Council 2003, Australian Government 2011), including purchased electricity would double-count those emissions.

Under this assumption, domestic firms produce locally when emissions are unregulated. While this assumption will not hold for all sectors in the general economy, it is reasonable for carbon-regulated sectors. Without such an assumption, there would be no domestic production to regulate.

Each firm selects the lowest-cost technology available, with  $c_i(\varepsilon)$  representing the total unit cost of domestic firms' preferred technology, and  $c_j$  representing the total unit cost of foreign firms' preferred technology, such that

$$c_i(\varepsilon) = \min_{k \in \{1,2\}} \{\gamma_k + \alpha_k \varepsilon, \delta \gamma_k + \tau\}, \quad \forall i \in \mathcal{N}_d \quad \text{and} \quad c_j = \min_{k \in \{1,2\}} \delta \gamma_k + \tau, \quad \forall j \in \mathcal{N}_f.$$

For ease of exposition, the unit production cost and the emissions intensity of domestic firms' preferred technology will be referred to as  $\gamma_i$  and  $\alpha_i$ , respectively. Similarly,  $\gamma_j$  and  $\alpha_j$  will refer to the unit production cost and emissions intensity, respectively, of foreign firms' preferred technology.

Table 1 summarizes cost and emissions parameters.

Parameter	Description
$\varepsilon$	Price per unit of CO <sub>2</sub> emissions
$\tau$	Transport cost per finished good unit
$F$	Fixed entry cost (e.g, domestic headquarters, customer acquisition)
$\gamma_i, \gamma_j$	Domestic and foreign firms' production and capital recovery cost
$\alpha_i, \alpha_j$	Emissions intensity of domestic and foreign firms' preferred technology
$\alpha_\tau$	Emissions intensity of transport
$\delta$	Discount factor for offshore production
$c_i(\varepsilon)$	Total unit cost of domestic firms' preferred technology
$c_j$	Total unit cost of foreign firms' preferred technology

**Table 1** Cost and emissions parameters in setting without border adjustment

Domestic firm  $i$  produces  $x_{i,l}$  units with its preferred technology/location option, with total domestic production  $X_d = \sum_{i=1}^{n_d} x_{i,d}$  and total production offshored by domestic producers  $X_o = \sum_{i=1}^{n_d} x_{i,o}$ . Foreign firm  $j$  produces  $y_j$  units with its preferred technology, with total production by foreign entrants  $Y = \sum_{j=1}^{n_f} y_j$ . The market is assumed to clear at price  $P(X_d, X_o, Y) = A - b(X_d + X_o + Y)$ , with  $A > n_d c_i(\varepsilon)$  to avoid the trivial case where no competitor produces, and with  $b > 0$ .<sup>3</sup> Therefore, domestic firm  $i$  solves

$$\begin{aligned} \max_{x_{i,l}} \pi_i(X_d, X_o, Y) &= \max_{x_{i,l}, \forall l \in \mathcal{L}} \sum_{l \in \mathcal{L}} \left[ P(X_d, X_o, Y) x_{i,l} - c_i(\varepsilon) x_{i,l} \right], \quad \forall i \in \mathcal{N}_d \\ \text{s.t.} \quad x_{i,l} &\geq 0, \quad \forall i \in \mathcal{N}_d, \quad l \in \mathcal{L}, \end{aligned} \quad (1)$$

while foreign competitor  $j$  solves

$$\begin{aligned} \max_{y_j} \pi_j(X_d, X_o, Y) &= \max_{y_j} \left[ P(X_d, X_o, Y) y_j - c_j y_j \right], \quad \forall j \in \mathcal{N}_f \\ \text{s.t.} \quad y_j &\geq 0, \quad \forall j \in \mathcal{N}_f. \end{aligned} \quad (2)$$

All proofs, including the joint concavity of (1) and (2), are provided in Technical Appendix T.1.

<sup>3</sup> Given the highly-commoditized nature of emissions-regulated sectors (e.g., power generation, cement, steel, lime, and pulp and paper), I assume that demand is homogenous with respect to production technology and location.



*Sunk capacity, demand uncertainty and capacity constraints.* I study the long-term equilibrium, focusing on effects of emissions regulation and border adjustment at steady state. This abstracts from the issue of sunk capacity, which could effect emissions and potentially total output in the short-run. Emissions would be greater in the short-run (vis-a-vis the long-run equilibrium) if firms' adopt clean technology in the long-run, unless emissions price were sufficiently great to cause firms to forego the remaining useful life of legacy capacity. On the other hand, if offshoring occurs in the long-run equilibrium, sunk capacity would delay this shift and emissions would be less in the short-run without border adjustment, but greater with it (vis-a-vis the long-run equilibrium). Since short-run marginal costs are less than the production and capital recovery costs pertinent in the long-run, emissions and total output would be greater in the short-run if firms had over-invested in capacity relative to the long-run equilibrium, which is less likely in sectors with positive growth.

I also abstract from demand uncertainty, and with it, capacity constraints. If these elements were incorporated, capacity that could serve both the offshore market (which is not pertinent in the deterministic setting) and the domestic market would profit from demand pooling – a reduction in overage and underage costs – with this effect decreasing in the correlation of domestic and offshore demand. To the extent that the deterministic setting reflects expected demand under uncertainty, total output and global emissions would be over-stated in the deterministic setting relative to expectations under uncertainty due to the right-censoring effect of capacity constraints. Further, if foreign firms adopt clean technology to serve the domestic market in equilibrium, overage could be used to serve the offshore market; a clean spill-over effect that would diminish with positive correlation between domestic and offshore demand.

### 3.2. Equilibrium technology choice and foreign entry

**COROLLARY 1.** *Clean technology will not be adopted at any  $\varepsilon$  if  $\tau < \gamma_2 - \delta\gamma_1 + \alpha_2 \left( \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} \right)$ .*

It follows from Assumption 2 that, without a border adjustment, foreign firms will not adopt clean technology in equilibrium. In terms of domestic firms, if the condition in Corollary 1 does not hold, then they would produce in the regulated region and adopt clean technology at the emissions price threshold  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ , which is derived by a cost comparison of type 1 and type 2. However, if the condition does hold, then the emissions price at which domestic firms would shift production offshore  $\varepsilon_o = \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$  is less than  $\varepsilon_2^d$ . In such a case, domestic firms would not adopt clean technology at any emissions price; it would be more profitable for them to operate dirty technology offshore than produce domestically. Under these conditions, a regulator could not incentivize clean technology adoption through emissions regulation without border adjustment.

The number of foreign firms entering the domestic market will depend on the number of domestic competitors already established in the market, their cost structure and market parameters. Firms

are assumed to compete operating profits down to the minimum level that motivates entry; that is,  $\max\{0, n_f | \pi_j^*(X_d, X_o, Y) = F\}$ . The following proposition characterizes equilibrium entry:

PROPOSITION 1. *Without border adjustment, the number of foreign firms entering the market is*

$$n_f^* = \max \left\{ 0, \frac{A - \delta\gamma_1 - \tau - n_d(\delta\gamma_1 + \tau - c_i(\varepsilon))}{\sqrt{Fb}} - n_d - 1 \right\}.$$

Under conditions such that domestic firms shift production offshore (i.e.,  $c_i(\varepsilon) = c_j$ ), the number of foreign entrants is independent of emissions price. On the other hand, if offshoring does not occur in equilibrium, the number of foreign firms competing in the domestic market increases in emissions price at a rate of  $\frac{n_d\alpha_i}{\sqrt{Fb}}$ . The latter is the scenario currently playing out within the European cement industry. Historically, significant transport costs led to large total landed costs for foreign competitors relative to domestic firms,  $c_j > c_i(0)$ . This limited entry by foreign competitors, with one study of the U.S. cement market reporting that 99.8% of cement was transported less than 500 miles (Jans and Rosenbaum 1997). However, with emissions costs under the EU-ETS threatening to dominate transport costs, European cement firms now see foreign producers as an existential threat to the continued production of cement within the EU (HeidelbergCement 2008).

### 3.3. Equilibrium quantities and emissions

As the purported driver of anthropogenic climate change, global emissions are relevant to the domestic regulator. Domestic emissions are also relevant if the regulator itself is exposed to emissions costs through Kyoto Protocol (or similar) commitments. Global emissions,  $e^g$ , and domestic emissions,  $e^d$ , are respectively defined as

$$e^g(X_d, X_o, Y) = X_d\alpha_i + X_o(\alpha_i + \alpha_\tau) + Y(\alpha_j + \alpha_\tau) \quad \text{and} \quad e^d(X_d) = X_d\alpha_i. \quad (3)$$

Analysis is organized here and in Section 4.3 based on the market structure that results under emissions regulation: a domestic oligopoly; foreign entry with domestic firms producing in the regulated region; and the offshoring of domestic production (with or without foreign entry).

#### 3.3.1. Domestic oligopoly

PROPOSITION 2. *Assume  $n_f^* = 0$  and  $\varepsilon < \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ . In equilibrium, a domestic oligopoly results with quantities of  $x_{i,d}^* = \frac{A - \gamma_i + \alpha_i\varepsilon}{b(n_d + 1)}$  and  $y_j^* = 0$ .*

From Proposition 1, it follows that foreign firms will not enter; that is  $n_f^* = 0$  if emissions price is less than the threshold  $\varepsilon_{enter} = \frac{(n_d + 1)(\delta\gamma_1 + \tau + \sqrt{Fb}) - n_d\gamma_i - A}{n_d\alpha_i}$ . Domestic firms produce in the regulated region if emissions price is less than the offshoring threshold  $\varepsilon_o = \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ . Under these conditions, a domestic oligopoly results, with domestic firms producing at quantities resembling well-known Cournot oligopoly quantities. In this setting, domestic quantities and total output, as well as domestic and global emissions, all trivially decrease in emissions price and decrease discontinuously at the threshold of clean technology adoption  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ , if  $\varepsilon_2^d \in [0, \varepsilon_{enter}]$ .

### 3.3.2. Foreign entry without offshoring

PROPOSITION 3. Assume  $n_f^* > 0$  and  $\varepsilon < \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ . In equilibrium,

- a) Foreign entry results with quantities  $x_{i,d}^* = \frac{\sqrt{Fb}}{b} + \frac{\delta\gamma_1 + \tau - \gamma_i - \alpha_i \varepsilon}{b}$  and  $y_j^* = \frac{\sqrt{Fb}}{b}$ .
- b) Foreign entry strictly increases in  $\varepsilon$ , while domestic quantities strictly decrease in  $\varepsilon$ .
- c) Total output is fixed in  $\varepsilon$ .
- d) Domestic emissions strictly decrease in  $\varepsilon$ , while global emissions strictly increase in  $\varepsilon$ .

With domestic firms producing in the regulated region, foreign entry occurs when  $\varepsilon \in [\varepsilon_{enter}, \varepsilon_o)$ . If this interval is null,  $\varepsilon_{enter} > \varepsilon_o$ , then entry will not arise in equilibrium at any emissions price. Given that  $\varepsilon \in [\varepsilon_{enter}, \varepsilon_o)$ , domestic firm  $i$ 's production exceeds foreign firm  $j$ 's since  $\gamma_i + \alpha_i \varepsilon < \delta\gamma_1 + \tau$  when there is not offshoring. Total domestic production decreases with respect to emissions price at rate  $-\frac{n_d \alpha_i}{b}$ . As noted in the discussion of Proposition 1, the number of foreign entrants increases in emissions price at a rate of  $\frac{n_d \alpha_i}{\sqrt{Fb}}$ . Given each foreign firm's equilibrium production,  $y_j^* = \frac{\sqrt{Fb}}{b}$ , total foreign production increases at a rate of  $\frac{n_d \alpha_i}{b}$  in emissions price. Therefore, total output in the sector is independent of emissions price in this setting, with decreases in domestic output balanced by equal increases in foreign entry. Propositions 3a-c are robust to shifts in domestic technology. If domestic firms adopt cleaner technology in equilibrium, the shift in market share toward foreign firms in  $\varepsilon$  is attenuated (since  $\alpha_2 < \alpha_1$ ), but holds directionally. Given that total production remains unchanged when there is leakage due to entry, the shift from domestic to foreign production results in a strict increase in global emissions since  $\alpha_i \leq \alpha_j = \alpha_1$  (per Proposition 1) and  $\alpha_\tau > 0$ .

### 3.3.3. Offshoring with and without foreign entry

PROPOSITION 4. Assume  $\varepsilon \geq \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ . In equilibrium,

- a) Domestic firms shift production offshore with domestic and foreign firm quantities of

$$x_{i,o}^* = \begin{cases} \frac{A - \delta\gamma_1 - \tau}{b(n_d + 1)} & \text{if } \varepsilon_{enter} \geq \varepsilon_o \\ \frac{\sqrt{Fb}}{b} & \text{otherwise} \end{cases} \quad \text{and} \quad y_j^* = \begin{cases} 0 & \text{if } \varepsilon_{enter} \geq \varepsilon_o \\ \frac{\sqrt{Fb}}{b} & \text{otherwise.} \end{cases}$$

- b) Foreign entry and domestic quantities are fixed in  $\varepsilon$ .
- c) Global emissions strictly increase as a consequence of offshoring.

When  $\varepsilon \geq \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ , it is more profitable for domestic firms to operate offshore with technology 1 than to produce with the lowest-cost technology in the regulated region. If domestic firms produce offshore, emissions regulation no longer affects their costs. Therefore, if  $\varepsilon_{enter} \geq \varepsilon_o$ , foreign entry will not result as a consequence of carbon regulation at any emissions price. Under such an offshore oligopoly, domestic firm quantities resemble well-known Cournot oligopoly quantities. However, if  $\varepsilon_{enter} < \varepsilon_o$ , domestic and foreign firms each produce quantities of  $\frac{\sqrt{Fb}}{b}$ .

Without a border adjustment, domestic and foreign quantities are independent of  $\varepsilon$  at any  $\varepsilon \geq \varepsilon_o$ . The regulator therefore has limited ability to impact global emissions. Increasing emissions price beyond  $\varepsilon_o$  yields no incremental emissions reduction. Further, the domestic offshoring that results if  $\varepsilon > \varepsilon_o$  increases emissions intensity; domestic firms use the dirtiest technology when producing offshore and generate  $\alpha_\tau$  in transport emissions by importing into the domestic region.

### 3.4. Discussion of results

Figures 1a and 1b illustrate quantity and entry results from Propositions 2-4. Parameters for all numerical illustrations are provided in Appendix A.

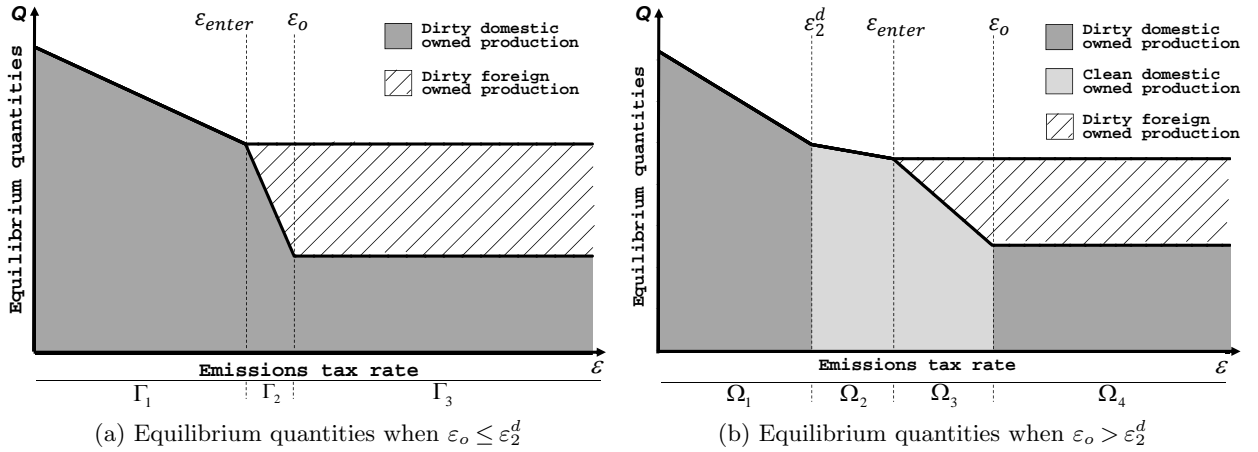


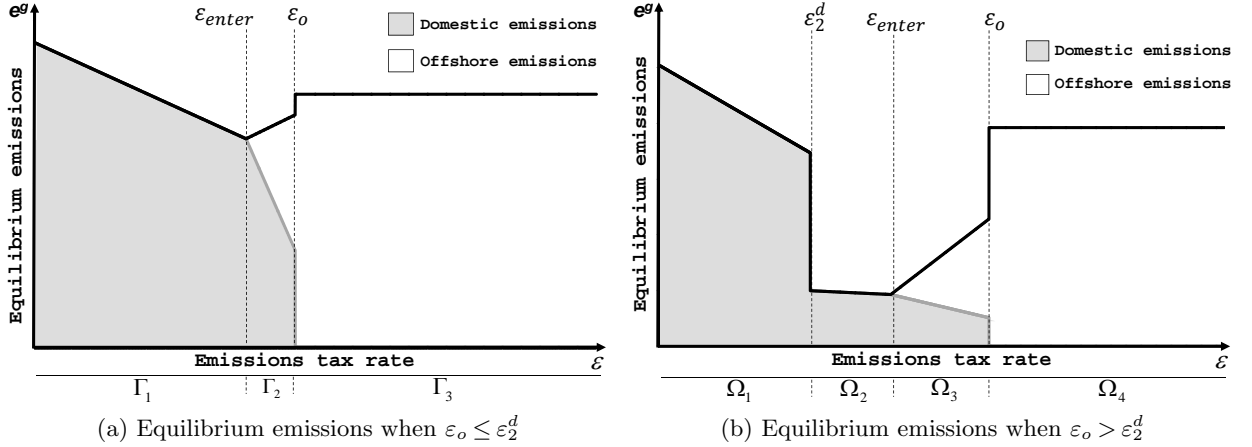
Figure 1 Illustrative examples of equilibrium quantities sensitivity to emissions price without border adjustment

In Figure 1a, there is a domestic oligopoly over the interval  $\Gamma_1$ , with production decreasing in  $\varepsilon$ . At point  $\varepsilon_{enter} = \frac{(n_d+1)(\delta\gamma_1+\tau+\sqrt{Fb})-n_d\gamma_i-A}{n_d\alpha_i}$ , entry conditions are satisfied. Therefore, foreign entry increases in  $\varepsilon$  over  $\Gamma_2$  per Proposition 3b, while domestic quantities decrease, with total output constant in  $\varepsilon$  over the interval. Point  $\varepsilon_o = \frac{\delta\gamma_1+\tau-\gamma_i}{\alpha_i}$  indicates the offshoring threshold, beyond which both domestic- and foreign-owned capacity operate outside the regulated region and are fixed in  $\varepsilon$  per Proposition 4b. Figure 1b is similar except  $\varepsilon_2^d < \varepsilon_o$ , where  $\varepsilon_2^d = \frac{\gamma_2-\gamma_1}{\alpha_1-\alpha_2}$ . The lower emissions intensity of technology 2 decreases exposure to emissions price, which reduces the rate at which domestic production decreases in intervals  $\Omega_2$  and  $\Omega_3$ , and decreases the rate at which foreign firms enter in  $\Omega_3$ . Per Proposition 3c, total output is constant in  $\varepsilon$  over  $\Omega_3$ . These results imply that domestic firms' production decreases monotonically in emissions price without a border adjustment, while foreign entry monotonically increases.

