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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, potentially increasing overall carbon emissions in the process. Carbon tariffs have emerged as a possible mechanism to address this concern by imposing carbon costs on imports at the regulated region's border. Advocates claim that such a mechanism would level the playing field whereas opponents argue that such a tariff is anti-competitive. This paper analyzes how carbon tariffs affect technology choice, regional competitiveness, and global emissions through a model of imperfect competition between "domestic" (i.e., carbon-regulated) firms and "foreign" (i.e., unregulated) firms, where domestic firms have the option to offshore production and the number of foreign entrants is endogenous. Under a carbon tariff, results indicate that foreign firms would adopt clean technology at a lower emissions price than domestic producers, with the number of foreign entrants increasing in emissions price only over intervals where foreign firms hold this technology advantage. Further, domestic firms would only offshore production under a carbon tariff to adopt technology strictly cleaner than technology utilized domestically. As a consequence, under a carbon tariff, foreign market share is non-monotonic in emissions price, and global emissions conditionally decrease. Without a carbon tariff, foreign share monotonically increases in emissions price, and a shift to offshore production results in a strict increase in global emissions.

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Key words: Carbon regulation; Carbon leakage; Technology choice; Imperfect competition

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1. Introduction

Under emissions regulation such as the European Union Emissions Trading Scheme (EU-ETS) and California's pending Assembly Bill 32 (AB32), imports entering the region fall outside the regulatory regime and incur no carbon costs. With carbon regulation driving projected production cost increases in excess of 40% within some industries, this asymmetry endows production facilities located outside the regulated region with a windfall cost advantage, significantly altering the competitive landscape.

This cost advantage provides competitors outside the regulated region (i.e., "foreign" firms) with the opportunity to increase penetration into the regulated (i.e., "domestic") region, increasing penetration in sectors where they already compete, and potentially entering sectors where transport costs have prohibited a significant foreign presence (e.g., cement and steel in Europe). Further, the comparative economics resulting from this regulatory asymmetry can lead firms with domestic production to shift their facilities offshore in order to avoid carbon-related costs. Foreign entry and offshoring are both sources of *carbon leakage* – the shift of domestic production, and associated carbon impacts, to offshore locations as a result of emissions abatement policy. As a consequence of carbon leakage, whole industries may potentially be flushed from the regulated region. As stated by the Chairman of the third largest cement producer in the world, "The cost advantages of China would almost double as a result of CO2 expense, making competitive domestic production in Europe no longer an option" (HeidelbergCement 2008).

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 argue that such a measure would level the playing field by treating domestic and offshore production equivalently. Opponents argue that border adjustments impose a trade barrier and are anti-competitive. Within Europe, EU member states would have to vote unanimously to add a border adjustment to the EU-ETS, and both Britain and the Netherlands have publicly opposed such a measure. Within the US, the Waxman-Markey bill (H.R. 2454, 2009) passed successfully through the House of Representatives and included a border adjustment. However, while praising the proposed legislation as a whole, President Obama criticized the border adjustment, stating that "we have to be very careful about sending any protectionist signals" (Broder 2009).

Given the ongoing debate related to the implementation of border adjustments, the present paper explores the impact of this policy choice on technology adoption and regional competitiveness. The impact of carbon regulation with and without border adjustments is analyzed through a model of Cournot competition between a set of "domestic" firms established within the regulated region and an endogenous number of "foreign" firms entering the regulated region. Note that, in the case of local regulation, such as emissions regulation within California under AB32, "foreign" competitors would include firms in neighboring states who choose to compete in the emissions-regulated California market. Each firm competes for the domestic market by choosing production levels from a common set of technologies that vary in their emissions intensity and production and capital recovery costs. Domestic production incurs carbon costs dependent on the emissions intensity of the chosen technology, with domestic firms possessing the option to offshore production to avoid these costs. Imports to the domestic region incur a transport cost, with foreign firms also incurring a fixed entry cost.

To facilitate analysis, I define three sets of emissions price thresholds – thresholds for the adoption of cleaner technologies, foreign entry, and offshoring. Results indicate that, under a border adjustment, foreign firms' technology choice is more sensitive to domestic emissions regulation than domestic technology choice: when exposed to the same cost per unit of emissions, offshore production adopts cleaner technology at a lower emissions price than domestic production. This contrasts the setting without border adjustment where foreign firms' technology choice is insensitive to emissions price. Further, foreign entry is shown to increase monotonically in emissions price when there is no border adjustment. However, with border adjustments in place, entry increases conditionally over emissions price intervals where foreign firms utilize cleaner technology than domestic firms and strictly decreases in emissions price under a border adjustment when domestic and foreign firms operate identical technologies. This latter result lends credence to the argument that border adjustments could potentially prove anti-competitive. Further, without border adjustments, global emissions are shown to strictly increase as a result of leakage while global emissions conditionally decrease due to leakage when border adjustments are in place, providing an argument for border adjustment proponents.

The following section reviews literature related to the issues of regulatory asymmetry and border adjustment. Section 3 develops the model and solves for equilibrium quantities, profits, and emissions. Sections 4 and 5 explore technology choice, foreign entry, offshoring and resulting production decisions without and with border adjustment, respectively, and analyzes the consequences for global emissions. Implications and promising directions for future work are discussed in Section 6.

2. Literature Review

Academics have weighed in on the issue of carbon leakage and border adjustment within the fields of Public Policy and Economics. 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 is set to expire (e.g., van Asselt and Brewer 2010; Kuik and Hofkes 2010; Monjon and Quirion 2010). Therefore, one of the key issues within the Policy literature relates to the legality of border adjustments as a leakage-mitigating mechanism considering 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 conditionally legal, but as yet untested before a WTO panel, with the principle condition for legality being the elimination of the free allocation of allowances (Grubb and Neuhoff 2006; de Cendra 2006). Others conclude that border adjustments may only be legal under WTO and GATT law for inputs directly incorporated into finished goods (e.g., clinker into cement), but legality is less likely for inputs, such as energy, that are not incorporated into the finished product (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 sector-specific flat carbon cost based on the emissions intensity of the "best available technology" – i.e., a cost independent of the technology used to produce the import. The present paper accommodates both of these proposed border adjustment regimes.

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, Ponssard and Walker (2008) numerically estimate leakage within EU cement under full cap-and-trade allowance auctioning. While both Demailly and Quirion (2006) and Ponssard and

Walker (2008) 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 offshore production. Lockwood and Whaley (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 its impact.

Technology innovation and adoption in response to environmental regulation has been a focal interest within the Environmental Economics literature, with Jaffe et al. (2002) and Popp, et al. (2008) providing thorough reviews. However, the studies reviewed and the majority of the technology innovation and adoption literature in Environmental Economics do not address issues related to carbon leakage and border adjustment, which are of primary interest here. Requate (2006) provides a review of literature pertaining to environmental policy under imperfect competition with the vast majority of the studies considering homogenously regulated firms without technology choice. Of the exceptions, Bayindir-Upmann (2004) considers imperfect competition under asymmetric emissions regulation (and a labor tax) between a set of regulated firms and a set of unregulated 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 study leakage through an analytical model of imperfect competition between two asymmetrically regulated regions, showing that the regulated region's ability to change technology attenuates leakage effects. Fowlie (2009) studies leakage under imperfect competition when firms operate different but exogenous technologies and then simulates California's electricity sector, 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 of imperfect competition, aggregating bilateral trade data into regions and commodity groups, 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 in conjunction with their focus on leakage, and only Di Maria and van der Werf (2006) allow for technology choice.

The study of emissions regulation in general is far more nascent within Operations Management (OM), without any work related to leakage and border adjustment to the author's knowledge. Krass et al. (2010) and Drake et al. (2010) both consider technology choice under emissions regulation in non-competitive 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 and that all firms operate in a single region and face the same regulatory environment (i.e., no leakage). Islegen and Reichstein (2009) also study technology choice in a competitive sector under emissions regulation, exploring 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.

Within the general OM literature, Cournot competition has been widely used as a foundation to study various competitive environments. It has been used to study competitive investment in flexible technologies (e.g., Röller and Tombak 1993; Goyal and Netessine 2007), competition when firms are able to share asymmetric information (e.g., Li 2002; Ha and Tong 2008), competition across multi-echelon supply chains (e.g., Carr and Karmarker 2005; Ha et al. 2011), and competition within specific markets such as the energy sector (e.g., Hobbs and Pang 2007) and the influenza vaccine market (Deo and Corbett 2009). The present paper employs Cournot competition to study the impact of asymmetric emissions regulation with and without border adjustment when firms' technology choices and the number of foreign entrants are endogenous.

This paper contributes to the OM literature by introducing the issues of border adjustment and carbon leakage. As the analysis that ensues makes evident, border adjustments (or lack thereof) play a vital role in determining firms' technology and production choices, both of which are fundamental OM decisions that ultimately determine economic and environmental performance. Border adjustments also play a pivotal role in determining the nature of regional competitiveness and the potential for carbon leakage, which represents an emerging and important cause of offshoring.

The paper also contributes to the general literature by studying the impact of border adjustment policy when firms choose production technologies. This represents a critical contribution as results here illustrate that the border adjustment policy decision and firms' technology choices interact to fundamentally determine the nature of regional competitiveness, the risk of carbon leakage, and the potential for carbon regulation to achieve a reduction in global emissions. As such, this paper raises important implications related to the role and feasibility of border adjustments in mitigating leakage effects that can result from current, uncoordinated emissions abatement efforts.

3. Competition under a Regionally Asymmetric Emissions Regulation

Under current emissions regulation, domestic production incurs emissions costs while offshore production does not. As a result, imports can compete within the carbon-regulated region with a new-found advantage. Such asymmetric regulation has the potential to alter the competitive balance between domestic and foreign firms. All proofs are provided in Appendix 1.

3.1. Model development

A regulator imposes an emissions price ε for each unit of emissions generated through domestic production. Within this environment, a set of domestic firms $\mathcal{N}_d = \{1, \ldots, n_d\}$ engages in Cournot competition with a of set foreign firms $\mathcal{N}_o = \{0, \ldots, n_o\}$[1]. Each domestic firm $i \in \mathcal{N}_d$ can choose their production location, $l \in \mathcal{L} = \{d, o\}$, where d indicates domestic production and o indicates offshore production. In other words, firms with established domestic production (i.e., those firms belonging to $\mathcal{N}_d$) can continue to operate within the domestic region or choose to offshore. However, each potential foreign entrant $j \in \mathcal{N}_o$ can only choose to produce offshore. This assumes that the domestic market is mature prior to the implementation of emissions regulation, which is the case for emissions regulated sectors – e.g., cement, steel, glass, pulp and paper.

Foreign firms can choose to enter and compete in the domestic market, but only if they can earn an operating profit of at least $F > 0$, where F represents a fixed entry cost – e.g., investment in distribution infrastructure and customer acquisition. Alternatively, F can be thought of as the

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

minimum operating profit required to motivate a foreign firm to enter the domestic market. The firms that enter also incur transport cost $\tau > 0$ for each unit imported into the domestic market.

Both domestic and foreign firms develop capacities by choosing from a common set of production technologies $\mathcal{K} = \{1, \ldots, m\}$, with $\gamma_k > 0$ representing the unit production and capital recovery cost of the k^{th} technology and $\alpha_k \geq 0$ representing the k^{th} technology's emissions intensity (i.e., emissions per unit of production), where $k \in \mathcal{K}$. Offshore production generates an additional $\alpha_\tau > 0$ emissions per unit through transport. Further, foreign firms incur a per unit border adjustment cost of $\beta_k \geq 0$ (with $\beta_k = 0$, $\forall k$ representing the case with no border adjustment implemented). These border adjustment costs are general here, but will be characterized as symmetric in Section 5. A discount factor $\delta \in (0,1)$ represents the difference in production and capital recovery cost between offshore and domestic regions (due to differences in labor and other input costs), which is assumed to be less than 1 in regions where offshore production would be attractive. Therefore, the per unit landed cost of technology k operated in location l is

$$c_{k,l}(\varepsilon, \beta) = \begin{cases} \gamma_k + \alpha_k \varepsilon & \text{if } l = d \\ \delta\gamma_k + \tau + \beta_k & \text{if } l = o. \end{cases}$$

Table 1 summarizes set notation while Table 2 summarizes cost and emissions parameters.

Index	**Set**	**Elements**
$i =$ domestic competitor	$\mathcal{N}_d$	$\{1, \ldots, n_d\}$
$j =$ foreign competitor	$\mathcal{N}_o$	$\{1, \ldots, n_o\}$
$k =$ production technology	$\mathcal{K}$	$\{1, \ldots, m\}$
$l =$ production location	$\mathcal{L}$	$d =$ domestic $o =$ offshore

Table 1 Indices, sets and elements for competitors, locations and technologies.

Among domestic competitors, firm i chooses quantities $x_{i,k,l}$ for each technology k and location l, with X_d representing total domestic production, $\sum_{i=1}^{n_d} \sum_{k=1}^{m} x_{i,k,d}$. Total production offshored by domestic competitors is defined as $X_o = \sum_{i=1}^{n_d} \sum_{k=1}^{m} x_{i,k,o}$. Among foreign competitors, firm j chooses quantities $y_{j,k}$, with total production by foreign entrants defined as $Y = \sum_{j=1}^{n_o} \sum_{k=1}^{m} y_{j,k}$. The market is assumed to clear at price $P(X_d, X_o, Y) = A - b(X_d + X_o + Y)$ with $A > \min_{k \in \mathcal{K}} c_{k,l}(\varepsilon, \beta)$ to avoid the trivial case where no competitor produces, and $b > 0$.

Parameter	Description
ε	Price per unit of emissions
τ	Transport cost per finished good unit
β_k	Border adjustment cost per finished good unit for technology $k \in \mathcal{K}$
F	Fixed entry cost (e.g, distribution infrastructure, customer acquisition)
γ_k	Per unit production and capital recovery cost of technology $k \in \mathcal{K}$
α_k	Emissions intensity of technology $k \in \mathcal{K}$
α_τ	Emissions intensity of transport
δ	Discount factor for offshore production
$c_{k,l}(\varepsilon, \beta_k)$	Total per unit cost of technology $k \in \mathcal{K}$ from location $l \in \mathcal{L}$

Table 2 Cost and emissions parameters.