Emissions regulation without border adjustment limits the policy's ability to impact global emissions. Increases in emissions price beyond  $\varepsilon_o$  incentivize no response from competitors in terms of output or technology choice since all production takes place offshore. The issue of an industry offshoring *en masse* as a consequence of carbon costs is not purely of academic interest. Studies

of the European cement industry suggest that all production in Italy, Greece, Poland, and the United Kingdom would shift offshore at an emissions price of 25 Euro per ton of CO<sub>2</sub> – less than the projected emissions costs under EU-ETS Phase III – with this offshoring increasing global emissions by an estimated minimum of 7 million tons of CO<sub>2</sub> (Boston Consulting Group 2008).

Emissions effects are illustrated in Figures 2a and 2b, but are more pronounced in Figure 2b, where leakage implies a shift from technology 2 production to technology 1 production.



**Figure 2** Illustrative examples of global emissions sensitivity to emissions price without border adjustment.

In settings within which domestic firms produce locally,  $\varepsilon < \varepsilon_o$ , increases in emissions price beyond  $\varepsilon_{enter}$  lead to the counterintuitive effect of increasing global emissions despite reductions in domestic emissions. Under such circumstances, a portion of domestic production is displaced by offshore production that is more emissions-intensive (when transport is taken into account). As a consequence, the only interval over emissions prices in which the regulator can reduce *global* emissions without a border adjustment is in the case of a domestic oligopoly.

#### 4. 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 environmental effects of carbon leakage. It is therefore important to understand how border adjustments impact technology choices, production decisions, and regional competitiveness. Border adjustments are explored here through symmetric carbon costs for domestic and offshore goods production.<sup>4</sup>

<sup>4</sup>Grubb and Neuhoff (2006) argue that a “symmetric” border adjustment is nondiscriminatory and therefore the most likely to be feasible under WTO and GATT law (given the elimination of freely-allocated emissions allowances).

#### 4.1. Model development

The model here resembles that in Section 3 except that each imported unit now incurs a border adjustment  $\beta_k = \alpha_k \varepsilon \forall k \in \{1, 2\}$ . Hat notation distinguishes parameters of firms' preferred technology when a border adjustment is in place from those when it is not, with  $\hat{c}_i(\varepsilon)$  and  $\hat{c}_j(\varepsilon)$  representing the total cost of domestic and foreign firms' preferred technology, respectively:

$$\hat{c}_i(\varepsilon) = \min_{k \in \{1, 2\}} \{\gamma_k + \alpha_k \varepsilon, \delta \gamma_k + \beta_k(\varepsilon) + \tau\}, \quad \forall i \in \mathcal{N}_d \quad \text{and} \quad \hat{c}_j(\varepsilon) = \min_{k \in \{1, 2\}} \{\delta \gamma_k + \beta_k(\varepsilon) + \tau\}, \quad \forall j \in \mathcal{N}_f.$$

Similarly,  $\hat{\gamma}_i$ ,  $\hat{\alpha}_i$ ,  $\hat{\gamma}_j$ , and  $\hat{\alpha}_j$  denote the production cost and emissions efficiency of domestic and foreign firms' preferred technology. In a border adjustment setting, domestic and foreign firms solve objectives (1) and (2), respectively, after substituting  $\hat{c}_i(\varepsilon)$  for  $c_i(\varepsilon)$  and  $\hat{c}_j(\varepsilon)$  for  $c_j(\varepsilon)$ .

#### 4.2. Equilibrium technology choice and foreign entry

A border adjustment significantly affects technology adoption for both domestic and foreign firms, which the following proposition makes evident.

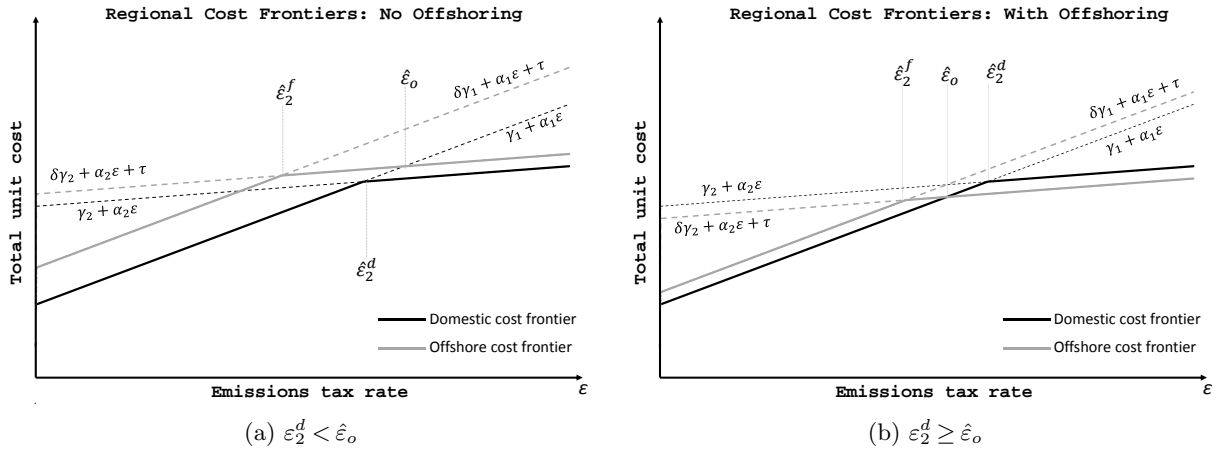
**PROPOSITION 5.** *In equilibrium, a) There is an  $\varepsilon$  at which domestic firms adopt clean technology; b) conditional on entry, foreign firms adopt clean technology at a lower emissions price than firms producing domestically do; and c) if domestic firms shift production offshore, they do so at emissions price  $\hat{\varepsilon}_o = \frac{\delta \gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  and adopt cleaner technology than they had operated domestically.*

With a border adjustment, there is an emissions price at which domestic firms adopt clean technology. Since offshore facilities' are exposed to emissions costs, domestic firms still have an incentive to reduce emissions if they produce offshore simply by serving the region. Further, given that offshore production and capital recovery costs are less than domestic production and capital recovery costs ( $\delta < 1$  by Assumption 1), foreign firms adopt clean technology to serve the domestic market at a lower emissions price than domestic firms do. The threshold emissions price at which foreign firms adopt clean technology is  $\hat{\varepsilon}_2^f = \delta \left( \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} \right)$ . Clean technology is adopted in the domestic region at  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ , identical to the adoption threshold without border adjustment.<sup>5</sup> While  $\hat{\varepsilon}_2^f < \varepsilon_2^d$  follows clearly from their characterizations, it runs counter to intuition. Under a border adjustment, foreign firms importing into the domestic market are more sensitive to the region's regulation than domestic producers. Conditional upon entry, foreign firms operate cleaner technology than locally producing domestic firms when  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ , and operate identical technology when  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ .

Under a border adjustment, offshoring always results in the adoption of cleaner technology. Consider the cost frontiers of domestic- and offshore-operated technologies depicted in Figures 3a

<sup>5</sup> Hat notation is dropped for  $\varepsilon_2^d$  to indicate the equivalency of the clean technology domestic adoption threshold with and without border adjustment.

and 3b. Given a symmetric border adjustment, the offshore cost frontier parallels the domestic cost frontier when the preferred technology in each region is the same; that is,  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d]$ . However, over emissions price intervals in which offshore production uses cleaner technology – when  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d]$  – the offshore cost frontier is less steep than the domestic cost frontier. It is only possible for these cost frontiers to intersect over emissions price intervals in which the preferred offshore technology is cleaner than the preferred domestic technology. As a consequence, a border adjustment implies that domestic firms adopt cleaner technology than they had used domestically when they shift offshore. These frontiers further imply that, if  $\delta + \frac{\tau}{\gamma_2} > 1$  (which is equivalent to  $\varepsilon_2^d < \hat{\varepsilon}_o$ , where  $\hat{\varepsilon}_o = \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$ ), domestic adoption of clean technology would preempt offshoring and domestic firms would operate within the regulated region at any emissions price. Without technology choice, it is clear from the figures that offshore and domestic production costs under a border adjustment would be parallel, and there would be no offshoring at any emissions price.



**Figure 3** Total cost frontiers when technologies are operated domestically (black) and offshore (gray). When  $\varepsilon$  is sufficiently great, domestic firms adopt clean technology in the regulated region (Figure 3a) or when they shift offshore (Figure 3b). The domestic adoption of clean technology preempts offshoring in 3a and offshoring preempts the domestic adoption of clean technology in 3b.

Technology adoption under a border adjustment differs markedly from adoption without such a policy, but a border adjustment's impact on foreign entry is less pronounced.

**COROLLARY 2.** *With a border adjustment, the number of foreign firms entering the market is*

$$n_f^* = \max \left\{ 0, \frac{A - \delta\hat{\gamma}_j - \hat{\alpha}_j\varepsilon - \tau - n_d(\delta\hat{\gamma}_j + \hat{\alpha}_j\varepsilon + \tau - \hat{c}_i(\varepsilon))}{\sqrt{Fb}} - n_d - 1 \right\}.$$

The number of foreign entrants under a border adjustment structurally resembles the number without such a mechanism (given in Proposition 1). While it appears that the right-hand argument of Corollary 2 is at least  $\frac{(n_d+1)\alpha_2\varepsilon}{\sqrt{Fb}}$  less than the right-hand argument in Proposition 1, such level comparisons between settings make the assumption that  $\varepsilon$  is the same with and without border adjustment. As shown in Section 5, this is not, in general, the case if the regulator can control  $\varepsilon$ .

### 4.3. Equilibrium quantities and emissions

As in Section 3, results are organized here by the market structure that emerges in equilibrium: domestic oligopoly, entry without offshoring, and offshoring with or without entry.

#### 4.3.1. Domestic oligopoly

**COROLLARY 3.** *Assume  $n_f^* = 0$ , and  $\varepsilon < \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  or  $\delta + \frac{\tau}{\gamma_2} > 1$ . In equilibrium, a domestic oligopoly results with quantities of  $x_{i,d}^* = \frac{A - \hat{\gamma}_i - \hat{\alpha}_i \varepsilon}{b(n_d + 1)}$  and  $y_j^* = 0$ .*

If domestic firms produce offshore in equilibrium, they do so at  $\varepsilon \geq \hat{\varepsilon}_o$ . However, when  $\delta + \frac{\tau}{\gamma_2} > 1$ , the domestic technology threshold  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$  is less than the offshoring threshold  $\varepsilon_o = \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ . Therefore, if  $\varepsilon < \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  or  $\delta + \frac{\tau}{\gamma_2} > 1$ , domestic firms produce within the regulated region by Corollary 5c. The conditions in Corollary 3 therefore result in a domestic oligopoly in equilibrium, in which case quantities are identical with and without a border adjustment.

#### 4.3.2. Foreign entry without offshoring

**PROPOSITION 6.** *Assume  $n_f^* > 0$ , and  $\varepsilon < \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  or  $\delta + \frac{\tau}{\gamma_2} > 1$ . In equilibrium,*

- a) *Foreign entry results with quantities  $x_{i,d}^* = \frac{\sqrt{Fb}}{b} + \frac{\delta\hat{\gamma}_j + \hat{\alpha}_j \varepsilon + \tau - \hat{\gamma}_i - \hat{\alpha}_i \varepsilon}{b}$  and  $y_j^* = \frac{\sqrt{Fb}}{b}$ .*
- b) *Foreign entry increases in  $\varepsilon$  if foreign firms operate cleaner technology and  $\frac{\alpha_1}{\alpha_2} > 1 + \frac{1}{n_d}$ , but otherwise decreases in  $\varepsilon$ .*
- c) *Domestic production decreases in  $\varepsilon$  if foreign firms operate cleaner technology, but otherwise is fixed in  $\varepsilon$ .*
- d) *Total output strictly decreases in  $\varepsilon$ .*
- e) *Global emissions decrease in foreign entry iff  $\alpha_\tau < (\alpha_1 - \alpha_2) + \frac{\alpha_2(\alpha_2 + \alpha_\tau)}{n_d(\alpha_1 - \alpha_2)}$ .*

Foreign entry is nonmonotonic or strictly decreases under a border adjustment. This differs from the setting without border adjustment, in which entry monotonically increases in  $\varepsilon$ . Entry decreases in  $\varepsilon$  when foreign firms operate the same technology that domestic firms do;  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ , recalling that  $\hat{\varepsilon}_2^f = \delta \left( \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} \right)$  and  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ . But entry can increase in  $\varepsilon$  when foreign firms operate cleaner technology than domestic firms;  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . As a consequence foreign firms exit the market at the threshold  $\hat{\varepsilon}_{exit}^1 = \{\varepsilon \in [0, \hat{\varepsilon}_2^f) | n_f = 0\}$  when both domestic and foreign firms prefer technology 1, and at  $\hat{\varepsilon}_{exit}^2 = \{\varepsilon \geq \varepsilon_2^d | n_f = 0\}$  when both sets of firms operate technology 2, where  $n_f$  is the right-hand argument in Corollary 2. Foreign firms enter the market under border adjustment at the threshold  $\hat{\varepsilon}_{enter} = \{\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d) | n_f = 0\}$  when foreign firms operate cleaner technology than domestic firms.

Following from Corollary 2, the number of entrants increases in  $\varepsilon$  within this interval at a rate of  $\frac{-\alpha_2 + n_d(\alpha_1 - \alpha_2)}{\sqrt{Fb}}$ , which is nonnegative when  $\frac{\alpha_1}{\alpha_2} \geq 1 + \frac{1}{n_d}$ . The LHS of this condition is greater than 1 and the RHS decreases in the number of domestic competitors; conditional on foreign entry, more competitive domestic markets *decrease* the hurdle beyond which entry will increase in  $\varepsilon$ . The



environmental benefit derived from cleaner foreign production dominates the negative impact of additional transport emissions when the conditions of Proposition 6e hold, resulting in a decrease in global emissions as a consequence of increased foreign entry. This differs notably from the case with no border adjustment, in which global emissions strictly increase within incremental entry.

Over intervals in which foreign firms operate cleaner technology than domestic firms,  $x_{i,d}^*$  decreases in  $\varepsilon$  at a rate of  $-\frac{\alpha_1 - \alpha_2}{b}$ . Over intervals in which foreign and domestic firms operate identical technologies,  $x_{i,d}^*$  is independent of  $\varepsilon$ . This inelasticity of domestic firm quantities in  $\varepsilon$  over intervals in which firms operate the same technology limits the regulator's ability to impact domestic emissions to intervals over  $\varepsilon$  in which foreign firms operate cleaner technology. This differs from the setting without border adjustment in which  $x_{i,d}^*$  strictly decreases in  $\varepsilon$ .

Total output decreases in  $\varepsilon$  under a border adjustment. When domestic and foreign firms operate identical technologies, total foreign quantities decrease in  $\varepsilon$  per Proposition 6a and domestic quantities remain fixed per Proposition 6b. When foreign firms operate cleaner technology than domestic firms, per Proposition 6a, the rate of total production increase among foreign firms in  $\varepsilon$  is  $\frac{n_d(\alpha_1 - \alpha_2) - \alpha_2}{b}$ , while the rate of total domestic decrease in production is  $-\frac{n_d(\alpha_1 - \alpha_2)}{b}$ , resulting in total output decreasing in  $\varepsilon$  at a rate of  $-\frac{\alpha_2}{b}$ . This differs from the setting with no border adjustment, in which total output is fixed with respect to emissions price under entry conditions.