Objectives and metrics Firms choose quantities to maximize profits while anticipating competitors' decisions, so domestic firm i maximizes profits

$$\max_{x_{i,k,l},\forall k,l} \pi_i(X_d, X_o, Y) = \max_{x_{i,k,l},\forall k,l} \sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}} \Big[P(X_d, X_o, Y)\, x_{i,k,l} - c_{k,l}(\varepsilon, \beta_k)\, x_{i,k,l}\Big], \;\forall i \in \mathcal{N}_d \quad (1)$$

$$\text{s.t.} \quad x_{i,k,l} \geq 0, \quad \forall i \in \mathcal{N}_d,\; k \in \mathcal{K},\; l \in \mathcal{L},$$

while foreign competitor j solves

$$\max_{y_{j,k},\forall k} \pi_j(X_d, X_o, Y) = \max_{y_{j,k},\forall k} \sum_{k\in\mathcal{K}} \Big[P(X_d, X_o, Y)\, y_{j,k} - c_{k,o}(\varepsilon, \beta_k)\, y_{j,k}\Big], \forall j \in \mathcal{N}_o \quad (2)$$

$$\text{s.t.} \quad y_{j,k} \geq 0, \quad \forall j \in \mathcal{N}_o,\; k \in \mathcal{K}.$$

The Kyoto Protocol was intended to abate emissions at the global level to combat the suspected anthropogenic driver of climate change. Therefore, define global emissions e^g as

$$e^g(X_d, X_o, Y) = \sum_{i=1}^{n_d} \sum_{k=1}^{m} \alpha_k x_{i,k,d} + \sum_{k=1}^{m} \left[\sum_{i=1}^{n_d} (\alpha_k + \alpha_\tau)\, x_{i,k,o} + \sum_{j=1}^{n_o} (\alpha_k + \alpha_\tau)\, y_{j,k}\right]. \quad (3)$$

Since ratifying nations are obligated to meet agreed-upon Kyoto reductions or face financial consequences, the regulator of the domestic region may also be concerned with its regional emissions. The first term in (3) characterizes domestic emissions, and will be indicated throughout.

Let domestic firm i's preferred technology be represented by $k^*_{i,d}$ and its production cost by $\hat{c}_{i,k^*_d}(\varepsilon, \beta_k)$, so

$$\hat{c}_{i,k^*_d}\left(\varepsilon, \beta_{k^*_d}\right) = \min_{k\in\mathcal{K}} \{c_{k,d}(\varepsilon, \beta_k), c_{k,o}(\varepsilon, \beta_k)\}, \;\forall i \in \mathcal{N}_d. \quad (4)$$

Further, let foreign firm j's preferred technology be represented by $k^*_{j,o}$ and its cost by $\hat{c}_{j,k^*_o}(\varepsilon, \beta_k)$,

$$\hat{c}_{i,k^*_o}\left(\varepsilon, \beta_{k^*_o}\right) = \min_{k\in\mathcal{K}} c_{k,o}(\varepsilon, \beta_k), \;\forall j \in \mathcal{N}_o. \quad (5)$$

Equations (4) and (5) capture the following: domestic firms can produce locally or choose to relocate offshore. Of their $2m$ possibilities, domestic firms will utilize the technology/location pair with the lowest cost. The foreign firm, on the other hand, does not have the option to produce domestically. Therefore, foreign firms choose the lowest cost technology from among their m possibilities. It is important to note that the lowest cost domestic technology may differ from the lowest cost offshore technology. Since technology preference is symmetric for all domestic firms, and similarly symmetric for all foreign firms, I drop the i and j notation. Lastly, only feasible technologies are included in $\mathcal{K}$ – i.e., each technology is preferred at some emissions price.

Assumption 1. *Each technology under consideration is preferred at some emissions price,* $\exists\, \varepsilon |\, c_{k,d}(\varepsilon, \beta_k) = \hat{c}_{k_d^*}\left(\varepsilon, \beta_{k_d^*}\right),\ \forall k \in \mathcal{K}$.

Denote r as the region of domestic firms' lowest cost option, so that $r = d$ if $\hat{c}_{k_d^*}\left(\varepsilon, \beta_{k_d^*}\right) \neq \hat{c}_{k_o^*}\left(\varepsilon, \beta_{k_o^*}\right)$, and $r = o$ otherwise. Within the remainder of the paper, production and capital recovery costs, emissions intensity and the border adjustment costs of the domestic firms' preferred technology/location pair are noted as $\hat{\gamma}_d(\varepsilon)$, $\hat{\alpha}_d(\varepsilon)$ and $\hat{\beta}_d(\varepsilon)$, respectively. Similarly, the production and capital recovery cost, emissions intensity and border adjustment of foreign firms' preferred technology are noted as $\hat{\gamma}_o(\varepsilon)$, $\hat{\alpha}_o(\varepsilon)$ and $\hat{\beta}_o(\varepsilon)$. Each of these parameters depends on emissions price as the preferred technology varies in ε. However, for the sake of brevity, this dependency will be excluded from future notation where it is clear.

3.2. Number of foreign entrants

Within the emissions regulated setting, the number of foreign firms entering the domestic market will depend on the number of domestic competitors already established within the market, their cost structure and market parameters. Therefore a method similar to that employed by Deo and Corbett (2009) is used to endogenize the number of foreign entrants. Foreign firms compete operating profits down to the minimum level that motivates entry – i.e., $\max\{0, n_o^* | \pi_j^*(X_d, X_o, Y, n_o^*) = F\}$. The following proposition characterizes the number of foreign entrants.

Proposition 1. *At equilibrium, the following number of foreign firms will compete in the domestic market*

$$n_o^* = \max\left\{0, \frac{A - \hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) - n_d\left(\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)\right)}{\sqrt{Fb}} - n_d - 1\right\}. \tag{6}$$

The number of foreign firms that choose to compete within the domestic market increases in the market size, A, and decreases in the foreign competitors' total landed cost, $\hat{c}_{k_o^*}(\cdot)$ and the number of domestic competitors, as might be expected. Consider the weighted difference $n_d\left(\hat{c}_{k_o^*}(\cdot) - \hat{c}_{k_d^*}(\cdot)\right)$. Defining $N^* = n_d + n_o^*$ as the number of total firms competing at equilibrium and assuming $n_o^* > 0$, then N^* is independent of n_d when domestic firms have offshored production. Under such conditions, an increase in n_d is offset by an equivalent decrease in n_o^*, so that the total number of competitors remains unchanged. Therefore, when domestic firms produce offshore and $n_o^* > 0$, the total number of firms competing within the domestic market depends only on the cost structure of foreign firms, $\hat{c}_{k_o^*}(\cdot)$ and F, and market parameters A and b.

When the domestic firm produces locally, N^* increases in the number of domestic firms at a rate of $1 - \frac{\hat{c}_{k_o^*}(\cdot) - \hat{c}_{k_d^*}(\cdot)}{\sqrt{Fb}}$. Note that the equilibrium number of competitors will decrease with the addition of a domestic firm if $\hat{c}_{k_o^*}(\cdot) - \hat{c}_{k_d^*}(\cdot) > \sqrt{Fb}$. Further, assuming no border adjustment (i.e., $\beta_k = 0$) and domestic production as the lowest cost option, then $\hat{c}_{k_o^*}(\cdot) - \hat{c}_{k_d^*}(\cdot)$ decreases in ε by $n_d\hat{\alpha}_d$. As a consequence, the number of foreign firms competing within the domestic market increases in emissions price at a rate equivalent to $\frac{n_d\hat{\alpha}_d}{\sqrt{Fb}}$. This 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 – i.e., $\hat{c}_{k_o^*}(\cdot)$ significantly greater than $\hat{c}_{k_d^*}(\cdot)$. This limited entry by foreign competitors into the European cement market to less than 5% of total sales. However, with emissions costs under the EU-ETS dominating those transport costs, 95% of the European cement capacity added since 2004 is represented by finishing facilities located near ports – i.e., capacity added by firms preparing to import into the region.

As implied by Proposition 1, there are conditions when no foreign competitors enter, and conditions when they do. I consider the latter case here and the former in subsection 3.4.

3.3. Firm decisions and performance *with* foreign entry

The following proposition describes the Cournot-Nash equilibrium when foreign firms enter the domestic market:

PROPOSITION 2. *Foreign firms will compete in the domestic market when* $\hat{c}_{k_o^*}(\cdot) + n_d\Big(\hat{c}_{k_o^*}(\cdot) - \hat{c}_{k_d^*}(\cdot)\Big) + \sqrt{Fb}(n_d+1) < A$, *with resulting domestic firm equilibrium quantities of*

$$x^*_{i,k_d^*,r}\left(\varepsilon,\hat{\beta}_d\right) = \frac{\sqrt{Fb}}{b} + \frac{\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)}{b}, \tag{7}$$

$$x^*_{i,k,r}\left(\varepsilon,\hat{\beta}_d\right) = 0,\ \forall k \in \mathcal{K}\backslash k_d^* \quad \text{and} \quad x^*_{i,k,-r}\left(\varepsilon,\hat{\beta}_d\right) = 0,\ \forall k \in \mathcal{K}, \quad \forall i \in \mathcal{N}_d,$$

and foreign firm equilibrium quantities of

$$y^*_{j,k_o^*}\left(\varepsilon,\hat{\beta}_o\right) = \frac{\sqrt{Fb}}{b}, \quad \text{and} \quad y^*_{j,k}\left(\varepsilon,\hat{\beta}_o\right) = 0,\ \forall k \in \mathcal{K}\backslash k_o^*, \quad \forall j \in \mathcal{N}_o. \tag{8}$$

The joint concavity of domestic and foreign firm objectives (Equations 1 and 2) is provided within Appendix 1.

Given that the number of foreign competitors is endogenized here, it is not surprising that the equilibrium quantities in Proposition 2 no longer depend on n_o. More surprising is that these quantities also no longer depend on the number of domestic competitors, n_d, despite potential differences in offshore and domestic production economics. This is due to N^* being fixed when domestic producers choose to offshore and decreasing in n_d at fixed rate $\frac{\hat{c}_{k_o^*}(\cdot)-\hat{c}_{k_d^*}(\cdot)}{\sqrt{Fb}}$ when domestic firms produce locally. It is also clear from a casual comparison of (7) and (8) that domestic firm production is strictly greater than foreign firm production when their lowest cost option is local, and that production is equivalent when they offshore in equilibrium.

Market and performance metrics follow directly from the equilibrium quantities indicated by Proposition 2, with a market price of $P^*(X_d, X_o, Y) = \sqrt{Fb} + \hat{c}_o\left(\varepsilon,\hat{\beta}_o\right)$. At this equilibrium price, firm's earn $\sqrt{Fb}$ greater than the marginal producer's cost. This results in foreign firm operating profits of $\pi_j^*(X_d, X_o, Y) = F,\ \forall j \in \mathcal{N}_o$ and domestic profits of

$$\pi_i^*(X_d, X_o, Y) = \frac{\left(\sqrt{Fb} + \hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)\right)^2}{b},\ \forall i \in \mathcal{N}_d. \tag{9}$$

If domestic firms' best option is to produce locally, then profit increases in the domestic firms' total landed cost advantage. However, if domestic firms' lowest cost option is to offshore, then they each earn a profit equivalent to foreign firms' cost to enter the domestic market (or reservation profit), F. When offshoring, domestic firms become symmetric to foreign firms in both quantities and profit, with their only remaining advantage being a reserved place in the market as incumbents.

Further, foreign entry as characterized by (6) along with production at the equilibrium quantities characterized by (7) and (8) generates the following global emissions:

$$e^g\left(\varepsilon, \hat{\beta}_d, \hat{\beta}_o\right) = \begin{cases} n_d \hat{\alpha}_d \left(\frac{\sqrt{Fb}+\hat{c}_{k_o^*}(\cdot)-\hat{c}_{k_d^*}(\cdot)}{b}\right) + (\hat{\alpha}_o + \alpha_\tau)\left(\frac{A-\hat{c}_{k_o^*}(\cdot)-n_d\left(\hat{c}_{k_o^*}(\cdot)-\hat{c}_{k_d^*}(\cdot)\right)-\sqrt{Fb}(n_d+1)}{b}\right) & \text{if } r=d, \\ (\hat{\alpha}_o+\alpha_\tau)\left(\frac{n_d\sqrt{Fb}}{b} + \frac{A-\hat{c}_{k_o^*}(\cdot)-\sqrt{Fb}(n_d+1)}{b}\right) & \text{otherwise.} \end{cases} \tag{10}$$

When domestic firms opt to produce locally (i.e., where $r=d$), the first term characterizes domestic emissions. Assuming $n_o^*>0$, then an incremental increase in ε to the point at which domestic firms shift production offshore leads to a change in global emissions. Define ε^o as the point where domestic firms choose to offshore and ι as very small. Then global emissions increase as a result of offshoring by $n_d\left(\frac{\sqrt{Fb}}{b}\right)\left[\hat{\alpha}_o(\varepsilon^o)+\alpha_\tau-\hat{\alpha}_d(\varepsilon^o-\iota)\right]$. This difference is the equilibrium quantity produced by the n_d domestic firms once they offshore, as given by (7) when $\hat{c}_{k_d^*}(\cdot)=\hat{c}_{k_d^*}(\cdot)$, multiplied by the relative change in emissions intensity. As will be shown, without a border adjustment, this difference is strictly positive, while with a border adjustment it is conditionally negative.

3.4. Firms decisions and performance *without* foreign entry

When foreign competitors opt not to enter – i.e., under endogenous *non*-entry – equilibrium quantities are described by the following corollary.

Corollary 1. *If $\hat{c}_{k_o^*}(\cdot)+n_d\left(\hat{c}_{k_o^*}(\cdot)-\hat{c}_{k_d^*}(\cdot)\right)+\sqrt{Fb}(n_d+1)\geq A$, a domestic oligopoly results. Offshore competitors do not compete in the domestic marketplace and domestic competitors produce at Cournot oligopoly quantities*

$$x^*_{i,k_d^*,r}\left(\varepsilon,\hat{\beta}_d\right)=\frac{A-\hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)}{b\,(n_d+1)}, \tag{11}$$

$$x^*_{i,k,r}\left(\varepsilon,\hat{\beta}_d\right)=0,\ \forall k\in\mathcal{K}\backslash k_d^* \quad \text{and} \quad x^*_{i,k,-r}\left(\varepsilon,\hat{\beta}_d\right)=0,\ \forall k\in\mathcal{K},\quad \forall i\in\mathcal{N}_d.$$

Such a scenario results in the well-known Cournot oligopoly market price and firm profits of

$$P^*(X_d, X_o, Y) = \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right) + \frac{A - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)}{n_d + 1},$$

and

$$\pi_i^*(X_d, X_o, Y) = \frac{\left(A - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)\right)^2}{b\left(n_d + 1\right)^2}, \ \forall i \in \mathcal{N}_d, \tag{12}$$

respectively.