#### 4.3.3. Offshoring with and without foreign entry

PROPOSITION 7. Assume  $\varepsilon \geq \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  and  $1 \geq \delta + \frac{\tau}{\gamma_2}$ . In equilibrium,

a) Domestic firms produce offshore, with domestic and foreign firm quantities of

$$x_{i,o}^* = \begin{cases} \frac{A - \delta\gamma_2 - \alpha_2\varepsilon - \tau}{b(n_d+1)} & \text{if } \varepsilon \leq \frac{A - \delta\gamma_2 - \tau - (n_d+1)\sqrt{Fb}}{\alpha_2} \\ \frac{\sqrt{Fb}}{b} & \text{otherwise} \end{cases} \quad \text{and} \quad y_j^* = \begin{cases} 0 & \text{if } \varepsilon \leq \frac{A - \delta\gamma_2 - \tau - (n_d+1)\sqrt{Fb}}{\alpha_2} \\ \frac{\sqrt{Fb}}{b} & \text{otherwise} \end{cases}$$

b) Total foreign and domestic production strictly decreases in  $\varepsilon$ .

c) Global emissions decrease as a consequence of offshoring at  $\varepsilon = \hat{\varepsilon}_o$  if  $\alpha_1 - \alpha_2 > \alpha_\tau$ .

d) Global emissions strictly decrease in  $\varepsilon$ .

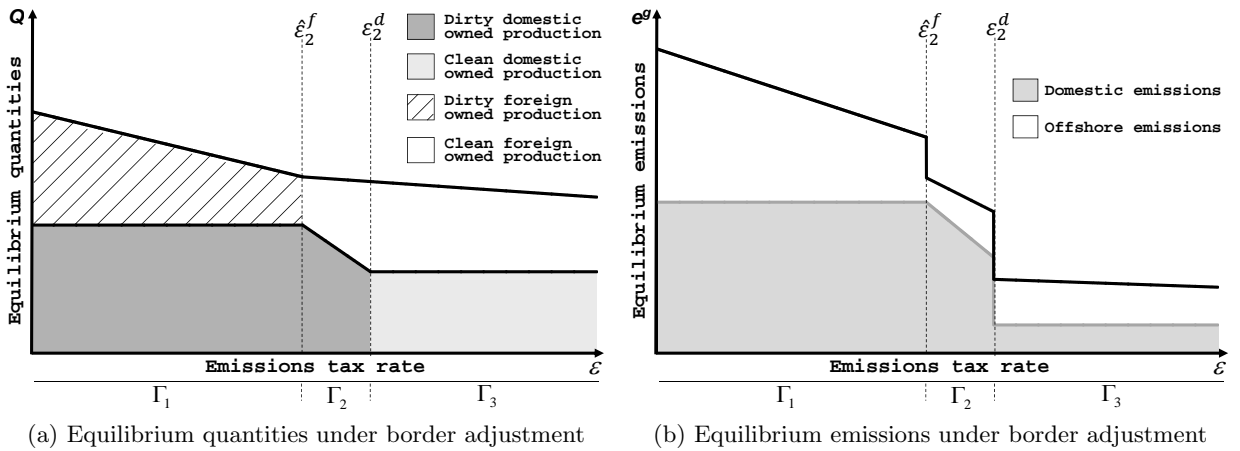
Domestic firms produce offshore in equilibrium under a border adjustment when  $\varepsilon \geq \hat{\varepsilon}_o$ , recalling that  $\hat{\varepsilon}_o = \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$ , if (and only if)  $\hat{\varepsilon}_o \leq \varepsilon_2^d$ , which is equivalent to  $1 \geq \delta + \frac{\tau}{\gamma_2}$ . It is counterintuitive that domestic firms may produce offshore when import carbon costs are symmetric to domestic carbon costs. However, it is optimal to do so over emissions price intervals in which foreign firms operate cleaner technology in equilibrium, as discussed following Proposition 5c. Quantities under offshoring depend on whether or not entry conditions are met. When  $\varepsilon \leq \frac{A - \delta\gamma_2 - \tau - (n_d+1)\sqrt{Fb}}{\alpha_2}$ , foreign firms do not enter under offshoring conditions. This results in an offshore oligopoly, with domestic firm (and total) quantities decreasing in  $\varepsilon$  at a rate of  $-\frac{\alpha_2}{b(n_d+1)}$ . When  $\varepsilon > \frac{A - \delta\gamma_2 - \tau - (n_d+1)\sqrt{Fb}}{\alpha_2}$ ,

foreign firms enter, with the number of entrants decreasing in  $\varepsilon$  at a rate of  $-\frac{\alpha_2}{\sqrt{Fb}}$  and domestic quantities fixed in  $\varepsilon$ , for a total output decrease in  $\varepsilon$  of  $-\frac{\alpha_2}{b}$ .

Global emissions decrease as a consequence of offshoring if  $\alpha_1 - \alpha_2 > \alpha_\tau$ ; that is, if the difference emissions intensity between clean and dirty technologies is great than the emissions intensity of transport. In addition to potentially decreasing at the point of offshoring, global emissions decrease in  $\varepsilon$  in an offshoring equilibrium. In this setting, unlike the setting without border adjustment, leakage resulting from both foreign entry and offshoring can lead to global emissions improvement when a border adjustment is implemented.

#### 4.4. Discussion of results

Figures 4a and 4b illustrate selected firm decisions and performance results from above.



**Figure 4** Examples of equilibrium quantities and emissions sensitivity to emissions price with border adjustment.

In Figure 4a, domestic and foreign firms operate dirty technology over  $\Gamma_1$ , with foreign entry decreasing over that range and domestic production constant, per Proposition 6b and 6c. At point  $\hat{\varepsilon}_2^f = \delta \left( \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} \right)$ , foreign firms adopt technology 2 (at a lower  $\varepsilon$  than domestic firms, per Proposition 5b). Therefore, foreign firms use cleaner technology than domestic firms and, as a consequence (given that  $\frac{\alpha_1}{\alpha_2} \geq 1 + \frac{1}{n_d}$  in this example), entry increases and domestic production decreases in  $\varepsilon$  over  $\Gamma_2$  per Propositions 6b and 6c. In  $\Gamma_2$ , if  $\frac{\alpha_1}{\alpha_2} < 1 + \frac{1}{n_d}$ , then both domestic and foreign production would decrease, but foreign production would do so at a lesser rate. At point  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ , domestic firms also adopt cleaner technology and, again, domestic production is fixed while foreign production decreases in  $\varepsilon$ . Finally, per Proposition 6d, total production decreases in  $\varepsilon$  over all intervals. In this setting,  $1 < \delta + \frac{\tau}{\gamma_2}$ , so domestic firms do not produce offshore at any emissions price; offshoring is preempted by domestic clean technology adoption. If  $1 \geq \delta + \frac{\tau}{\gamma_2}$ , domestic firms would produce offshore at  $\hat{\varepsilon}_o = \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$ , adopting clean technology when they did so.

As seen in Figures 4a and 4b, with a border adjustment, increases in  $\varepsilon$  not only lead to the adoption of cleaner technology among domestic firms (an effect noted above to be limited without

a border adjustment), but can also result in foreign firms adopting cleaner technology to serve the domestic market. This obviously has implications for global emissions. While carbon leakage with no border adjustment always increases global emissions, leakage can result in global emissions *improvement* under a symmetric border adjustment, as seen in Figure 4b over  $\Gamma_2$ .

In addition to these border adjustment advantages, there are also drawbacks. While the goal of emissions regulation is to reduce global emissions, there can be costs associated with failing to achieve domestic emissions targets. Under a border adjustment, a regulator may not be able to achieve these targets directly, as domestic emissions are unresponsive to changes in  $\varepsilon$  when domestic and foreign production use the same technology, as in regions  $\Gamma_1$  and  $\Gamma_3$ . The regulator may therefore become more reliant on Joint Implementation or Clean Development Mechanism allowances, which can be costly and subject to an uncertain review process. Further, foreign entry conditionally decreases in  $\varepsilon$  when foreign firms operate cleaner technology than domestic firms as in region  $\Gamma_2$ , and strictly decreases in  $\varepsilon$  when domestic and foreign firms operate similar technology. In settings where foreign firms compete in the domestic market when  $\varepsilon = 0$ , this implies that a border adjustment can increase domestic market share relative to the unregulated baseline, arguably giving credence to concerns about the potential anti-competitiveness of border adjustments.

*Challenges in implementing a border adjustment.* If a regulator chose to adopt a border adjustment, it would face challenges in implementing the policy. First, there are legality concerns. Policy scholars have argued that a symmetric border adjustment is legal under WTO and GATT law so long as regulated domestic sectors are not awarded free emissions allowances (Grubb and Neuhoff 2006). Even so, due to the difficulty in measuring emissions, many legal battles would likely ensue, delaying the policy's implementation (Kanter 2009, December 17). This relates to another set of challenges: reporting and monitoring. Emissions are not contained in an imported good, they are emitted into the atmosphere. Therefore, they must be measured at the point of production rather than through inspection at the border. Given the potential for noncompliance and misreporting in such a setting, auditing processes and policies for dealing with fraudulent claims would have to be established. Working in a border adjustment favor, emissions regulation effects a limited number of sectors, and the sectors targeted for border adjustment could be prioritized and limited further (e.g., the European Commission has explored such a policy for the cement and steel sectors only).

## 5. Domestic Regulator's Decision and Welfare Performance

Sections 3 and 4 focused on the operational drivers underpinning the welfare effects of emissions regulation: technology choice, facility location, production quantities, and the emissions that result. In this section, welfare itself is the focus.

In setting an emissions price, the welfare-maximizing domestic regulator must consider emissions revenues, its own costs due to domestic emissions, and emissions-driven social costs in addition

to the traditional welfare drivers of firm profits and consumer surplus. The latter elements are straightforward. Total domestic firm profits are  $n_d \pi_i(\cdot)$ , with  $\pi_i(\cdot)$  defined by (1). Given the demand curve in Sections 3 and 4, consumer surplus is  $\psi(\varepsilon) = \frac{1}{2}[A - P(\cdot)](X + Y)$ , which is equivalent to  $\psi = \frac{1}{2}b(n_d x_i^*(\varepsilon) + n_f^*(\varepsilon)y_j^*(\varepsilon))^2$ .

Unit border adjustment costs are  $\beta_j$ , with  $\beta_j = 0$  without border adjustment and  $\beta_j = \alpha_j$  with border adjustment. Since domestic and foreign firms use identical technology when producing offshore, imports to the region incur border adjustment  $\beta_j$  when produced by either type of firm. The domestic regulator therefore garners emissions revenues,  $\rho(\varepsilon) = (X_d \alpha_i + (X_o + Y)\beta_j)\varepsilon$ . Domestic firms' emissions costs are a transfer payment to the regulator. Therefore, if there is no border adjustment, or if there is no foreign entry under a border adjustment, emissions revenues and domestic firm emissions costs negate one another with respect to welfare effects.

The regulator itself may incur per ton carbon cost  $\varepsilon_r \geq 0$ . In some cases, such as California under Assembly Bill 32, the regulator does not incur this cost (i.e.,  $\varepsilon_r = 0$ ). In other cases it does, such as the European Union under its Kyoto Protocol commitments. In either case, the financial cost of emissions incurred by the regulator is  $\eta(\varepsilon, \varepsilon_r) = e^d(\varepsilon)\varepsilon_r$ .

The per-ton social cost of emissions,  $\varepsilon_s \geq 0$ , is the monetized climate change damage associated with a one-ton increase in carbon dioxide equivalent emissions. These costs have been estimated by the U.S. Government as beginning at \$21.40 in 2010 and steadily increasing to \$44.90 by 2050 (Greenstone et al. 2011).<sup>6</sup> Such social costs provide the impetus for emissions regulation and are included in the regulator's welfare problem as  $\xi(\varepsilon, \varepsilon_s) = (e^d(\varepsilon) + (e^g(\varepsilon) - e^d(\varepsilon)))\varepsilon_s$ , where domestic and global emissions,  $e^d$  and  $e^g$ , are defined in (3).

In light of the above, the regulator maximizes welfare,  $W$ , through the following objective:

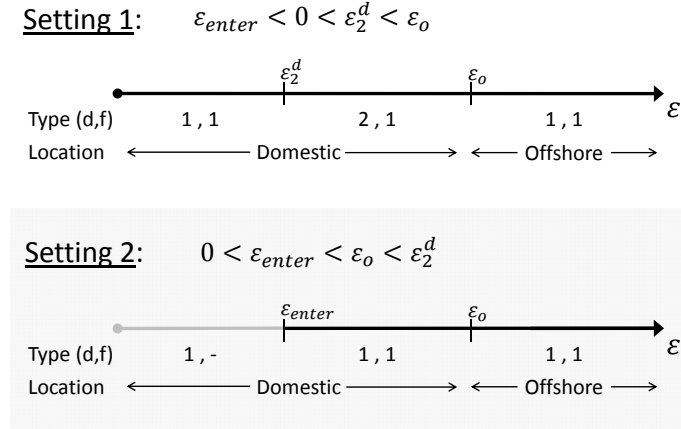
$$\begin{aligned} \max_{\varepsilon} W &= \max_{\varepsilon} \pi(\varepsilon) + \psi(\varepsilon) + \rho(\varepsilon, \beta_j) - \eta(\varepsilon, \varepsilon_r) - \xi(\varepsilon, \varepsilon_s). \\ &\text{s.t. } \varepsilon \geq 0. \end{aligned} \quad (4)$$

The regulator's problem without border adjustment is explored in Section 5.1, and its problem with a border adjustment is explored in Section 5.2.

### 5.1. Welfare-maximizing emissions price *without* border adjustment

As shown in Sections 3 and 4, emissions price impacts firms' location, technology, and entry decisions at specific thresholds. Therefore, when the welfare-maximizing regulator sets emissions price, it must account for these thresholds and the related changes in firm decisions. Given the discontinuous nature of firms' decisions, seven possible scenarios arise in the setting without border adjustment. Each scenario is enumerated in Figure B.1 of Appendix B, but two representative settings form the basis for the analysis that follows.

<sup>6</sup> Both the 2010 and the 2050 estimates are based on 2007 dollars and a 3% discount rate.



**Figure 5** Domestic (d) and foreign (f) technology type and domestic firm location in focal settings without border adjustment. Black indicates foreign entry intervals and gray indicates intervals without entry.

In setting 1 of Figure 5, foreign firms compete in the domestic market at  $\varepsilon = 0$ . Since foreign entry does not decrease in  $\varepsilon$  when there is no border adjustment, entry persists over all possible  $\varepsilon$ . In this setting, the technology adoption threshold is less than the offshoring threshold,  $\varepsilon_2^d < \varepsilon_o$ , so there is an interval of emissions prices in which domestic firms would adopt clean technology,  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$ . In setting 2, foreign firms do not compete when emissions are unregulated. Domestic firms compete solely against each other in a domestic oligopoly over the interval  $\varepsilon \in [0, \varepsilon_{enter})$ . At  $\varepsilon > \varepsilon_{enter}$ , domestic firms also compete in the market. Domestic firms produce offshore in this setting at  $\varepsilon_o < \varepsilon_2^d$ , so clean technology is not adopted at any emissions price.

As shown in Appendix T.1, without a border adjustment, social welfare is concave in  $\varepsilon$  under a domestic oligopoly, linear under foreign entry when domestic firms operate in the regulated region, and independent of  $\varepsilon$  when domestic firms operate offshore.

*Setting 1.* Social welfare increases in  $\varepsilon$  when domestic firms produce in the regulated region with technology  $k$  and compete against foreign entrants, iff  $\varepsilon_s < \varepsilon_{s,k}$ , where

$$\varepsilon_{s,1} = -\frac{\sqrt{Fb} + \delta\gamma_1 - \alpha_1\varepsilon_r + \tau - \gamma_1}{\alpha_\tau} \quad \text{and} \quad \varepsilon_{s,2} = -\frac{\sqrt{Fb} + \delta\gamma_1 - \alpha_2\varepsilon_r + \tau - \gamma_2}{\alpha_1 + \alpha_\tau - \alpha_2},$$

which are obtained by solving for the  $\varepsilon_s$  such that  $\frac{\partial W}{\partial \varepsilon} = 0$ . In settings in which domestic firms produce in the regulated region and foreign firms compete, entry increases in  $\varepsilon$  per Proposition 3b, which, in turn, increases global emissions per Proposition 3d. Such an increase in global emissions becomes more costly from a welfare perspective as  $\varepsilon_s$  increases. Therefore, under foreign entry, welfare decreases in  $\varepsilon$  over  $\varepsilon \in [0, \varepsilon_2^d)$  and  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$  if  $\varepsilon_s$  is greater than  $\varepsilon_{s,1}$  and  $\varepsilon_{s,2}$ , respectively.