Similarly, global emissions under this scenario equate to total output under a traditional Cournot oligopoly multiplied by the applicable emissions intensity

$$e^g\left(\varepsilon, \hat{\beta}_d, \hat{\beta}_o\right) = \begin{cases} n_d \hat{\alpha}_d \left(\frac{\left(A - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)\right)}{b(n_d+1)}\right) & \text{if } r = d, \\ n_d\left(\hat{\alpha}_d + \alpha_\tau\right)\left(\frac{\left(A - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)\right)}{b(n_d+1)}\right) & \text{otherwise.} \end{cases} \tag{13}$$

4. Firm Decisions and Performance *without* Border Adjustment

Emissions regulation in effect today is not currently supported by border adjustment mechanisms. This allows goods produced offshore to compete within the domestic market without incurring the carbon costs associated with local production. While implementing a border adjustment may appear to be a straight-forward solution to this asymmetry, the potential for such a measure to be interpreted as a trade barrier, and thereby initiate a reciprocal tariff, has thus far stymied debate on the issue. As a consequence, emissions cost asymmetry of goods sold within the domestic market may persist indefinitely. I explore that setting here[2], with $\beta_k = 0$, $\forall k \in \mathcal{K}$.

Order all technologies from dirtiest to cleanest and assume non-zero emissions so that $\alpha_k > \alpha_{k'} > 0$, $\forall k < k' \in \mathcal{K}$. Given this ordering, note that Assumption 1 implies that production cost increases in type, $\gamma_k < \gamma_{k'}, \forall k < k' \in \mathcal{K}$. If a type were dominated in both cost and environmental impact, it would be infeasible and dropped from the choice set. Then make the following additional assumption:

[2] This section also structurally supports a flat carbon tariff such as one based on the best available technology as proposed by Ismer and Nuehoff (2007). A flat carbon tariff is independent of the technology that imports are produced with, and therefore does not incent technology change among foreign firms. Such a tariff could be incorporated within the transport cost, τ, with the results of this section holding.

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

This second assumption ensures that domestic firms will prefer to produce locally when emissions are unregulated, i.e., $c_{1,d}(0,0) < c_{1,o}(0,0)$. While this assumption will obviously not hold for all sectors in the general economy, it is reasonable for carbon-regulated sectors. Domestic carbon regulation would be unnecessary in sectors where such an assumption does not hold, as production would offshore even when carbon costs are zero. Without such an assumption, there would be no domestic production to regulate.

4.1. Emissions price thresholds

Three classes of emissions price thresholds are of interest: the emissions prices that lead to a change in technology choice; that result in foreign entry; and that lead to the offshoring of domestic production. Without a border adjustment, foreign firms always choose technology 1 to serve domestic demand as $\delta\gamma_1 < \delta\gamma_k$, $\forall k >\in \mathcal{K}$ and offshore production is not exposed to carbon costs. Therefore, production costs are insensitive to ε and no emissions threshold leads to the adoption of cleaner technology by foreign firms. For domestic firms, define $\varepsilon_k^d = \frac{\gamma_k - \gamma_{k-1}}{\alpha_{k-1} - \alpha_k}$ as the lowest emissions price at which domestic production with technology k is preferred over domestic production with technology $k-1$. Assumption 1 implies that technology k is the domestic firm preferred technology at emissions price ε_k^d – i.e., $k \succ k' \in \mathcal{K} \backslash k$ when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^d)$. Without a border adjustment, the regulator's ability to induce domestic firms to adopt technology $k > 1$ through emissions price can be limited.

Remark 1. Without a border adjustment, technology $k > 1$ will not be adopted at any emissions price if $\tau < \gamma_k - \delta\gamma_1 + \alpha_k \varepsilon_k^d$, $\forall k \in \{2, \ldots, m\}$.

In this setting, offshoring with technology 1 would be preferred to using technology k domestically if $c_{1,o}(\varepsilon_k^d, 0) < c_{k,d}(\varepsilon_k^d, 0), \forall\ k' < k \in \mathcal{K}$, with this inequality leading to the condition in Remark 1. In sectors where this holds, domestic firms would prefer to offshore production than switch to cleaner domestic technology k. Define $\varepsilon^o = \frac{\delta\gamma_1 + \tau - \hat{\gamma}_d}{\hat{\alpha}_d}$ as the minimum emissions price at which domestic firms would choose to offshore production without a border adjustment. Lastly, define $\varepsilon^e = \frac{(n_d+1)(\gamma_1+\sqrt{Fb})-n_d\hat{\gamma}_d-A}{n_d\hat{\alpha}_d}$ as the minimum emissions price at which foreign firms enter the domestic market without a border adjustment.

4.2. Equilibrium quantities

Define total output as $n_d x^*_{i,k^*_d,r}\left(\varepsilon, \hat{\beta}_d\right) + n^*_o y^*_{j,k^*_o}\left(\varepsilon, \hat{\beta}_o\right)$. Then, in light of the above thresholds, Propositions 1 and 2 imply the following:

PROPOSITION 3. *Assume $\beta_k = 0$, $\forall k \in \mathcal{K}$. Total output is fixed in ε when $\varepsilon \geq \varepsilon^e$.*

As previously noted in the discussion of Proposition 1, the number of foreign entrants increases in emissions price at a rate of $\frac{n_d\hat{\alpha}_d}{\sqrt{Fb}}$. From Proposition 2, the equilibrium production of a foreign firm is $\frac{\sqrt{Fb}}{b}$, so total production by foreign firms increases at a rate of $\frac{n_d\hat{\alpha}_d}{b}$ in emissions price. It is also clear from Proposition 2 that the total rate of change in production among domestic firms with respect to emissions price is $n_d\frac{dx^*_{i,k^*_d,r}}{d\varepsilon} = -\frac{n_d\hat{\alpha}_d}{b}$. Therefore, total output is inelastic in emissions price after foreign entry, with increases resulting from incremental entry balanced by domestic production decreases. While total output remains inelastic in emissions price, note that domestic share decreases and total foreign share increases in emissions price until domestic firms opt to offshore production. This result is robust to shifts in domestic technology, holding even if domestic and offshore production utilize different technologies. Shifting to a cleaner technology reduces the rate of share change in ε between domestic and foreign firms' production (by reducing $\hat{\alpha}_d$), but total output remains fixed with respect to emissions price. Consistent with this result, Bayindir-Upmann (2004) also finds that an increase in emissions price leads to increased foreign entry while total output remains constant. Proposition 2 therefore generalizes that finding to settings with technology choice.