There is a disjoint change in social welfare at  $\varepsilon_2^d$  and  $\varepsilon_o$ , the points at which domestic firms adopt clean technology and move offshore, respectively. Define the former as  $\Delta_2$  and the latter as  $\Delta_o$ , where

$$\Delta_2 = n_d \left( \frac{\sqrt{Fb}}{b} + \frac{\delta\gamma_1 + \tau - \gamma_1 - \alpha_1\varepsilon_2^d}{b} \right) ((\varepsilon_s + \varepsilon_r)(\alpha_1 - \alpha_2) - \gamma_2 + \gamma_1), \quad \text{and} \quad (5)$$

$$\Delta_o = -n_d \left( \frac{\sqrt{Fb}}{b} \right) \left( (\alpha_1 + \alpha_\tau - \alpha_i) \varepsilon_s - \gamma_i - \alpha_i \varepsilon_r + \delta \gamma_1 + \tau \right).$$

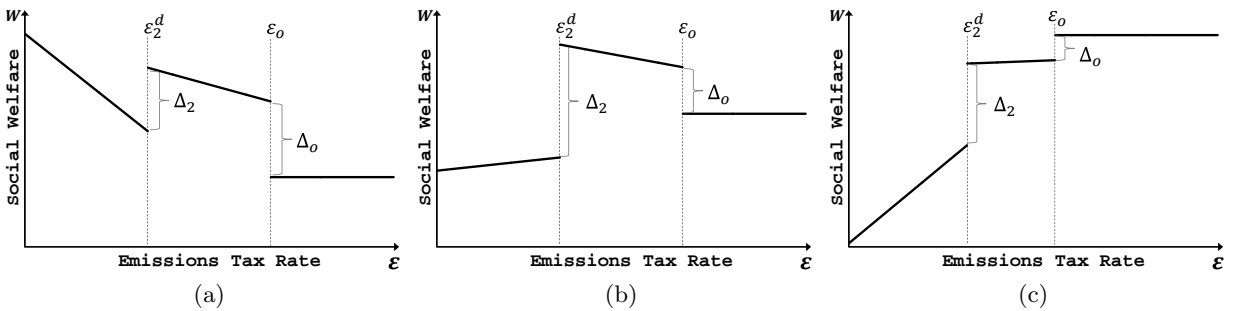
Welfare at emissions price  $\varepsilon_2^d$  with technology 2 is compared to welfare at emissions price  $\varepsilon_2^d$  with technology 1 to obtain  $\Delta_2$ , and  $\Delta_o$  obtained similarly. The left term of  $\Delta_2$  is total domestic production at the point of clean technology adoption. The right term is the per-unit welfare benefit/cost of switching to clean technology. It is straightforward to show that  $\Delta_2 > 0$  iff  $\varepsilon_2^d < (\varepsilon_s + \varepsilon_r)$ . The adoption of clean technology reduces  $\xi$  and  $\eta$ , providing welfare benefits. However, it also reduces  $\rho$ , decreasing welfare. Firm profits and consumer surplus are unaffected by the adoption of clean technology at  $\varepsilon_2^d$ ; technology 1 and 2 total unit costs are identical, resulting in identical quantities.

The left term of  $\Delta_o$  is total domestic production at the point of offshoring and the right term is the unit welfare benefit/cost of offshoring, where  $\gamma_i$  and  $\alpha_i$  are the production cost and emissions intensity of the technology that the domestic firm used in the regulated region.<sup>7</sup> Offshoring increases  $\xi$  and decreases  $\rho$ , both reducing welfare, and it decreases  $\eta$ , increasing welfare. As a consequence, offshoring can only provide a welfare benefit without a border adjustment if  $\varepsilon_r \gg \varepsilon_s$ .

Analysis of the regulator's optimal emissions price is facilitated by focusing on the social cost of emissions and the conditions that determine whether welfare increases or decreases in each interval.

**PROPOSITION 8.** *Assume  $\varepsilon_{enter} < 0 < \varepsilon_2^d < \varepsilon_o$ . The set of possible welfare-maximizing emissions prices can be characterized based on the social cost of emissions:*

- a) *If  $\varepsilon_s > \varepsilon_{s,1}$  and  $\varepsilon_s > \varepsilon_{s,2}$ , then  $\varepsilon^* \in \{0, \varepsilon_2^d, \varepsilon_o\}$ .*
- b) *If  $\varepsilon_s \in (\varepsilon_{s,2}, \varepsilon_{s,1})$ , then  $\varepsilon^* \in \{\varepsilon_2^d, \varepsilon_o\}$ .*
- c) *If  $\varepsilon_s < \varepsilon_{s,1}$  and  $\varepsilon_s < \varepsilon_{s,2}$ , then  $\varepsilon^* = \varepsilon_o$ .*



**Figure 6** Figures 6a-6c correspond to Proposition 8a-8c. The magnitude of the social cost of emissions,  $\varepsilon_s$ , relative to the thresholds  $\varepsilon_{s,1}$  and  $\varepsilon_{s,2}$  determines whether welfare increases or decreases over each interval. The disjoint changes in social welfare,  $\Delta_2$  and  $\Delta_o$ , at the points of technology adoption and offshoring, respectively, contribute in determining possible welfare-maximizing emissions prices.

<sup>7</sup>  $\Delta_2$  and  $\Delta_o$  are characterized here for the case in which foreign firms compete in the market. The characterization for the case in which foreign firms do not compete is identical after substituting total output under a domestic oligopoly,  $n_d \left( \frac{A - \gamma_i + \alpha_i \varepsilon}{b(n_d + 1)} \right)$ , at emissions price  $\varepsilon_2^d$  and  $\varepsilon_o$ , respectively, for the total output terms (5) above.

The assumption  $\varepsilon_{enter} < 0 < \varepsilon_2^d < \varepsilon_o$  establishes setting 1. In this setting, when domestic firms produce in the regulated region, the magnitude of the social cost of emissions relative to the thresholds  $\varepsilon_{s,1}$  and  $\varepsilon_{s,2}$  determines whether welfare increases or decreases when domestic firms use technologies 1 and 2, respectively. Given that  $\varepsilon_s$  is greater than  $\varepsilon_{s,1}$  and  $\varepsilon_{s,2}$  in Proposition 8a, social welfare decreases over both intervals. In this case,  $\Delta_2$  and  $\Delta_o$  can be positive or negative. If either is sufficiently positive, the welfare-maximizing price would be  $\varepsilon_2^d$  or  $\varepsilon_o$ , respectively, with  $\Delta_2$  increasing in  $\varepsilon_s$ ,  $\varepsilon_r$ , and  $\alpha_1$  and  $\Delta_o$  increasing in  $\varepsilon_r$  and  $\alpha_2$ . Similarly, focusing on Proposition 8b, welfare increases over the interval  $\varepsilon \in [0, \varepsilon_2^d)$  and decreases over the interval  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$  as  $\varepsilon_s$  is less than  $\varepsilon_{s,1}$  and greater than  $\varepsilon_{s,2}$ . When  $\varepsilon_{s,1} > \varepsilon_{s,2}$  and  $\varepsilon_s > \varepsilon_{s,2}$  (as is the case in Proposition 8b), then  $\Delta_2 > 0$ , which eliminates zero as a possible welfare-maximizing emissions price. Related to Proposition 8c, when  $\varepsilon_s$  is sufficiently small that welfare increases over  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$ , then  $\varepsilon_r$  must be sufficiently great that  $\varepsilon_s < \varepsilon_{s,1}$  and  $\Delta_o > 0$ , making  $\varepsilon^* = \varepsilon_o$  the only feasible solution.

*Setting 2.* In setting 2, over the interval  $\varepsilon \in [0, \varepsilon_{enter}]$ , domestic firms compete without foreign entry, with welfare concave in emissions price as previously noted. It facilitates analysis here and in Section 5.2 to introduce notation related to potential optima. Define  $E_{k,l}^m(\varepsilon_s)$  as the emissions price that solves the first order conditions for the interval within which domestic firms operate technology  $k$  from location  $l$  while competing against foreign firms that operate technology  $m \in \{1, 2\}$ . The superscript is dropped for intervals in which foreign firms do not compete. Therefore, over the interval  $\varepsilon \in [0, \varepsilon_{enter}]$  in setting 2,  $E_{1,d}(\varepsilon_s)$  solves the FOC, with

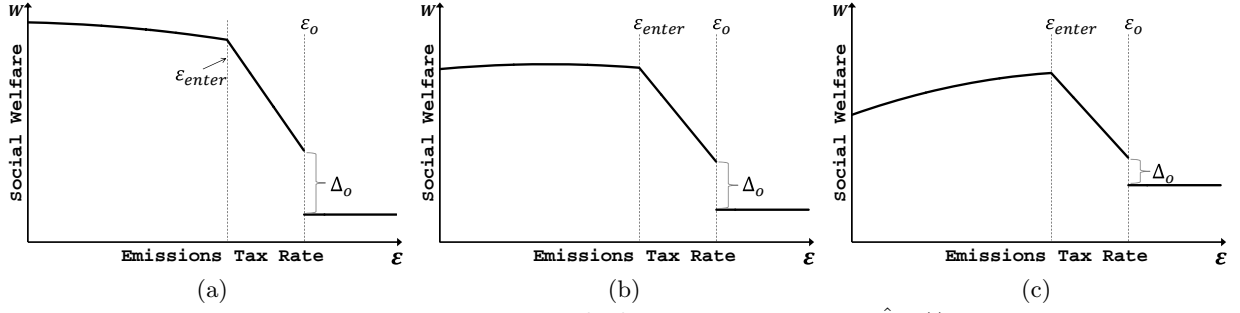
$$E_{1,d}(\varepsilon_s) = \frac{(\varepsilon_s + \varepsilon_r)(n_d + 1)}{n_d} - \frac{A - \gamma_1}{n_d \alpha_1}.$$

If  $E_{1,d}(\varepsilon_s) \in [0, \varepsilon_{enter}]$ , then it is the local optimum. Further, as in Setting 1, welfare increases if  $\varepsilon_s < \varepsilon_{s,1}$  over the entry interval in which domestic firms produce in the regulated region.

**PROPOSITION 9.** *Assume  $0 < \varepsilon_{enter} < \varepsilon_o < \varepsilon_2^d$ . The set of possible welfare-maximizing emissions prices can be characterized as follows:*

- a) *If  $E_{1,d}(\varepsilon_s) < 0$ , then  $\varepsilon^* \in \{0, \varepsilon_o\}$ .*
- b) *If  $E_{1,d}(\varepsilon_s) \in [0, \varepsilon_{enter}]$ , then  $\varepsilon^* \in \{E_{1,d}(\varepsilon_s), \varepsilon_o\}$ .*
- c) *If  $E_{1,d}(\varepsilon_s) > \varepsilon_{enter}$  and  $\varepsilon_s > \varepsilon_{s,1}$ , then  $\varepsilon^* \in \{\varepsilon_{enter}, \varepsilon_o\}$ .*
- d) *If  $\varepsilon_s < \varepsilon_{s,1}$ , then  $E_{1,d}(\varepsilon_s) > \varepsilon_{enter}$  and  $\varepsilon^* = \varepsilon_o$ .*

The assumption  $0 < \varepsilon_{enter} < \varepsilon_o < \varepsilon_2^d$  establishes setting 2. Focusing on Proposition 9a (and the corresponding Figure 7a), due to the concavity of welfare when domestic firms operate in the regulated region without foreign entry, if  $E_{1,d}(\varepsilon_s) < 0$ , welfare decreases over  $\varepsilon \in [0, \varepsilon_{enter}]$ . Possible welfare-maximizing emissions prices are therefore restricted to 0 and  $\varepsilon_o$ . The latter is the optimal emissions price if  $\Delta_o$  is sufficiently great, with  $\Delta_o$  increasing in  $\varepsilon_r$  and  $\alpha_1$ . For Proposition 9b, when



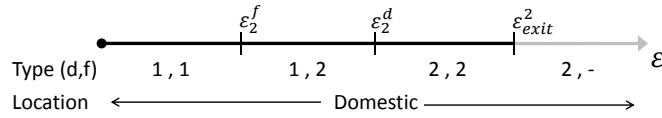
**Figure 7** Figures 7a-7c correspond to Proposition 9a-9c. The relationship of  $\hat{E}_{1,d}(\cdot)$  to 0 and  $\varepsilon_{enter}$  determines whether welfare increases, decreases or has an interior optimum over  $\varepsilon \in [0, \varepsilon_{enter}]$ . The direction of change over the entry interval  $\varepsilon \in (\varepsilon_{enter}, \varepsilon_o)$  and the disjoint changes in social welfare at  $\Delta_o$  contribute to determining possible welfare-maximizing emissions prices.

the local optimum  $E_{1,d}(\varepsilon_s)$  is interior to  $\varepsilon \in [0, \varepsilon_{enter}]$ , the welfare-maximizing emissions price must be either  $E_{1,d}(\varepsilon_s)$  or  $\varepsilon_o$ , depending on the magnitude and direction of  $\Delta_o$ . When  $E_{1,d}(\varepsilon_s) > \varepsilon_{enter}$ , as in Propositions 9c and 9d, welfare increases over  $\varepsilon \in [0, \varepsilon_{enter}]$ . In this case, welfare can increase or decrease over the entry interval  $\varepsilon_e \in [\varepsilon_{enter}, \varepsilon_o)$ . However, welfare decreases over  $\varepsilon_e \in [\varepsilon_{enter}, \varepsilon_o)$  if  $\varepsilon_s > \varepsilon_{s,1}$ , as is the case in Proposition 9c. If  $\varepsilon_s < \varepsilon_{s,1}$ , then welfare increases in the entry interval. This can only occur if the emissions cost that the regulator incurs is sufficiently great; i.e.,  $\varepsilon_r > \frac{\sqrt{Fb} + \delta\gamma_1 + \tau - \gamma_1}{\alpha_1}$ . Such a condition implies that  $E_{1,d}(\varepsilon_s) > \varepsilon_{enter}$  and that  $\Delta_o > 0$ . As a consequence,  $\varepsilon_o$  is the only feasible solution in Proposition 9d.

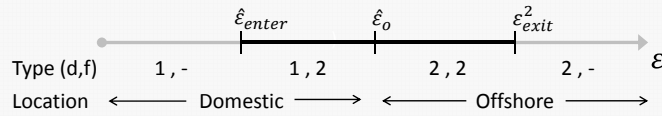
## 5.2. Welfare-maximizing emissions price *with* border adjustment

As was the case without border adjustment, the emissions price thresholds driving technology adoption, foreign entry (and exit), and offshoring lead to eight potential scenarios under a border adjustment. These scenarios are all enumerated in Figure B.2 of Appendix B. However, two focal settings develop general insights related to border adjustment effects.

**Setting 1:**  $0 < \hat{\varepsilon}_2^f < \varepsilon_2^d < \hat{\varepsilon}_{exit}^2$  and  $\hat{\varepsilon}_2^f < \hat{\varepsilon}_{exit}^1$



**Setting 2:**  $\hat{\varepsilon}_{exit}^1 \leq 0 < \hat{\varepsilon}_{enter} < \hat{\varepsilon}_o < \hat{\varepsilon}_{exit}^2$  and  $\hat{\varepsilon}_o < \varepsilon_2^d$



**Figure 8** Domestic (d) and foreign (f) technology type and domestic firm location in focal settings with border adjustment. Black indicates foreign entry intervals and gray indicates intervals without entry.

As shown in Appendix T.1, welfare is concave over all intervals under border adjustment.



*Setting 1.* This setting arises when a border adjustment is implemented in setting 1 from Section 5.1 if  $A$  is sufficiently great that foreign firms remain in the market over the interval  $\varepsilon \in [0, \hat{\varepsilon}_2^f]$ . There are two points of disjoint welfare change: the benefit/cost from domestic adoption of clean technology,  $\hat{\Delta}_2^d$ , and the benefit/cost from foreign adoption of clean technology,  $\hat{\Delta}_2^f$ . Similar to the case without border adjustment,  $\hat{\Delta}_2^d$  is obtained by comparing welfare at the threshold  $\hat{\varepsilon}_2^d$  with domestic firms producing with technology 2 versus with domestic firms producing with technology 1. The welfare change for foreign firm clean technology adoption is obtained similarly, with

$$\hat{\Delta}_2^d = n_d \left( \frac{\sqrt{Fb}}{b} + \frac{\delta\gamma_2 + \alpha_2\varepsilon_2^d + \tau - \gamma_1 - \alpha_1\varepsilon_2^d}{b} \right) ((\varepsilon_s + \varepsilon_r)(\alpha_1 - \alpha_2) - \gamma_2 + \gamma_1) \quad \text{and}$$

$$\hat{\Delta}_2^f = \left( \frac{A - (n_d + 1) \left( \delta\gamma_2 + \alpha_2\hat{\varepsilon}_2^f + \tau + \sqrt{Fb} \right) + n_d(\gamma_1 + \alpha_1\hat{\varepsilon}_2^f)}{b} \right) ((\alpha_1 - \alpha_2)\varepsilon_s - \delta(\gamma_2 - \gamma_1)).$$

The welfare drivers related to the domestic adoption of clean technology are identical to those without border adjustment: A decrease in  $\xi$  and  $\eta$  improves welfare while a decrease in  $\rho$  decreases welfare. Therefore, the marginal benefit/cost of adoption (the right-hand term of  $\hat{\Delta}_2^d$ ) is identical under both scenarios, with  $\hat{\Delta}_2^d > 0$  iff  $\varepsilon_2^d < (\varepsilon_s + \varepsilon_r)$ . However, the magnitude of technology adoption welfare effects is strictly greater under a border adjustment,  $|\hat{\Delta}_2^d| > |\Delta_2^d|$ , because total domestic production (the right-hand term) is  $\frac{\alpha_2\varepsilon_2^d + \delta(\gamma_2 - \gamma_1)}{b}$  greater as a consequence of border adjustment<sup>8</sup>. Welfare drivers resulting from the adoption of clean technology by foreign firms are similar, except that such adoption does not reduce  $\eta$ . Therefore,  $\hat{\Delta}_2^f > 0$  iff  $\hat{\varepsilon}_2^f < \varepsilon_s$ .

Since welfare is concave over all intervals in the setting, analysis of  $\hat{\varepsilon}^*$  resembles that for the domestic oligopoly interval in setting 2 of Section 5.1, requiring the characterization of  $\hat{E}_{k,l}^m(\varepsilon_s)$  for each interval. With the intuition developed in Section 5.1, the relevant insights under a border adjustment can most economically be given directly from the FOC solutions.