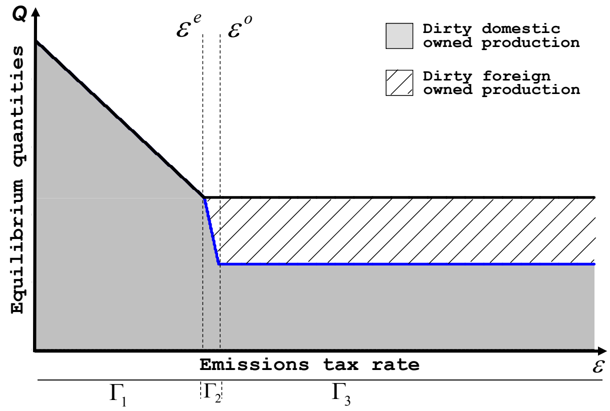
COROLLARY 2. *Assume $\beta_k = 0$, $\forall k \in \mathcal{K}$. Equilibrium quantities are fixed in ε when $\varepsilon \geq \varepsilon^o$.*

This comports well with intuition; without a border adjustment, changes in domestic emissions prices have no impact on offshore production. With no border adjustment, n^*_o no longer depends on emissions price when domestic firms offshore production – i.e., when $\hat{c}_{k_d^*}(\cdot) = \hat{c}_{k_o^*}(\cdot)$, as evident in Proposition 1. Likewise, from Proposition 2, domestic equilibrium quantities $x^*_{i,k_d^*,r}(\cdot)$ are no longer dependent on emissions price when $\hat{c}_{k_d^*}(\cdot) = \hat{c}_{k_o^*}(\cdot)$. This implies not only that total output is independent of ε (as in Proposition 3), but that both foreign firm production and domestic firm production decisions are inelastic in ε when $\varepsilon > \varepsilon^o$. Note also that Corollary 2 implies that if $\varepsilon^e > \varepsilon^o$, then foreign firms will not enter at any emissions price.

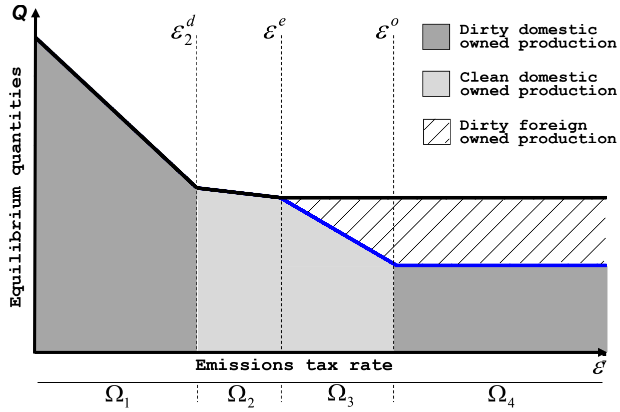
If emissions price is less than the threshold that results in the offshoring of domestic production, and less than the threshold that results in foreign entry, then firms operate in a domestic oligopoly with local production. In such a setting, it is clear from Corollary 1 that domestic quantities decrease in emissions price. It is also clear from the discussion of Proposition 3 that domestic quantities decrease in the interval $[\varepsilon^e, \varepsilon^o)$, while the number of foreign entrants strictly increases over the same interval. Without a border adjustment, this implies the following:

Remark 2. Assume $\beta_k = 0$, $\forall k \in \mathcal{K}$. Domestic quantities strictly decrease in ε for any $\varepsilon < \varepsilon^o$, while foreign entry strictly increases in ε when $\varepsilon \in [\varepsilon^e, \varepsilon^o)$.

These results are illustrated in Figures 1(a) and 1(b).



(a) Equilibrium quantities when $\varepsilon^o \leq \varepsilon_2^d$



(b) Equilibrium quantities when $\varepsilon^o > \varepsilon_2^d$

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

Within Figure 1a, a domestic oligopoly exists over the interval Γ_1, with production decreasing in ε. At point ε^e, entry conditions are satisfied. Therefore, foreign entry increases in ε over Γ_2 per Remark 2, while domestic quantities decrease. Point ε^o indicates the offshoring threshold, beyond which both domestic- and foreign-owned capacity operate outside the regulated region and are fixed in ε per Corollary 2. Figure 1b is similar except the production and capital recovery cost of technology 2 has been decreased to allow for its adoption, which occurs at point ε_2^d. The reduced emissions intensity of type 2 technology decreases the domestic firms' exposure to emissions price, which reduces the rate at which domestic production decreases in intervals Ω_2 and Ω_3, and decreases the rate at which foreign firms enter over Ω_3. Per Proposition 3, total output is constant in ε over Ω_3 as market share shifts toward foreign firms.

4.3. Emissions performance

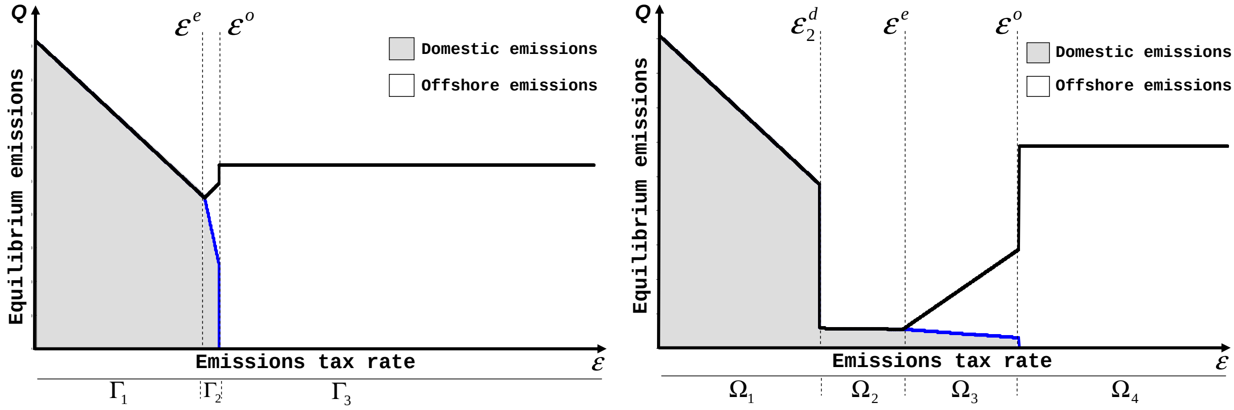
As a consequence of Corollary 2, the regulator possesses a limited ability to impact global emissions when there is no border adjustment. Increasing emissions price beyond ε^o yields no further emissions reduction as such increases have no impact on offshore technology or quantity decisions. Further, a shift of domestic production offshore as a result of $\varepsilon > \varepsilon^o$ leads to a strict increase in emissions intensity; domestic firms utilize the dirtiest technology when producing offshore and generate α_τ in transport emissions by importing into the domestic region.

Remark 3. Assume $\beta_k = 0$, $\forall k \in \mathcal{K}$. Global emissions strictly increase as a result of carbon leakage due to offshoring.

Carbon leakage due to foreign entry results from increases in emissions price when domestic firms produce locally and the entry condition given in Proposition 2 is met. Although total output remains inelastic to emissions price in such a setting, it is clear from Proposition 3 that production shifts offshore as a consequence of increased foreign entry as ε increases within the interval $[\varepsilon^e, \varepsilon^o)$. Given that total production remains unchanged (by Proposition 3), when leakage due to entry occurs, it results in a strict increase in global emissions relative to the displaced domestic production as $\hat{\alpha}_d \leq \hat{\alpha}_o = \alpha_1$, and $\alpha_\tau > 0$. This is formalized with the following remark:

Remark 4. Assume $\beta_k = 0$, $\forall k \in \mathcal{K}$. Carbon leakage due to foreign entry increases in ε when $\varepsilon \in [\varepsilon^e, \varepsilon^o)$, with emissions from entry strictly greater than emissions from displaced domestic production.

These emissions effects are illustrated in Figures 2a and 2b, but are clearly more pronounced in Figure 2b where leakage implies a shift from cleaner domestic production (with technology 2) to dirtier offshore production (with technology 1). While it may seem as though a regulator would avoid setting an emissions price within intervals Ω_3 or Ω_4, they impose a single emissions price for multiple sectors, which limits their ability to target a price for any given sector precisely.



(a) Equilibrium emissions when $\varepsilon^o \leq \varepsilon_2^d$ (b) Equilibrium emissions when $\varepsilon^o > \varepsilon_2^d$

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

4.4. Discussion and summary

Emissions regulation without border adjustment limits the legislation's ability to impact global emissions, effectively imposing an upper bound on its ability to impact both levels of production and shifts to cleaner technologies. Increases in emissions price beyond ε^o incentivize no response from competitors in terms of output or technology choice as all production takes place offshore, beyond the regulatory umbrella. Therefore, if the emissions price under which domestic production would move offshore is less than the price that would results in foreign entry (i.e., $\varepsilon^o < \varepsilon^e$), then offshoring preempts such entry. Likewise, if the emissions price that motivates offshoring is less than that which incentivizes a shift to cleaner technology k (i.e., $\varepsilon^o < \varepsilon_k^d$) then offshoring preempts that technology adoption. It should be noted that 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 CO2 – which is less than projected emissions costs under EU-ETS Phase III – with this offshoring increasing global emissions by a minimum estimate of 7 million tons of CO2 (Boston Consulting Group 2008).

Within settings where domestic firms produce locally (i.e., $\varepsilon < \varepsilon^o$), increases in emissions price beyond ε^e lead to the counter-intuitive effect of increasing global emissions despite reductions in domestic emissions. Under such circumstances, a portion of domestic production is displaced by more emissions intensive offshore production (accounting for transport). As a consequence, the only interval over emissions prices where the regulator can reduce *global* emissions without a border adjustment are in cases of domestic oligopoly – settings where all production is local. Even then, such reductions imply a reduction in firm profits and consumer surplus, aside from the specific points where the emissions price increase incentivizes technology change, i.e., at $\varepsilon = \varepsilon^d_k$. This clearly poses a trade-off in terms of managing social welfare. Results in settings without border adjustment are summarized below in Figure 3.

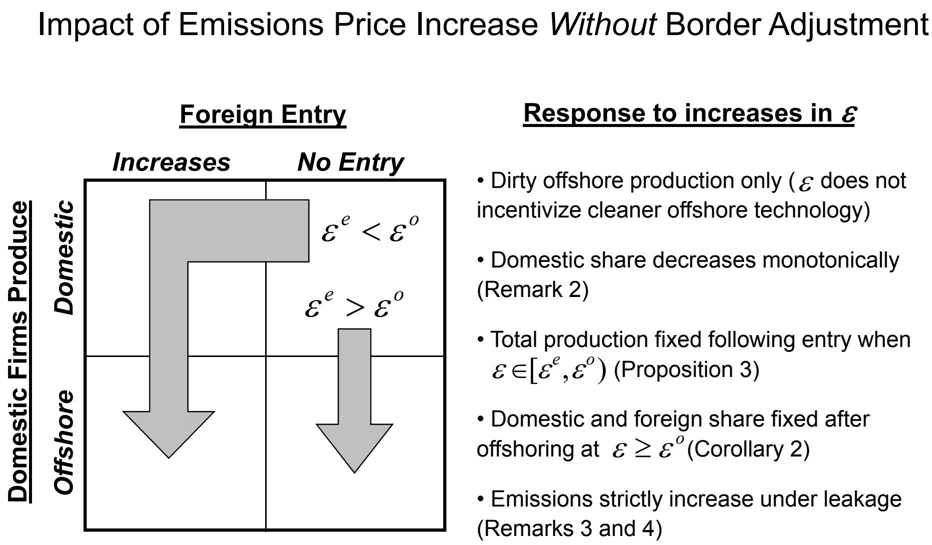


Figure 3 **Entry and offshoring paths and results under increasing emissions price without border adjustment.**

5. Firm Decisions and Performance *with* Border Adjustment

While not currently in effect today, much debate related to emissions regulation has centered on the implementation of border adjustments. It is therefore important to understand how border adjustments impact technology choices, production decisions and ultimately performance. I consider that setting here by applying identical carbon costs to domestic and offshore goods produced with the same technology[3] – i.e., imposing a border adjustment such that $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$. Note that transport emissions α_τ do not incur carbon costs under such a border adjustment.

5.1. Emissions price thresholds

Consider again the three classes of emissions thresholds identified in the previous subsection – the emissions price thresholds that result in a technology shift, the threshold that results in foreign entry, and the threshold that results in the offshoring of domestic production – which are noted with $\tilde{\cdot}$ in this border adjustment setting.

Define $\tilde{\varepsilon}_k^d = \frac{\gamma_k - \gamma_{k-1}}{\alpha_{k-1} - \alpha_k}$, $\forall k > 1 \in \mathcal{K}$ as the emissions price at which domestic preference switches to technology k from technology $k-1$ under a border adjustment, and define $\tilde{\varepsilon}_k^o = \delta \left(\frac{\gamma_k - \gamma_{k-1}}{\alpha_{k-1} - \alpha_k} \right)$, $\forall k > 1 \in \mathcal{K}$ as the emissions price at which preference for offshore production technologies does the same. As a consequence of both domestic and foreign firms facing identical carbon costs for a given technology, the adoption of clean technologies for offshore production differs significantly under a border adjustment. In the setting without a border adjustment, offshore production always utilized the dirtiest technology to serve the domestic market. However, with a border adjustment, foreign firms adopt clean technologies at a lower emissions price than domestic firms, up to the point where domestic firms offshore production. Defining k^o as the technology at which domestic firms offshore, the following Lemma formally states this sensitivity:

LEMMA 1. *Assume $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$. Conditional on entry, foreign firms adopt clean technologies at a lower emissions price than firms producing domestically, i.e., $\tilde{\varepsilon}_k^o < \tilde{\varepsilon}_k^d$, $\forall k \in \{2, \ldots, k^o\}$.*

Given a border adjustment and that offshore production and capital recovery costs are less than domestic production and capital recovery costs (i.e., $\delta < 1$), foreign firms adopt clean technologies to serve the domestic market at lower emissions prices than domestic firms up to the point where

[3] Grubb and Neuhoff (2006) proposed such a "symmetric" border adjustment as non-discriminatory and therefore most likely to be feasible under WTO and GATT law (given the elimination of freely-allocated emissions allowances).

domestic firms opt to offshore. While this result follows clearly from a comparison of $\tilde{\varepsilon}_k^d$ and $\tilde{\varepsilon}_k^o$, it runs counter to intuition. Under a border adjustment, the technology choices of foreign firms importing into the domestic market are more sensitive to the domestic region's emissions regulation than domestic producer's technology choices. Conditional upon entry, foreign firms operate cleaner technology than locally producing domestic firms when $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$, and operate identical technology when $\varepsilon \in \left[\tilde{\varepsilon}_k^d, \tilde{\varepsilon}_{k+1}^o\right)$, $\forall k \in \{2, \ldots, k^o\}$.