Interval	FOC Solutions
$\varepsilon \in [0, \hat{\varepsilon}_2^f]$	$\hat{E}_{1,d}^1(\varepsilon_s) = \frac{(\alpha_1 + \alpha_\tau)\varepsilon_s}{\alpha_1}$
$\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d]$	$\hat{E}_{1,d}^2(\varepsilon_s) = \frac{(\alpha_2 + \alpha_\tau)\alpha_2\varepsilon_s - n_d(\alpha_1 - \alpha_2)\sqrt{Fb}}{\alpha_2^2} - \frac{n_d(\alpha_1 - \alpha_2)((\alpha_2 + \alpha_\tau - \alpha_1)\varepsilon_s + \delta\gamma_2 + \tau - \gamma_1 - \alpha_1\varepsilon_r)}{\alpha_2^2}$
$\varepsilon \in [\varepsilon_2^d, \hat{\varepsilon}_{exit}^d]$	$\hat{E}_{2,d}^2(\varepsilon_s) = \frac{(\alpha_2 + \alpha_\tau)\varepsilon_s}{\alpha_2}$
$\varepsilon \geq \hat{\varepsilon}_{exit}^d$	$\hat{E}_{2,d}^2(\varepsilon_s) = \frac{(\varepsilon_s + \varepsilon_r)(n_d + 1)\alpha_2 + \gamma_2 - A}{\alpha_2 n_d}$

**Table 2** Setting 1 emissions price intervals and their FOC solutions,  $\hat{E}_{k,d}^m(\cdot)$

Table 2 provides each emissions price interval in setting 1 and their respective FOC solutions. In the first interval,  $\varepsilon \in [0, \hat{\varepsilon}_2^f]$ , domestic and foreign firms compete while producing with technology

<sup>8</sup>  $\hat{\Delta}_2^d$  is characterized for the case where foreign firms compete in the market. The characterization for the case where foreign firms do not compete is identical after substituting total output under a domestic oligopoly,  $n_d \left( \frac{A - \gamma_1 + \alpha_1\varepsilon_2^d}{b(n_d + 1)} \right)$ .

1, with the domestic firm operating in the regulated region. The FOC solution in this setting is  $\hat{E}_{1,d}^1(\varepsilon_s)$ , which is the local optimum if it falls within the bounds 0 and  $\hat{\varepsilon}_{enter}$ . In the case of the last interval, if  $\hat{E}_{2,d}^1$  is greater than  $\hat{\varepsilon}_{exit}^2$ , then it is a local optimum.

It is clear from Table 2 that when foreign firms compete in the market,  $\hat{\varepsilon}^* > 0$  if  $\varepsilon_s > 0$ . At any nonzero social cost of carbon, the FOC solution to the first interval in the setting,  $\hat{E}_{1,d}^1$ , is positive. As a consequence,  $\hat{\varepsilon}^* = 0$  cannot solve the regulator's welfare maximization. This differs from the emissions regulation setting with foreign entry but without a border adjustment, which is evident in Figure 6a, where  $\varepsilon_s = 30$  and  $\varepsilon^* = 0$ .

It is also evident from Table 2 that  $\hat{E}_{k,l}^m(\cdot)$  is independent of  $\varepsilon_r$  when foreign and domestic firms compete with like technologies (the first and third intervals in the table). This results from domestic firms' optimal quantity being independent of  $\varepsilon_r$  over these intervals per Proposition 3c.

*Setting 2.* This setting arises when a border adjustment is implemented in setting 1 from Section 5.1 if thresholds  $\hat{\varepsilon}_{enter}$  and  $\hat{\varepsilon}_o$  are less than  $\varepsilon_2^d$ . There is a single disjoint welfare change in this setting: the benefit/cost resulting from offshoring,  $\hat{\Delta}_o$ , with

$$\hat{\Delta}_o = -n_d \left( \frac{\sqrt{Fb}}{b} \right) ((\alpha_2 + \alpha_r - \alpha_1)\varepsilon_s - \gamma_1 - \alpha_1\varepsilon_r + \delta\gamma_2 + \tau). \quad (6)$$

The welfare effect increases due to a decrease in  $\eta$ , decreases due to a reduction in  $\rho$ , and can increase or decrease due to a change in  $\xi$ . The latter can increase or decrease because global emissions decrease as a consequence of offshoring under a border adjustment if  $\alpha_1 > \alpha_2 + \alpha_r$ , but increase otherwise, per Proposition 7c. As before, the right term is the marginal benefit/cost of offshoring while the left is total domestic production in the setting.<sup>9</sup>

Analysis of  $\hat{\varepsilon}^*$  follows from characterizing  $\hat{E}_{k,l}^m(\varepsilon_s)$  for each interval. Given the similarity to the preceding discussion, a detailed analysis here would be redundant, so the solutions to the FOCs are presented in Table C.1 within Appendix C.<sup>10</sup>

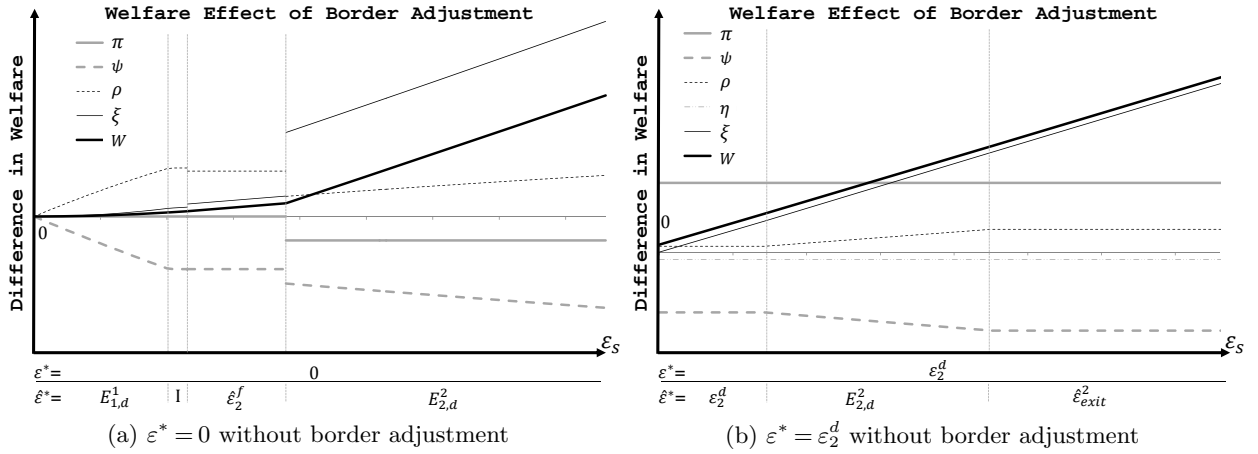
### 5.3. Welfare comparison *with* entry at $\varepsilon = 0$

Determining the value of a border adjustment policy requires a comparison of welfare effects with and without such a mechanism. Given the uncertainty around the social cost of carbon, understanding the sensitivity of  $\varepsilon^*$  and welfare differences to such costs is also important.<sup>11</sup>

<sup>9</sup> The characterization of  $\hat{\Delta}_o$  for settings in which foreign firms do not compete in the market is identical to (6) after substituting total output under a domestic oligopoly,  $n_d \left( \frac{A - \gamma_1 + \alpha_1 \hat{\varepsilon}_o}{b(n_d + 1)} \right)$ , for total domestic output under foreign entry.

<sup>10</sup> It is worth noting, in the absence of foreign entry,  $\hat{E}_{1,d}(\cdot)$  with a border adjustment is identical to  $E_{1,d}(\cdot)$  without, which is evident by comparing the first interval in Table C.1 of Appendix C to  $E_{1,d}(\cdot)$  given in Section 5.1.

<sup>11</sup> While Greenstone et al. (2011) provides a social cost of carbon point estimate of \$21.40 per ton of CO<sub>2</sub>, they provide a 95<sup>th</sup> percentile estimate of \$64.90 per ton of CO<sub>2</sub>.



**Figure 9** Figures 9a and 9b illustrate the difference in welfare effects, and the sensitivity of these effects and the welfare-maximizing emissions price to  $\varepsilon_s$ , with and without border adjustment. In Figure 9a, there is an interval where  $\hat{\varepsilon}^*$  results in foreign firms adopting clean technology while domestic firms do not. In Figure 9b, there is an interval where  $\hat{\varepsilon}^*$  results in foreign firms exiting the domestic market.

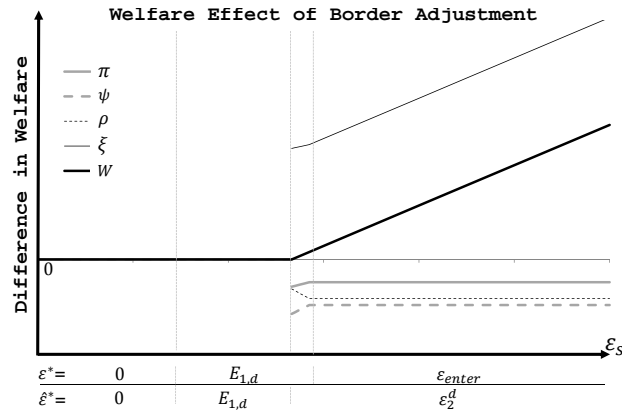
The examples above illustrate the difference in welfare effects with and without a border adjustment policy, and the sensitivity of these effects to the social cost of carbon. Focusing on Figure 9a,  $\varepsilon^* = 0$  and  $\hat{\varepsilon}^*$  varies over  $\varepsilon_s$ . In the first interval, where  $\hat{\varepsilon}^* = \hat{E}_{1,d}^1$ , domestic and foreign firms both use technology 1. Given that  $\hat{E}_{1,d}^1$  increases in  $\varepsilon_s$  and both sets of firms operate technology 1, foreign quantities under border adjustment decrease in  $\varepsilon_s$  (Proposition 6b) and domestic quantities are fixed in  $\varepsilon_s$  (Proposition 6c). This decrease in total output results in a decrease in consumer surplus,  $\psi$ , over the interval. In terms of total welfare, this decrease is offset by an increase in emissions revenues,  $\rho$ , and by a decrease in the total social cost of carbon,  $\xi$ , with the latter dominated by consumer surplus effects due to the low social cost of carbon within the interval. Over the next two intervals,  $\hat{\varepsilon}^*$  is equal to the threshold at which foreign firms adopt type 2 technology (the third interval), or just less where  $I = \hat{\varepsilon}_2^f - \iota$ , with  $\iota > 0$  arbitrarily small. The latter is the optimal emissions price in the interval in which  $\hat{\varepsilon}_2^f > \varepsilon_s$ . Over such an interval,  $\Delta_2^f < 0$  (as described above), so the adoption of clean technology by foreign firms would have a negative welfare effect. When  $\varepsilon^* = \hat{\varepsilon}_2^f$ , the welfare-maximizing emissions price is such that foreign firms adopt clean technology while domestic producers do not, which calls into question the fairness of a border adjustment policy in such settings. In both of these intervals,  $\hat{\varepsilon}^*$  is fixed in  $\varepsilon_s$ , so quantities and emissions levels remain constant. However,  $\xi$  increases over the interval, which follows from  $\varepsilon_s$  increasing and a difference in global emissions with and without border adjustment. Over the last interval in Figure 9a,  $\hat{\varepsilon}^* = E_{2,d}^2(\varepsilon_s)$ , which increases in  $\varepsilon_s$ . Effects in this interval therefore parallel those in the first interval. However the contribution of the social cost of carbon to the difference in total welfare is far more pronounced given the greater values of  $\varepsilon_s$ .

In Figure 9b, domestic quantities and emissions are again constant at all values of  $\varepsilon_s$ , but in this case  $\varepsilon^*$  is the threshold of domestic clean technology adoption,  $\varepsilon_2^d$ . While  $\hat{\varepsilon}^*$  is also  $\varepsilon_2^d$  under

border adjustment when  $\varepsilon_s$  is low. However, under border adjustment emissions price applies to both domestic and foreign firm production. It follows that foreign entry is less under border adjustment (Corollary 5), leading to greater domestic profit, lower consumer surplus, and fewer global emissions. The latter becomes increasingly valuable from a welfare perspective as  $\varepsilon_s$  increases. The second interval is similar to the last interval of the preceding example. Over the last interval,  $\hat{\varepsilon}^* = \hat{\varepsilon}_{exit}^2$ ; the emissions price at which foreign firms exit the domestic market. Therefore, Figure 9b illustrates a setting under which a border adjustment could be viewed as anticompetitive. Foreign entry that existed in the domestic market when  $\varepsilon = 0$  is driven from the market.

#### 5.4. Welfare comparison *without* entry at $\varepsilon = 0$

The examples above provide welfare comparisons with foreign entry when  $\varepsilon = 0$ . The following example illustrates a setting where a domestic oligopoly exists when emissions are unregulated.



**Figure 10** Unlike in Figures 9a and 9b, there is a domestic oligopoly when emissions are unregulated in this example. The domestic oligopoly persists at all levels of  $\varepsilon_s$ , but the regulator can incentivize clean technology adoption with border adjustment and cannot without it.

As evident in Figure 10, in settings in which there is a domestic oligopoly without regulation (when  $\varepsilon = 0$ ), there is no difference in welfare with and without a border adjustment if  $\varepsilon_s$  is sufficiently low. This follows from an identical welfare-maximizing emissions price with and without a border adjustment and from border adjustment not impacting foreign firms (because there is no entry). However, even without foreign entry, border adjustment provides a welfare advantage if  $\varepsilon_s$  is sufficiently great. In this example,  $\varepsilon_o < \varepsilon_2^d$  without a border adjustment, but  $\hat{\varepsilon}_o < \varepsilon_2^d$  with one; i.e., the regulator cannot incentivize clean technology adoption without a border adjustment (Corollary 1), but can with one (Proposition 5a). Therefore, at the  $\varepsilon_s$  at which it is optimal under a border adjustment to increase  $\hat{\varepsilon}^*$  to  $\varepsilon_2^d$  it is not optimal to do so without a border adjustment.

Over the interval in which  $\varepsilon^* = E_{1,d}$  and  $\hat{\varepsilon}^* = \varepsilon_2^d$ , domestic firms use cleaner technology with border adjustment than without it. This increases welfare due to a reduction in  $\xi$ , while welfare

decreases due to lower  $\pi$ ,  $\psi$  (both due to reduced quantities), and  $\rho$  (due to the lower emissions intensity of technology 2). This nets an overall welfare gain as  $\varepsilon_s$  increases. The welfare-maximizing emissions price with a border adjustment,  $\varepsilon_2^d$ , is fixed in  $\varepsilon_s$ , while  $E_{1,d}$  increases in  $\varepsilon$ , narrowing the quantity difference. Over the final interval, the welfare-maximizing emission price without border adjustment becomes  $\varepsilon_{enter}$ . Increasing emissions price further without a border adjustment would result in foreign entry, which would lead to greater global emissions (Propositions 3d).

In this example, border adjustment enables the regulator to set an emissions price that results in clean technology adoption by domestic firms, which results in lower global emissions. As  $\varepsilon_s$  increases, the value attributed to this difference increases as well, which increases the welfare advantage of border adjustment. This example is pertinent to the cement sector in Europe which historically has operated as a domestic oligopoly, and for which  $\varepsilon_2^d > \varepsilon_o$ ; the estimated adoption threshold of carbon capture and storage technology, the industry's most promising emissions-mitigating technology-in-development, exceeds the estimated emissions cost of offshoring (European Cement Research Academy 2009, Boston Consulting Group 2008).

In each of the cases illustrated here and in Section 5.3, welfare under border adjustment is no less than welfare without a border adjustment, and the benefit that border adjustment provides increases in  $\varepsilon_s$ . In general, a border adjustment provides a greater advantage at a greater per-ton social cost of carbon. A border adjustment provides a welfare advantage in these settings due to cleaner foreign production when entry occurs, as seen over intervals in Figure 9a; due to the preservation of domestic firm profits, as seen in Figure 9b; and due to the ability to induce clean technology adoption among domestic firms in settings in which it is not possible to do so without a border adjustment, as seen in Figure 10.<sup>12</sup> However, these examples also highlight concerns related to the fairness and potential anticompetitive nature of border adjustments. The welfare-maximizing emissions price under a border adjustment can result in clean technology adoption by foreign firms but not by domestic firms, as seen in Figure 9a, or result in driving foreign competitors from the domestic market, as seen in Figure 9b. Sectors in which these latter issues are likely to arise could be selectively avoided if border adjustments were applied to specific industries, as debated in Europe, rather than applied as a blanket policy to all emissions-regulated sectors as proposed in the Waxman-Markey Bill (U.S. Congress, House 2009).

*The risk of "reciprocal" tariffs.* In addition to the welfare drivers included in (4), the domestic regulator must consider the risk of "reciprocal" tariffs that developing economic powers have threatened (e.g., Rappeport 2009, April 21; Kanter 2009, December 17). These "reciprocal" tariffs would almost certainly target sectors other than those covered by the border adjustment. The

<sup>12</sup> While not shown here, it is also straightforward to illustrate an example where a border adjustment provides a welfare advantage due to cleaner offshoring.

European Commission, for example, has debated border adjustment in the steel and cement sectors, but Europe is not an exporter of these goods to developing economies. Therefore, a “reciprocal” tariff would have to target arbitrary other sectors. Estimating the potential sectors selected and the magnitude of such a tariff is beyond the scope of this paper, but the domestic regulator would need to mitigate this threat (or weigh its potential fallout against the welfare advantages derived from a border adjustment) in order to fully assess the value of such a policy. A natural first step in mitigating the threat would be to target border adjustment only to sectors where foreign entry that existed prior to the implementation of emissions regulation would not be diminished.

## 6. Implications and Conclusions

Without a border adjustment, the domestic regulator’s ability to induce clean technology adoption is limited by the emissions price at which domestic production would move offshore (Corollary 1), a threshold that can occur at emissions prices sufficiently low to be of practical concern (Boston Consulting Group 2008). On the other hand, when a border adjustment is implemented, the domestic regulator is limited in its ability to decrease emissions in the region (Proposition 6c), which carries financial implications if the regulator faces emissions costs of their own. Further, foreign entry is shown to decrease in emissions price over intervals in which domestic production is inelastic in emissions price (Propositions 6b and 6c), suggesting that the debate related to whether border adjustments are potentially anticompetitive is likely to continue.

The popular belief is that a border adjustment eliminates the threat of carbon leakage. However, this is not always the case when firms choose production technologies and offshore producers hold a comparative cost advantage. In such a setting, foreign firms adopt clean technology at a lower emissions price than domestic firms (Proposition 5b), with entry conditionally increasing in emissions price over intervals in which foreign firms hold this advantage (Proposition 6b). Further, domestic firms conditionally move offshore despite a border adjustment, adopting cleaner technology when doing so (Proposition 5c). As a result, carbon leakage can occur under a border adjustment. When it does occur, global emissions conditionally *decrease* (Propositions 6e and 7c), which contrasts the increase that results in the absence of a border adjustment (Propositions 3d and 4c).

A border adjustment is shown to provide four conditional sources of welfare advantage: 1) the preservation of domestic firm profits by reducing or limiting foreign entry; 2) cleaner entry due to the adoption of lower-emissions technology by foreign firms; 3) cleaner domestic production in settings in which incentivizing the adoption of clean technology through emissions regulation is not possible without a border adjustment; and 4) cleaner offshoring by domestic firms. The latter two sources of advantage are mutually exclusive. In order to be accounted for in welfare analysis, all but the first of these potential sources of advantage require endogenous technology choice, highlighting the importance of incorporating this decision in assessments of border adjustment policy.

While a border adjustment provides clear advantages, it also raises issues related to its potential to prove anticompetitive. In some settings, the welfare-maximizing emissions price under border adjustment results in the adoption of clean technology by foreign firms but not by domestic firms. In other settings, it results in displacing foreign competition that would exist in the market without emissions regulation. A sector-specific border adjustment, as debated in Europe, could be targeted to avoid these issues and may therefore improve the likelihood of WTO approval.

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## Appendices

### A. Parameters for Numerical Illustrations

Figure(s)	$A$	$b$	$F$	$n_d$	$\gamma_1$	$\alpha_1$	$\gamma_2$	$\alpha_2$	$\delta$	$\tau$	$\alpha_\tau$	$\varepsilon_s$	$\varepsilon_r$
Figures 1a and 2a	120	.01	1000	4	70	.70	85	.20	.85	30	.15	-	-
Figures 1b and 2b	120	.01	1000	4	75	.70	85	.20	.85	30	.15	-	-
Figure 3a	-	-	-	-	50	1.0	70	.20	.75	20	-	-	-
Figure 3b	-	-	-	-	50	1.0	70	.20	.75	15	-	-	-
Figures 4a and 4b	120	.01	1000	4	50	.70	65	.20	.85	15	.10	-	-
Figure 6a	150	.05	1500	3	50	.75	60	.15	.80	25	.10	30	10
Figure 6b	150	.05	1500	3	50	.75	60	.15	.80	25	.10	30	40
Figure 6c	150	.05	1500	3	50	.75	58	.25	.80	25	.10	0	85
Figure 7a	120	.01	2000	4	50	.60	65	.20	.95	25	.05	20	0
Figure 7b	120	.01	2000	4	50	.60	65	.20	.95	25	.05	20	15
Figure 7c	120	.01	2000	4	50	.60	65	.20	.95	25	.05	20	30
Figure 9a	125	.01	1000	4	50	.75	60	.1	.75	25	.1	varies	0
Figure 9b	120	.01	1500	4	50	.80	60	.1	.75	25	.1	varies	20
Figure 10	120	.01	1500	4	50	.75	65	.15	.85	25	.1	varies	0

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

## B. Settings without and with Border Adjustment

### Settings *without* border adjustment

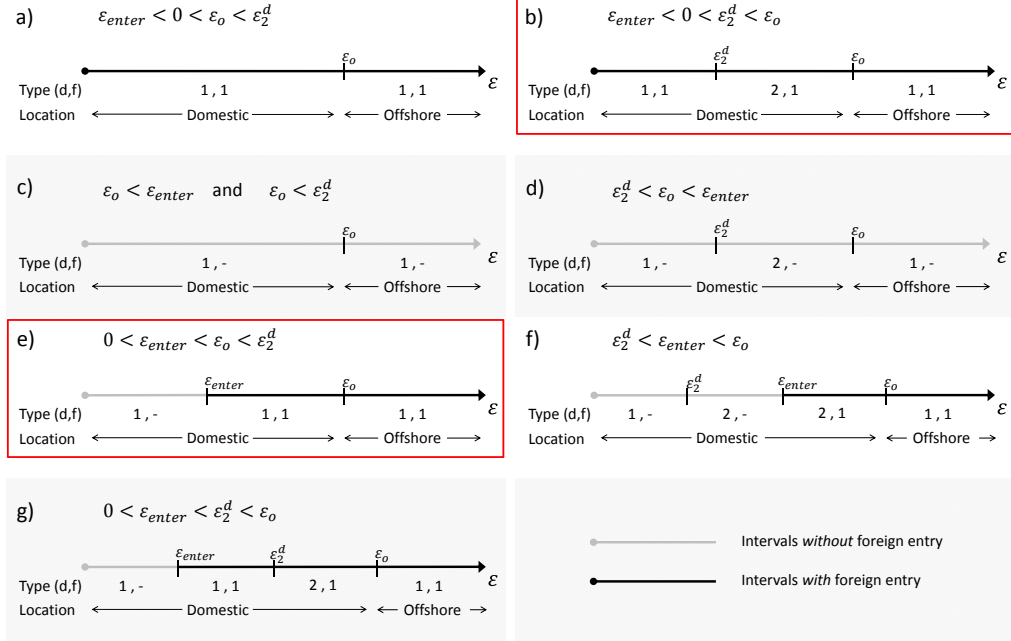


Figure B.1 Possible technology adoption, location, and foreign entry settings without border adjustment: b) corresponds to setting 1 in Section 5.1, and e) corresponds to setting 2 in Section 5.1.

### Settings *with* border adjustment

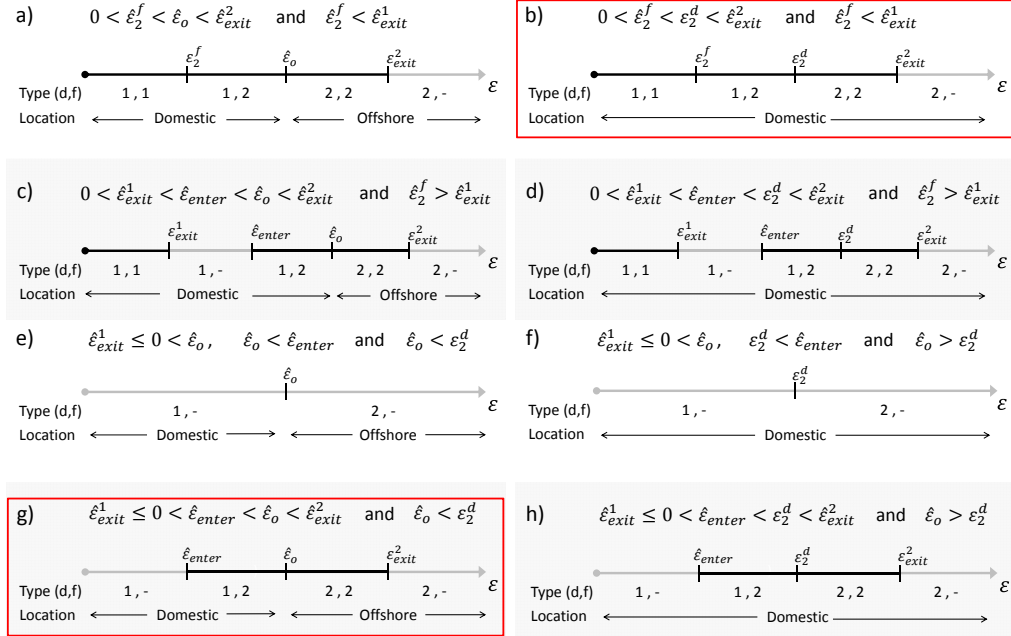


Figure B.2 Possible technology adoption, location and foreign entry settings with border adjustment: b) corresponds to Setting 1 within Section 5.2, and e) corresponds to setting 2 within Section 5.2.

### C. FOC Solutions in Setting 2 with Border Adjustment

Interval	FOC Solutions
$\varepsilon \in [0, \hat{\varepsilon}_{enter})$	$\hat{E}_{1,d}(\varepsilon_s) = \frac{(\varepsilon_s + \varepsilon_r)(n_d + 1)}{n_d} - \frac{A - \gamma_1}{n_d \alpha_1}$
$\varepsilon \in [\hat{\varepsilon}_{enter}, \hat{\varepsilon}_o)$	$\hat{E}_{1,d}^2(\varepsilon_s) = \frac{(\alpha_2 + \alpha_\tau)\alpha_2 \varepsilon_s - n_d(\alpha_1 - \alpha_2)\sqrt{Fb}}{\alpha_2^2} - \frac{n_d(\alpha_1 - \alpha_2)((\alpha_2 + \alpha_\tau - \alpha_1)\varepsilon_s + \delta\gamma_2 + \tau - \gamma_1 - \alpha_1 \varepsilon_r)}{\alpha_2^2}$
$\varepsilon \in [\hat{\varepsilon}_o, \hat{\varepsilon}_{exit}^2)$	$\hat{E}_{2,o}^2(\varepsilon_s) = \frac{(\alpha_2 + \alpha_\tau)\varepsilon_s}{\alpha_2}$
$\varepsilon \geq \hat{\varepsilon}_{exit}^2$	$\hat{E}_{2,o}^1(\varepsilon_s) = \frac{(n_d + 1)(\alpha_2 + \alpha_\tau)\varepsilon_s + (\delta\gamma_2 + \tau - A)n_d}{n_d^2 \alpha_2}$

Table C.1 Setting 2 emissions price intervals and their FOC solutions,  $\hat{E}_{k,d}^m(\cdot)$

## Technical Appendix

### T.1 Proofs

*Proof of joint concavity of firm objectives.* First order conditions for firm  $i \in \mathcal{N}_d$  and firm  $j \in \mathcal{N}_f$  are

$$\frac{\partial \pi_i(X_d, X_o, Y)}{\partial x_{i,l}} = A - b(X_o + X_d + Y) - bx_{i,l} - c_i(\varepsilon) = 0, \quad \forall i \in \mathcal{N}_d, \quad (\text{T.1})$$

and

$$\frac{\partial \pi_j(X_d, X_o, Y)}{\partial y_j} = A - b(X_o + X_d + Y) - by_j - \delta\gamma_j - \tau = 0, \quad \forall j \in \mathcal{N}_f. \quad (\text{T.2})$$

The joint concavity of firm objectives can be proven directly through the Hessian  $H(\pi)$ , where

$$H(\pi) = \begin{bmatrix} \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,l}^2} & \dots & \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,l} \partial x_{n_d,l}} & \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,l} \partial y_1} & \dots & \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,l} \partial y_{n_f}} \\ \vdots & \ddots & & & & \\ \frac{\partial^2 \pi_{n_d}(\cdot)}{\partial x_{n_d,l} \partial x_{1,l}} & & \frac{\partial^2 \pi_{n_d}(\cdot)}{\partial x_{n_d,l}^2} & & & \\ \frac{\partial^2 \pi_1(\cdot)}{\partial y_1 \partial x_{1,l}} & & & \frac{\partial^2 \pi_1(\cdot)}{\partial y_1^2} & & \\ \vdots & & & & \ddots & \\ \frac{\partial^2 \pi_{n_f}(\cdot)}{\partial y_{n_f} \partial x_{1,l}} & & & & & \frac{\partial^2 \pi_{n_f}(\cdot)}{\partial y_{n_f}^2} \end{bmatrix},$$

Based on the FOCs given by Equations (T.1) and (T.2), it is clear that the second derivative of domestic and offshore objectives are

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

while the cross-partials are

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

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 principle minors are strictly negative and all even-ordered leading principle minors are positive, thereby implying strict concavity.  $\square$

*Proof of Corollary 1* Given that  $\gamma_2 > \gamma_1$  under Assumption 2,  $\delta\gamma_1 + \tau < \delta\gamma_2 + \tau \forall \varepsilon$ . Therefore, foreign firms do not adopt clean technology as a consequence of emissions regulation. Domestic firms, if producing within the regulated region, would adopt clean technology at a minimum  $\varepsilon$  such that  $\gamma_1 + \alpha_1 \varepsilon = \gamma_2 + \alpha_2 \varepsilon$ , i.e., at the threshold  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ . Therefore, if  $\delta\gamma_1 + \tau < \gamma_2 + \alpha_2 \left( \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} \right)$ , then domestic firms would offshore rather than adopt type 2, and type 2 would not be adopted at any  $\varepsilon$ .  $\square$

*Proof of Proposition 1.* Equilibrium quantities under free entry are required to prove Proposition 1, and are defined by the following Lemma:

LEMMA 1. *With the number of domestic and foreign competitors fixed at  $n_d$  and  $n_f$ , respectively, domestic firms produce at equilibrium quantities*

$$x_{i,l}^* = \frac{A - c_i(\varepsilon)}{b(n_d + n_f + 1)} + \frac{n_f(c_j - c_i(\varepsilon))}{b(n_d + n_f + 1)},$$

and foreign firms will compete in the domestic market with equilibrium quantities of,

$$y_j^* = \frac{A - c_j}{b(n_d + n_f + 1)} - \frac{n_d(c_j - c_i(\varepsilon))}{b(n_d + n_f + 1)}.$$

**Proof of Lemma 1.** Since the problem is symmetric for all domestic firms and is likewise symmetric for all foreign firms, solving Equation (T.2) for  $y_j^*$  yields

$$y_j^* = \frac{A - c_j - bn_d x_{i,l}}{b(n_f + 1)}, \quad \forall j \in \mathcal{N}_f. \quad (\text{T.3})$$

Substituting (T.3) into  $Y = n_f y_j$  within Equation (T.1) and then solving for  $x_{i,l}$  yields

$$x_{i,l}^* = \frac{A - c_i(\varepsilon)}{b(n_d + n_f + 1)} + \frac{n_f(c_j - c_i(\varepsilon))}{b(n_d + n_f + 1)}, \quad \forall i \in \mathcal{N}_d, \quad (\text{T.4})$$

which, by substituting into Equation (T.3) yields

$$y_j^* = \frac{A - c_j}{b(n_d + n_f + 1)} - \frac{n_d(c_j - c_i(\varepsilon))}{b(n_d + n_f + 1)}, \quad \forall j \in \mathcal{N}_f. \quad (\text{T.5})$$

■

The number of offshore entrants follows directly from its definition,

$$\begin{aligned} \max_{y_j} \pi_j(X_d, X_o, Y) &= \max_{y_j} \left[ P(X_d, X_o, Y) y_j - c_j y_j \right] = F, \quad \forall j \in \mathcal{N}_f. \\ &\Rightarrow [A - b(n_d x_{i,l} + n_f y_j)] y_j - c_j y_j = F, \quad \forall j \in \mathcal{N}_f. \end{aligned}$$

The result then follows from the constraint that  $n_f \geq 0$  and standard algebra.

$$n_f^* = \max \left\{ 0, \frac{A - c_j - n_d(c_j - c_i(\varepsilon))}{\sqrt{Fb}} - n_d - 1 \right\}. \quad \square \quad (\text{T.6})$$

**Proof of Proposition 2** By the definition of  $c_i(\varepsilon)$ , when  $\varepsilon < \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$  domestic firms produce within the regulated region. Therefore, under the conditions of Proposition 2, a domestic oligopoly results with  $x_{i,d}$  following from Equation (T.4) when  $n_f^* = 0$  and  $c_i(\varepsilon) = \gamma_i + \alpha_i \varepsilon$ .

□

**Proof of Proposition 3.** By a direct comparison of domestic firm costs, the condition  $\varepsilon < \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$  implies that domestic firms produce within the domestic region rather than offshore.

Therefore, under the conditions of Proposition 3,  $c_i(\varepsilon) = \gamma_i + \alpha_i \varepsilon$ . The result follows by substituting the right-hand argument of (T.6) into the exogenous entry solutions for  $x_{i,l}$  and  $y_j$  given by Equations (T.4) and (T.5).

Foreign entry  $n_f^*$ , which is given by the right-hand argument of (T.6) when  $n_f^* > 0$  as in Proposition 3, and total foreign firm production,  $Y = n_f^* y_j$  both increase in  $\varepsilon$ , with

$$\frac{d n_f^*}{d \varepsilon} = \frac{n_d \alpha_i}{\sqrt{Fb}}, \quad \text{and} \quad \frac{d Y}{d \varepsilon} = \left( \frac{n_d \alpha_i}{\sqrt{Fb}} \right) \left( \frac{\sqrt{Fb}}{b} \right) = \frac{n_d \alpha_i}{b}. \quad (\text{T.7})$$

Total domestic production  $X_d + X_o = n_d x_{i,l}^*$  also increase under the conditions of Proposition 3a, with

$$\frac{d X_d + X_o}{d \varepsilon} = -\frac{n_d \alpha_i}{b}. \quad (\text{T.8})$$

Proposition 3b follows directly from (T.7) and (T.8). Proposition 3c follows by noting that total production increases in  $\varepsilon$  by foreign firms in (T.7) exactly offset production total domestic decreases in  $\varepsilon$  given by (T.8). Proposition 3d, follows from Proposition 3b, with domestic emissions  $n_d x_{i,d}^* \alpha_i$  decreasing at rate  $\frac{d n_d x_{i,d}^* \alpha_i}{d \varepsilon} = -\frac{n_d \alpha_i^2}{b}$ . Global emissions,  $n_d x_{i,d}^* \alpha_i + n_f^* y_j^* (\alpha_j + \alpha_\tau)$  with  $\frac{d n_d x_{i,d}^* \alpha_i + n_f^* y_j^* \alpha_j}{d \varepsilon} = -\frac{n_d \alpha_i^2}{b} + \frac{n_d \alpha_i}{b} (\alpha_j + \alpha_\tau) \geq \frac{n_d \alpha_i}{b} \alpha_\tau$ , given that  $\alpha_j \geq \alpha_i$ .  $\square$

**Proof of Proposition 4.** When  $\varepsilon > \varepsilon_o = \frac{\delta \gamma_1 + \tau - \gamma_i}{\alpha_i}$ , domestic firms offshore, which follows from the definition of  $c_i(\varepsilon)$ . Under offshoring, there are two cases to consider with respect to Proposition 4a: when foreign firms compete in equilibrium – i.e.,  $n_f^* > 0$  which occurs when  $\varepsilon \geq \varepsilon_o > \varepsilon_{enter}$  – and when they do not, i.e.,  $n_f^* = 0$  which occurs when  $\varepsilon \geq \varepsilon_o$  and  $\varepsilon_o \leq \varepsilon_{enter}$  (following from the definition of  $\varepsilon_{enter}$  and  $\varepsilon_o$ , and from Proposition 1). The proof in the case when foreign firms compete is symmetric to the proof of Proposition 3a, while noting that domestic firms adopt foreign firm economics under offshoring – i.e.,  $c_i(\varepsilon) = c_j = \gamma_1 + \tau$ . The result in the case of a domestic oligopoly (i.e.,  $\varepsilon_{enter} > \varepsilon_o$ , and therefore  $n_f^* = 0$ ) follows from (T.4) in the proof of Lemma 1 while noting that  $n_f^* = 0$  and  $c_i(\varepsilon) = \delta \gamma_1 + \tau$  when  $\varepsilon \geq \varepsilon_o$  and  $\varepsilon_o \leq \varepsilon_{enter}$ .

Proposition 4b follows from the equality of  $c_i(\varepsilon)$  and  $c_j$  under offshoring. Again, there are two cases to consider: the case when foreign firms have entered (i.e.,  $\varepsilon \geq \varepsilon_o > \varepsilon_{enter}$ ), and the case when there is a domestic oligopoly (i.e.,  $\varepsilon \geq \varepsilon_o$  and  $\varepsilon_o \leq \varepsilon_{enter}$ ). From Proposition 1 and Proposition 4a,  $\varepsilon \geq \varepsilon_o > \varepsilon_{enter}$  implies

$$n_f^* = \frac{A - \delta \gamma_1 - \tau}{\sqrt{Fb}} - n_d - 1 > 0 \quad \text{and} \quad x_{i,l}^* = y_j^* = \frac{\sqrt{Fb}}{b},$$

none of which depend on  $\varepsilon$ . Therefore, foreign entry and domestic quantities are fixed in  $\varepsilon$ .

By Proposition 4a, quantities when  $\varepsilon \geq \varepsilon_o$  and  $\varepsilon_o \leq \varepsilon_{enter}$  are

$$x_{i,l}^* = \frac{A - \delta \gamma_1 - \tau}{b(n_d + 1)}, \quad \text{and} \quad y_j^* = 0,$$

which do not depend on  $\varepsilon$ . Therefore Proposition 4b also holds when  $\varepsilon \geq \varepsilon_o$  and  $\varepsilon_o \leq \varepsilon_{enter}$ .

Proposition 4c follows from a comparison of global emissions  $e^g$  at the offshoring threshold  $\varepsilon_o = \frac{\delta\gamma_1 + \tau - \gamma_i}{\alpha_i}$ ,  $n_d x_{i,l}^* (\alpha_1 + \alpha_\tau) - n_d x_{i,l}^* \alpha_i \geq n_d x_{i,l}^* \alpha_\tau$ .  $\square$

**Proof of Proposition 5.** Proposition 5a follows from the definition of the total per unit cost of domestic firms' preferred technology,  $\hat{c}_i(\varepsilon)$ . Under a border adjustment, domestic firms will adopt clean technology at the minimum of  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$  and  $\hat{\varepsilon}_o = \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$ , which are both positive and finite given that  $\gamma_2 > \gamma_1$  and  $\alpha_1 > \alpha_2$ .

Proposition 5b follows from the offshore per unit production and capital cost advantage vis-a-vis domestic production. Under a symmetric border adjustment, foreign firms prefer technology 2 to technology 1 when  $\delta\gamma_2 + \alpha_2\varepsilon + \tau \leq \delta\gamma_1 + \alpha_1\varepsilon + \tau$ . Therefore, the lowest emissions price at which a foreign firm prefers technology 2 is  $\hat{\varepsilon}_2^f = \delta \left( \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} \right)$ . By a similar argument, the lowest price at which a firm producing domestically prefers technology 2 to technology 1 is at  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2}$ .  $\delta \in (0, 1)$  implies  $\hat{\varepsilon}_2^f < \varepsilon_2^d$  at emissions prices such that domestic firms produce locally.

Three cases must be considered with respect to Proposition 5c: when domestic and foreign firms produce with technology 1; when domestic and foreign firms both produce with technology 2; and when domestic firms produce with technology 1 and foreign firms produce with technology 2.

Case 1:  $\varepsilon < \hat{\varepsilon}_2^f$ . Note that  $\hat{c}_i(0) = \gamma_1 < \delta\gamma_1 + \tau = \hat{c}_j(0)$  by Assumption 3. As a consequence,  $\hat{c}_i(\varepsilon) = \gamma_1 + \alpha_1\varepsilon < \delta\gamma_1 + \alpha_1\varepsilon + \tau = \hat{c}_j(0) \quad \forall \varepsilon < \hat{\varepsilon}_2^f$ . Therefore, domestic firms will not offshore at any emissions price for which technology 1 is optimal for firms producing offshore.

Case 2:  $\varepsilon \geq \varepsilon_2^d$ . Assume  $\exists \varepsilon | \gamma_2 + \alpha_2\varepsilon < \delta\gamma_2 + \alpha_2\varepsilon + \tau$ . Under such an assumption, it is evident that  $\hat{c}_i(\varepsilon) = \gamma_2 + \alpha_2\varepsilon < \delta\gamma_2 + \alpha_2\varepsilon + \tau = \hat{c}_j(\varepsilon)$ ,  $\forall \varepsilon > \varepsilon_2^d$ . Therefore, if there exists an emissions price for which it is optimal for domestic firms to produce within the regulated region with technology 2, then domestic firms will not offshore at any  $\varepsilon$  greater than the domestic technology threshold,  $\varepsilon_2^d$ .

Case 3:  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Assume  $1 > \delta + \frac{\tau}{\gamma_2}$ . Then the domestic technology threshold is greater than the offshoring threshold  $\hat{\varepsilon}_o$ ,  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} > \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2} = \hat{\varepsilon}_o$ , which implies for an arbitrarily small  $\iota$

$$\hat{c}_i(\hat{\varepsilon}_o + \iota) = \min\{\gamma_1 + \alpha_1(\hat{\varepsilon}_o + \iota), \delta\gamma_2 + \alpha_2(\hat{\varepsilon}_o + \iota) + \tau\} = \delta\gamma_2 + \alpha_2(\hat{\varepsilon}_o + \iota) + \tau.$$

Assume instead that domestic firms operate technology 2 offshore, i.e.,  $\hat{c}_i(\varepsilon) = \hat{c}_j(\varepsilon) = \delta\gamma_2 + \alpha_2(\varepsilon) + \tau$ . Then, by case 2,  $\varepsilon_2^d = \frac{\gamma_2 - \gamma_1}{\alpha_1 - \alpha_2} > \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2} = \hat{\varepsilon}_o$ , which implies  $1 > \delta + \frac{\tau}{\gamma_2}$ . It follows from case 1, 2 and 3 that domestic firms will offshore iff the optimal offshore technology is cleaner than the optimal domestic technology, and  $1 > \delta + \frac{\tau}{\gamma_2}$ .  $\square$

**Proof of Corollary 2** The proof is symmetric to that of Proposition 1, and follows directly from Equation (T.6) while substituting  $\hat{c}_i(\varepsilon)$  for  $c_i(\varepsilon)$  and  $\hat{c}_j(\varepsilon) = \delta\gamma_j + \alpha_j\varepsilon + \tau$  for  $c_j$ .  $\square$

**Proof of Corollary 3** By Proposition 5c and the definition of  $\hat{c}_i(\varepsilon)$ , when  $\varepsilon < \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  domestic firms produce locally. Therefore, under the conditions of Proposition 3, a domestic oligopoly results with  $x_{i,d}$  following from Equation (T.4) when  $\hat{n}_f^* = 0$  and  $\hat{c}_i(\varepsilon) = \hat{\gamma}_i + \hat{\alpha}_i\varepsilon$ .  $\square$

**Proof of Proposition 6.** The proof of Proposition 6a is symmetric to that of Proposition 3. The result follows directly from  $\hat{n}_f^* > 0$  (and therefore  $\hat{n}_f^*$  is defined by the right-hand argument of Corollary 2), and by substituting  $\hat{c}_i(\varepsilon) = \hat{\gamma}_i + \hat{\alpha}_i\varepsilon$  for  $c_i(\varepsilon)$ , and  $\hat{c}_j(\varepsilon) = \delta\hat{\gamma}_j + \hat{\alpha}_j\varepsilon + \tau$  for  $c_j$  in Equations (T.4) and (T.5).

There are two cases to consider with respect to Proposition 6b: the case when foreign firms operate cleaner technology than domestic firms, and the case when domestic and foreign firms operate the same technology.

CASE 1:  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Foreign technology is cleaner than domestic technology when  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Further, by the conditions of Proposition 6,  $\hat{n}_f^* > 0$  and is defined by the right-hand argument of Corollary 2. In this case,  $\frac{d\hat{n}_f^*}{d\varepsilon} = \frac{-\alpha_2 + n_d(\alpha_1 - \alpha_2)}{\sqrt{Fb}}$ , which is non-negative when  $\frac{\alpha_1}{\alpha_2} \geq 1 + \frac{1}{n_d}$ , but is strictly negative when  $\frac{\alpha_1}{\alpha_2} < 1 + \frac{1}{n_d}$ .

CASE 2:  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Domestic and foreign firms operate the same technology when  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$  (type 1 if  $\varepsilon < \hat{\varepsilon}_2^f$ , and type 2 if  $\varepsilon > \varepsilon_2^d$ ). In such a case,  $\hat{\alpha}_i = \hat{\alpha}_j$ . It is clear from Corollary 2 (given that  $\hat{n}_f^* > 0$ ) that  $\frac{d\hat{n}_f^*}{d\varepsilon} = -\frac{\hat{\alpha}_j}{\sqrt{Fb}} < 0$ .

With respect to Proposition 6c, there are again two cases to consider: the case when foreign firms operate cleaner technology, and the case when domestic and foreign firms operate the same technology.

CASE 1:  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Foreign firms operate technology 2 and domestic operate technology 1 when  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . It is clear from Proposition 6a that total domestic production  $X_d + X_o = n_d x_{i,d}^*$  decreases in  $\varepsilon$ , with

$$\frac{d n_d x_{i,d}}{d\varepsilon} = n_d \left( \frac{\alpha_2 - \alpha_1}{b} \right) < 0.$$

CASE 2:  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Domestic and foreign firms operate the same technology when  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . In such a case,  $\hat{\alpha}_i = \hat{\alpha}_j$ , and it is clear from Proposition 6a that  $\frac{d n_d x_{i,d}}{d\varepsilon} = 0$  and total production by domestic firms is therefore fixed in emissions price.

For Proposition 6d, there are again two cases to consider: the case when foreign firms operate cleaner technology than domestic firms, and the case when domestic and foreign firms operate the same technology.

CASE 1:  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . Given that  $\hat{n}_f^*$ , when foreign firms operate technology 2 and domestic firms operate technology 1, it is evident from Corollary 2 and Proposition 6a that total production  $X_d + X_o + Y = n_d x_{i,d}^* + \hat{n}_f^* y_j^*$  decreases in  $\varepsilon$ , with

$$\frac{d X_o + X_d + Y}{d\varepsilon} = n_d \left( \frac{\alpha_2 - \alpha_1}{b} \right) + \left( \frac{-\alpha_2 + n_d(\alpha_1 - \alpha_2)}{\sqrt{Fb}} \right) \frac{\sqrt{Fb}}{b} = -\frac{\alpha_k}{b} < 0.$$

CASE 2:  $\varepsilon \notin [\hat{\varepsilon}_2^f, \varepsilon_2^d)$ . When domestic and foreign firms operate the same technology and  $\hat{n}_f^* > 0$ , it is also clear from Corollary 2 and Proposition 6a that total production  $X_d + X_o + Y = n_d x_{i,d}^* + \hat{n}_f^* y_j^*$  decreases in  $\varepsilon$ , with  $\frac{d X_o + X_d + Y}{d\varepsilon} = -\left( \frac{\alpha_k}{\sqrt{Fb}} \right) \frac{\sqrt{Fb}}{b} = -\frac{\alpha_k}{b} < 0$ .



By Proposition 6b, foreign entry can only increase in  $\varepsilon$  if  $\varepsilon \in [\hat{\varepsilon}_2^f, \varepsilon_k^2)$  and  $\frac{\alpha_k-1}{\alpha_k} \geq 1 + \frac{1}{n_d}$ . Under these conditions, and  $\hat{n}_f^* > 0$ , offshore firms operate technology 2 and domestic firms operate technology 1. As a consequence, global emissions,  $e^g$ , conditionally decreases in  $\varepsilon$ , as

$$\frac{d e^g(X_d, X_o, Y)}{d \varepsilon} = -n_d(\alpha_1 - \alpha_2)^2 + n_d\alpha_\tau(\alpha_1 - \alpha_2) - \alpha_2(\alpha_2 + \alpha_\tau)$$

is negative if  $\alpha_\tau(\alpha_1 - \alpha_2) < (\alpha_1 - \alpha_2)^2 + \frac{\alpha_2(\alpha_2 + \alpha_\tau)}{n_d}$ , but is otherwise positive, proving Proposition 3e.

□

**Proof of Proposition 7.** With respect to Proposition 7a, two cases must be considered: when domestic firms offshore and there is no foreign entry, i.e.,  $\hat{n}_f^* = 0$ ; and when domestic firms offshore and face competition from entrants, i.e.,  $\hat{n}_f^* > 0$ .

CASE 1:  $\hat{n}_f^* = 0$ . When  $\varepsilon \leq \frac{A - \delta\gamma_2 - \tau - (n_d+1)\sqrt{Fb}}{\alpha_2}$ ,  $\hat{n}_f^* = 0$  by Corollary 2. In such a case, domestic quantities follow from Equation T.4 with  $\hat{n}_f^* = 0$  and substituting  $\hat{c}_i(\varepsilon) = \delta\gamma_2 + \alpha_2\varepsilon + \tau$  for  $c_i(\varepsilon)$ .

CASE 2:  $\hat{n}_f^* > 0$ .  $\varepsilon > \frac{A - \delta\gamma_2 - \tau - (n_d+1)\sqrt{Fb}}{\alpha_2}$  implies  $\hat{n}_f^* > 0$  by Corollary 2. Under this condition,  $x_{i,o}^*$  and  $y_j^*$  are determined by Equations (T.4) and (T.5), respectively, while substituting the right-hand argument of Corollary 2 for  $\hat{n}_f^*$ , and  $\hat{c}_i(\varepsilon) = \hat{c}_j(\varepsilon) = \delta\gamma_2 + \alpha_2\varepsilon + \tau$  for  $c_i(\varepsilon)$  and  $c_j$ .

Proposition 7b follows from 7a when  $\hat{n}_f^* = 0$ , and from Proposition 7a and Corollary 2 when  $\hat{n}_f^* > 0$ . In the former case, clearly  $\frac{dX_o + X_d + Y}{d\varepsilon} = -\frac{n_d\alpha_2}{b(n_d+1)} < 0$ . In the latter case,  $\frac{dX_o + X_d + Y}{d\varepsilon} = -\frac{\alpha_2}{b} < 0$ .

Proposition 7c follows from a comparison of global emissions  $e^g$  at the offshoring threshold  $\hat{\varepsilon}_o = \frac{\delta\gamma_2 + \tau - \gamma_1}{\alpha_1 - \alpha_2}$  when technology 1 is utilized by domestic firms within the regulated region, and when technology 2 is utilized offshore. It is straightforward to show that global emissions are strictly less under offshoring if  $\alpha_1 - \alpha_2 > \alpha_\tau$  for the case when  $\hat{n}_f^* = 0$ , and when  $\hat{n}_f^* > 0$ .

Proposition 7d follows from the definition of global emissions, and the solutions provided for  $\hat{n}_f^*$  in Corollary 2 and for  $x_{i,o}^*$  and  $y_j^*$  in Proposition 7a. When  $\hat{n}_f^* = 0$ ,  $\frac{d e^g}{d \varepsilon} = -\frac{n_d\alpha_2(\alpha_2 + \alpha_\tau)}{b(n_d+1)}$ , and when  $\hat{n}_f^* > 0$ ,  $\frac{d e^g}{d \varepsilon} = -\frac{\alpha_2(\alpha_2 + \alpha_\tau)}{b}$ , which are both negative. □

**Proof of welfare concavity without border adjustment.** Table T.1 summarizes each element of domestic welfare under each potential equilibrium market structure:

	Domestic Oligopoly	Domestic Prod. & Entry	Offshore Prod. & Entry	Offshore Oligopoly
$\pi$	$n_d\pi_i^*(\cdot)$	$n_d\pi_i^*(\cdot)$	$n_d\pi_i^*(\cdot)$	$n_d\pi_i^*(\cdot)$
$\psi$	$\frac{1}{2}b(n_dx_i^*)^2$	$\frac{1}{2}b(n_dx_i^* + n_f^*y_j^*)^2$	$\frac{1}{2}b(n_dx_i^* + n_f^*y_j^*)^2$	$\frac{1}{2}b(n_dx_i^*)^2$
$\rho$	$n_dx_i^*\alpha_i\varepsilon$	$n_dx_i^*\alpha_i\varepsilon$	-	-
$\eta$	$n_dx_i^*\alpha_i\varepsilon_r$	$n_dx_i^*\alpha_i\varepsilon_r$	-	-
$\xi$	$n_dx_i^*\alpha_i\varepsilon_s$	$(n_dx_i^*\alpha_i + n_f^*y_j^*(\alpha_j + \alpha_\tau))\varepsilon_s$	$(n_dx_i^*(\alpha_i + \alpha_\tau) + n_f^*y_j^*(\alpha_j + \alpha_\tau))\varepsilon_s$	$n_dx_i^*(\alpha_i + \alpha_\tau)\varepsilon_s$

Table T.1 Welfare elements under the four possible equilibrium market structures without border adjustment.

With  $\pi_i$  given by (1),  $_f^*$  by Proposition 1, and domestic and foreign quantities for each market structure given by Propositions 2, 3a, and 4a, the welfare objective FOCs follow directly:

*Domestic Oligopoly FOC and concavity:*

$$\varepsilon = \frac{(\varepsilon_r + \varepsilon_s)(n_d + 1)\alpha_i - A + \gamma_i}{\alpha_i n_d} \quad (\text{T.9})$$

$$\frac{\partial^2 W}{\partial^2 \varepsilon} = -\frac{\alpha_i^2 n_d^2}{b(n_d + 1)^2} \quad (\text{T.10})$$

*Domestic Production and Foreign Entry first derivative and concavity:*

$$\frac{\partial W}{\partial \varepsilon} = -\frac{\alpha_i \left( \sqrt{Fb} + (\alpha_1 + \alpha_\tau - \alpha_i)\varepsilon_s + \tau - \gamma_i - \alpha_i \varepsilon_r + \delta \gamma_1 \right) n_d}{b} \quad (\text{T.11})$$

$$\frac{\partial^2 W}{\partial^2 \varepsilon} = 0 \quad (\text{T.12})$$

*Offshore Production and Foreign Entry FOC and concavity:* It is clear from Proposition 1 and Proposition 4a that, quantities and entry do not depend on  $\varepsilon$ , when domestic firms operate offshore and foreign firms compete in the market. Therefore  $\frac{\partial W}{\partial \varepsilon} = 0$ .

*Offshore Oligopoly FOC and concavity:* As above, it is clear from Proposition 1 and Proposition 4a that, in the case of an offshore oligopoly, quantities and entry do not depend on  $\varepsilon$ , and therefore  $\frac{\partial W}{\partial \varepsilon} = 0$ .

Based on (T.10), it is clear that welfare is concave in emissions price under a domestic oligopoly. Based on (T.12) and the independence of firm decisions wrt to  $\varepsilon$  when domestic firms operate offshore, it is clear the welfare is linear in  $\varepsilon$  under these market structures.  $\square$

**Proof of Proposition 8.** The properties defined in the following Lemma facilitate the proof.

LEMMA 2. a) Welfare increases over the interval  $\varepsilon \in [0, \varepsilon_2^d]$  iff  $\varepsilon_s < \varepsilon_{s,1} = -\frac{\sqrt{Fb} + \delta \gamma_1 - \alpha_1 \varepsilon_r + \tau - \gamma_1}{\alpha_\tau}$ , and over the interval  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o]$  iff  $\varepsilon_s < \varepsilon_{s,2} = -\frac{\sqrt{Fb} + \delta \gamma_1 - \alpha_2 \varepsilon_r + \tau - \gamma_2}{\alpha_1 + \alpha_\tau - \alpha_2}$ .

b) The disjoint change in social welfare resulting from the adoption of clean technology at  $\varepsilon_2^d$  is

$$\Delta_2 = \left( \frac{\sqrt{Fb}}{b} + \frac{\delta \gamma_1 + \tau - \gamma_1 - \alpha_1 \varepsilon_2^d}{b} \right) ((\varepsilon_s + \varepsilon_r)(\alpha_1 - \alpha_2) - \gamma_2 + \gamma_1) n_d.$$

c) The disjoint change in social welfare resulting from domestic firms offshoring at  $\varepsilon_o$  is

$$\Delta_o = -\frac{\sqrt{Fb}}{b} n_d ((\alpha_1 + \alpha_\tau - \alpha_2)\varepsilon_s - \gamma_2 - \alpha_2 \varepsilon_r + \delta \gamma_1 + \tau).$$

d) If  $\varepsilon_s < \varepsilon_{s,2}$ , then  $\Delta_o > 0$ .

**Proof of Lemma 2.** Lemma 2a follows directly from solving for the  $\varepsilon_s$  such that  $\frac{\partial W}{\partial \varepsilon} \geq 0$ , where

$$\frac{\partial W}{\partial \varepsilon} = -\frac{\left( \sqrt{Fb} + (\alpha_1 + \alpha_\tau - \alpha_i)\varepsilon_s - \alpha_i \varepsilon_r + \tau - \gamma_i + \delta \gamma_1 \right) n_d \alpha_i}{b}. \quad (\text{T.13})$$

Lemma 2b follows from a direct comparison welfare at  $\varepsilon = \varepsilon_2^d$ . Defining  $W_{k,l}^m(a)$  as welfare at  $\varepsilon = a$  when domestic firms operate technology  $k$  in region  $l$  while competing against foreign firms operating technology  $m$ . The disjoint social welfare gain for clean technology adoption follows directly;  $\Delta_2 = W_{2,d}^1(\varepsilon_2^d) - W_{1,d}^1(\varepsilon_2^d)$ .

Using the notation defined above, Lemma 2c follows directly from a comparison of welfare at  $\varepsilon_o$  when domestic firms produce offshore versus when they produce domestically;  $\Delta_o = W_{1,o}^1(\varepsilon_o) - W_{2,d}^1(\varepsilon_o)$ .

For Lemma 2d, first note that  $\Delta_o > 0$  iff  $\varepsilon_s < \frac{\gamma_2 - \delta\gamma_1 + \varepsilon_r\alpha_2 - \tau}{\alpha_1 + \alpha_\tau - \alpha_2}$ , which follows directly from Lemma 2c. It also follows directly that  $\varepsilon_{s,2} < \frac{\gamma_2 - \delta\gamma_1 + \varepsilon_r\alpha_2 - \tau}{\alpha_1 + \alpha_\tau - \alpha_2}$ . Therefore, if  $\varepsilon_s < \varepsilon_{s,2}$ , then  $\varepsilon_s$  must also be less than  $\frac{\gamma_2 - \delta\gamma_1 + \varepsilon_r\alpha_2 - \tau}{\alpha_1 + \alpha_\tau - \alpha_2}$ , and therefore  $\Delta_o > 0$ . ■

With respect to Proposition 8, welfare is linear over all intervals given that, without border adjustment,  $\frac{\partial^2 W}{\partial \varepsilon^2} = 0$  for all market structures aside from a domestic oligopoly (which is not included in Setting 1). Therefore, the welfare-maximizing emissions price must occur at a boundary, with the set of options limited to 0,  $\varepsilon_2^d - \iota$ ,  $\varepsilon_2^d$ ,  $\varepsilon_o - \iota$ , and  $\varepsilon_o$ , where  $\iota > 0$  and arbitrarily small.

*Proposition 8a:* By Lemma 2a, under the conditions of Proposition 8a, welfare decreases linearly over the intervals  $\varepsilon \in [0, \varepsilon_2^d)$  and  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$ . Therefore,  $\varepsilon_2^d - \iota$  and  $\varepsilon_o - \iota$  can be eliminated as potential boundary solutions.

*Proposition 8b:* By Lemma 2a, under the conditions of Proposition 8b, welfare increases linearly over the interval  $\varepsilon \in [0, \varepsilon_2^d)$ , and decreases linearly over the interval  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$ . Therefore, 0 and  $\varepsilon_o - \iota$  can be eliminated as potential boundary solutions.

*Proposition 8c:* By Lemma 2a, under the conditions of Proposition 8c, welfare increases linearly over the intervals  $\varepsilon \in [0, \varepsilon_2^d)$  and  $\varepsilon \in [\varepsilon_2^d, \varepsilon_o)$ . Therefore, 0 and  $\varepsilon_2^d$  can be eliminated as potential boundary solutions. By Lemma 2d,  $\Delta_o > 0$  and  $\varepsilon_o - \iota$  can be eliminated as a potential solution.

□

**Proof of Proposition 9.** The properties defined in the following Lemma facilitate the proof.

LEMMA 3. a) If it is interior,  $E_{1,d}(\varepsilon_s)$  is the local optima over the interval  $\varepsilon \in [0, \varepsilon_{enter}]$ , where

$$E_{1,d}(\varepsilon_s) = \frac{(\varepsilon_s + \varepsilon_r)(n_d + 1)}{n_d} - \frac{A - \gamma_1}{n_d\alpha_1}.$$

b) The disjoint change in social welfare resulting from domestic firms offshoring at  $\varepsilon_o$  is

$$\Delta_o = -n_d \left( \frac{A - \gamma_1 + \alpha_1\varepsilon}{b(n_d + 1)} \right) (\alpha_\tau\varepsilon_s - \gamma_2 - \alpha_1\varepsilon_r + \delta\gamma_1 + \tau).$$

c) If  $\varepsilon_s < \varepsilon_{s,1}$ , then  $\Delta_o > 0$ .

**Proof of Lemma 3.** Lemma 3a, follows directly from the FOC under a domestic oligopoly in settings without border adjustment, which is given by (T.9).

The proof of Lemma 3b is similar to that of Lemma 2b and 2c, and follows directly from a comparison of welfare at  $\varepsilon_o$  when domestic firms produce offshore versus when they produce domestically;  $\Delta_o = W_{1,o}^1(\varepsilon_o) - W_{1,d}^1(\varepsilon_o)$ . The key difference between this case and that in Lemma 2 is that, in setting 2, the offshoring comparison is relative to the domestic use of technology 1, rather than technology 2.

The proof for Lemma 3c, follows from a direct comparison of the social cost of carbon threshold for  $\Delta_o > 0$ , given above, to  $\varepsilon_{s,1}$ . The latter is  $\frac{\sqrt{Fb}}{\alpha\tau}$  less than the former. ■

Welfare increases over the interval  $\varepsilon \in (\varepsilon_{enter}, \varepsilon_o)$  if  $\varepsilon_s < \varepsilon_{s,1}$ , per Lemma 2a. If welfare decrease over the interval, then welfare is greater at  $\varepsilon = \varepsilon_{enter}$ , than it is at any point in the interval. If welfare increase over the interval, then  $\Delta_o > 0$  and welfare is greater at  $\varepsilon_o$  than it is as any point in the interval, per Lemma 3d.

*Proposition 9a:* Under the conditions of Proposition 9a, welfare decreases over the interval  $\varepsilon \in [0, \varepsilon_{enter}]$  due to the concavity of welfare in  $\varepsilon$ . Therefore, the only possible solutions are at the boundaries 0 and  $\varepsilon_o$ , with the latter following from the argument above.

*Proposition 9b:* Under the conditions of Proposition 9b,  $E_{1,d}(\varepsilon_s)$  is internal to  $\varepsilon \in [0, \varepsilon_{enter}]$ , and therefore the local optimal. As a consequence, the welfare-maximizing emissions price must be  $E_{1,d}(\varepsilon_s)$  or  $\varepsilon_o$ , with the latter following from the argument above.

*Proposition 9c:* Under the conditions of Proposition 9c, welfare increases over the interval  $\varepsilon \in [0, \varepsilon_{enter}]$  due to the concavity of welfare in  $\varepsilon$ , and welfare decreases over the interval  $\varepsilon \in (\varepsilon_{enter}, \varepsilon_o)$  by Lemma 2a. Therefore, the only possible solutions are at the boundaries  $\varepsilon_{enter}$  and  $\varepsilon_o$ , with the latter only if  $\Delta_o$  is sufficiently great.

*Proposition 9d:* Under the conditions of Proposition 9d, welfare increases over the interval  $\varepsilon \in [0, \varepsilon_{enter}]$  due to the concavity of welfare in  $\varepsilon$ , and welfare increases over the interval  $\varepsilon \in (\varepsilon_{enter}, \varepsilon_o)$  by Lemma 2a. Given the latter, welfare is greater over the interval  $\varepsilon \in (\varepsilon_{enter}, \varepsilon_o)$  than it is at any point in the interval  $\varepsilon \in [0, \varepsilon_{enter}]$ . By Lemma 3d,  $\Delta_o > 0$  and welfare is greater at  $\varepsilon = \varepsilon_o$  than at any point in the interval  $\varepsilon \in (\varepsilon_{enter}, \varepsilon_o)$ . It follows that  $\varepsilon_o$  must be the welfare-maximizing solution.

□

**Proof of concavity of regulator objective with border adjustment.** Table T.2 summarizes each element of domestic welfare under each potential equilibrium market structure:

With  $\pi_i$  given by (1),  $*$  by Proposition 1, and domestic and foreign quantities for each market structure given by Propositions 2, 3a, and 4a, the welfare objective FOCs follow directly:

	Domestic Oligopoly	Domestic Prod. & Entry	Offshore Prod. & Entry	Offshore Oligopoly
$\pi$	$n_d \hat{\pi}_i^*(\cdot)$	$n_d \hat{\pi}_i^*(\cdot)$	$n_d \hat{\pi}_i^*(\cdot)$	$n_d \hat{\pi}_i^*(\cdot)$
$\psi$	$\frac{1}{2} b (n_d x_i^*)^2$	$\frac{1}{2} b (n_d x_i^* + \hat{n}_f^* y_j^*)^2$	$\frac{1}{2} b (n_d x_i^* + \hat{n}_f^* y_j^*)^2$	$\frac{1}{2} b (n_d x_i^*)^2$
$\rho$	$n_d x_i^* \hat{\alpha}_i \varepsilon$	$(n_d x_i^* \hat{\alpha}_i + \hat{n}_f^* y_j^* \hat{\alpha}_j) \varepsilon$	$(n_d x_i^* \hat{\alpha}_i + \hat{n}_f^* y_j^* \hat{\alpha}_j) \varepsilon$	$n_d x_i^* \hat{\alpha}_i \varepsilon$
$\eta$	$n_d x_i^* \hat{\alpha}_i \varepsilon_r$	$n_d x_i^* \hat{\alpha}_i \varepsilon_r$	-	-
$\xi$	$n_d x_i^* \hat{\alpha}_i \varepsilon_s$	$(n_d x_i^* \hat{\alpha}_i + \hat{n}_f^* y_j^* (\hat{\alpha}_j + \alpha_\tau)) \varepsilon_s$	$(n_d x_i^* (\hat{\alpha}_i + \alpha_\tau) + \hat{n}_f^* y_j^* (\hat{\alpha}_j + \alpha_\tau)) \varepsilon_s$	$n_d x_i^* (\hat{\alpha}_i + \alpha_\tau) \varepsilon_s$

**Table T.2** Welfare elements under the four possible equilibrium market structures with border adjustment.

*Domestic Oligopoly FOC and concavity:*

$$\varepsilon = \frac{(\varepsilon_r + \varepsilon_s)(n_d + 1)\alpha_i + \gamma_i - A}{\alpha_i n_d} \quad (\text{T.14})$$

$$\frac{\partial^2 W}{\partial^2 \varepsilon} = -\frac{\alpha_i^2 n_d^2}{b(n_d + 1)^2} \quad (\text{T.15})$$

*Domestic Production and Foreign Entry FOC and concavity:*

$$\varepsilon = \frac{-(-\alpha_j + \alpha_i) \left( \varepsilon_s \alpha_j + (-\varepsilon_s - \varepsilon_r) \alpha_i + \delta \gamma_j + \alpha_\tau \varepsilon_s + \tau - \gamma_i + \sqrt{Fb} \right) n_d + (\alpha_j + \alpha_\tau) \alpha_j \varepsilon_s}{\alpha_j^2} \quad (\text{T.16})$$

$$\frac{\partial^2 W}{\partial^2 \varepsilon} = -\frac{\alpha_j^2}{b} \quad (\text{T.17})$$

*Offshore Production and Foreign Entry FOC and concavity:*

$$\varepsilon = \frac{(\alpha_2 + \alpha_\tau) \varepsilon_s}{\alpha_2} \quad (\text{T.18})$$

$$\frac{\partial^2 W}{\partial^2 \varepsilon} = -\frac{\alpha_2^2}{b} \quad (\text{T.19})$$

*Offshore Oligopoly FOC and concavity:*

$$\varepsilon = \frac{((\alpha_2 + \alpha_\tau) \varepsilon_s - A + \delta \gamma_2 + \tau) n_d + (\alpha_2 + \alpha_\tau) \varepsilon_s}{n_d^2 \alpha_2} \quad (\text{T.20})$$

$$\frac{\partial^2 W}{\partial^2 \varepsilon} = -\frac{n_d^2 \alpha_2^2}{b(n_d + 1)^2} \quad (\text{T.21})$$

It is clear from Equations (T.15), (T.17), (T.19), and (T.21) that welfare is concave in  $\varepsilon$  under each possible market structure.  $\square$