With offshore production adopting clean technologies at lower emissions prices than domestic production, emissions price can be sufficiently great to cause domestic firms to offshore. This is counter-intuitive under a border adjustment where carbon costs are identical for domestic and offshore production with a given technology, and when offshore production incurs transport costs. However, under a border adjustment, offshoring always leads to the adoption of a technology that is strictly cleaner than the technology utilized domestically, as summarized with the following proposition:

Proposition 4. *Assume $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$. Domestic firms only offshore to adopt a technology k^o strictly cleaner than the technology utilized domestically.*

Under border adjustment, offshore and domestic carbon costs are identical for a given technology. As a result, the cost frontier over emissions price of preferred offshore technologies parallels that of the preferred domestic technologies when that preferred technology is the same – i.e., when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$. However, over emissions price intervals where offshore production utilizes cleaner technology – i.e., when $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, the offshore cost frontier is less steep than the domestic cost frontier. Therefore, it is only possible for these cost frontiers to intersect over emissions price intervals where the preferred offshore technology is cleaner than the preferred domestic technology. As domestic production offshores at this point of intersection, offshoring implies that the domestic firm adopts cleaner technology than they had employed domestically. Further, offshoring is more likely as the emissions improvement achieved through cleaner technology (i.e., $\alpha_{k-1} - \alpha_k$) increases.

5.2. Equilibrium quantities

Foreign entry is non-monotonic when offshore production incurs carbon costs due to border adjustment. This differs from the setting without border adjustment where entry monotonically increases in ε. As a consequence, there are potentially multiple entry thresholds under a border adjustment, all defined by the entry condition given in Proposition 2. Entry decreases in ε when foreign firms operate the same technology as domestic firms, $\varepsilon \in \left[\tilde{\varepsilon}_k^d, \tilde{\varepsilon}_{k+1}^o\right)$. But entry can increase in ε when foreign firms operate cleaner technology than domestic firms, $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$.

PROPOSITION 5. *Assume $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$. When foreign firms compete in the domestic market, foreign entry increases in ε over the interval $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$, $\forall k \in \{2, \ldots, k^o\}$ when $\frac{\alpha_{k-1}}{\alpha_k} \geq 1 + \frac{1}{n_d}$, but otherwise strictly decreases in ε.*

Offshore firms utilize technology k and domestic firms produce with technology $k-1$ in the interval $[\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$, for all $k \in \{2, \ldots, k^o\}$. Following from Proposition 1, the number of entrants increases in ε within this interval at a rate of $\frac{-\alpha_k + n_d(\alpha_{k-1} - \alpha_k)}{\sqrt{Fb}}$, which is non-negative when $\frac{\alpha_{k-1}}{\alpha_k} \geq 1 + \frac{1}{n_d}$. The LHS of this condition is greater than one 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 ε. Recall that foreign firms' production is independent of ε per Proposition 2. As a consequence, total production from foreign entrants increases when the conditions of Proposition 5 are met. However, foreign entry decreases in ε under all other conditions – i.e., when the cleaner technology operated by foreign firms is not sufficiently clean for the inequality to hold, or when foreign and domestic firms operate identical technology. The regions of decrease are interesting here. They run counter to the impact of ε on offshore production without a border adjustment. Recall from discussion of Proposition 3 and Corollary 2 that, without a border adjustment, total offshore production increases in ε within the interval $[\varepsilon^e, \varepsilon^o)$, and is inelastic in ε when $\varepsilon > \varepsilon^o$. At no point does total offshore production decrease in ε when there is no border adjustment as it conditionally does with a border adjustment.

PROPOSITION 6. *Assume $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$. Conditional on foreign entry, total domestic firm production strictly decreases in ε when $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$, $\forall k \in \{2, \ldots, k^o\}$, but otherwise is fixed in ε.*

This result follows directly from Lemma 1 and Proposition 2. When foreign firms operate cleaner technology than domestic firms – i.e., when $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$, $\forall k \in \{2, \ldots, k^o\}$ – each domestic firm's equilibrium quantity decreases in ε at a rate of $\frac{\alpha_k - \alpha_{k-1}}{b}$. When foreign and domestic firms face equivalent carbon costs and operate identical technologies – i.e., when $\varepsilon \in \left[\tilde{\varepsilon}_k^d, \tilde{\varepsilon}_{k+1}^o\right)$, $\forall k \in \{2, \ldots, k^o\}$ and when $\varepsilon > \tilde{\varepsilon}_{k^o}^d$ – it is clear from Proposition 2 that domestic firm quantities $x^*_{i,k_d^*,r}(\cdot)$ are independent of ε. This implies that the regulator will be unable to influence domestic emissions under a border adjustment when domestic and foreign firms choose to operate the same technology (given that foreign firms are competing in the domestic market). This would impact the regulator's ability to meet its emissions targets, which could prove costly if financial penalties are involved such as under Kyoto commitments. Note also that the inelasticity of $x^*_{i,k_d^*,r}(\cdot)$ in ε when firms operate the same technology differs from the setting with no border adjustment where domestic quantities decrease in ε for any $\varepsilon \in [0, \varepsilon^o)$ as summarized by Remark 2.

Together, Propositions 5 and 6 raise another important and potentially controversial difference between the two border adjustment settings. Under a border adjustment mechanism, there are regions where the regulator can shift market share in the favor of domestic firms by increasing emissions price, which they are incapable of doing through emissions price without a border adjustment. In settings where foreign firms compete in the domestic market when $\varepsilon = 0$, this implies that emissions regulation combined with a border adjustment can increase domestic market shares relative to the unregulated baseline, arguably giving credence to concerns over the potential anti-competitiveness of such a mechanism.

While total output in the setting with no border adjustment is fixed in $\varepsilon > \min\{\varepsilon^e, \varepsilon^o\}$, per Proposition 3 and Corollary 2, with a border adjustment in place, total output strictly decreases.

COROLLARY 3. *Assume $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$. Total output strictly decreases in ε.*

When the conditions for a domestic oligopoly are met, this result follows directly from Corollary 1. When domestic firms and foreign firms both compete and operate identical technologies, Proposition 5 shows that total foreign quantities decrease in ε, while Proposition 6 indicates that domestic quantities remain fixed. And finally, when foreign firms operate cleaner technology than domestic firms, the rate of total production increase among foreign firms in ε is $\frac{n_d\left(\alpha_{k-1}-\alpha_k\right)-\alpha_k}{b}$, while the rate of total domestic decrease in production is $-\frac{n_d\left(\alpha_{k-1}-\alpha_k\right)}{b}$, resulting in a rate of decrease for total production of $-\frac{\alpha_k}{b}$. All said, this implies a reduction in total output in ε under a border adjustment, which differs from the setting with no border adjustment where total output is fixed with respect to emissions price when $\varepsilon > \min\{\varepsilon^e, \varepsilon^o\}$.

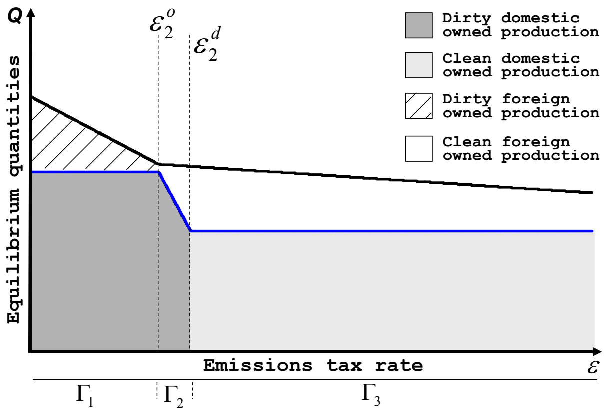
5.3. Emissions performance

Implementing a balanced border adjustment equips the regulator with a greater ability to use emissions price as a lever to encourage the adoption of clean technologies. Increases in emissions price will 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 the potential impact that emissions regulation can have on global emissions. While carbon leakage with no border adjustment always leads to an increase in global emissions, under a balanced border adjustment carbon leakage can result in global emissions *improvement*.

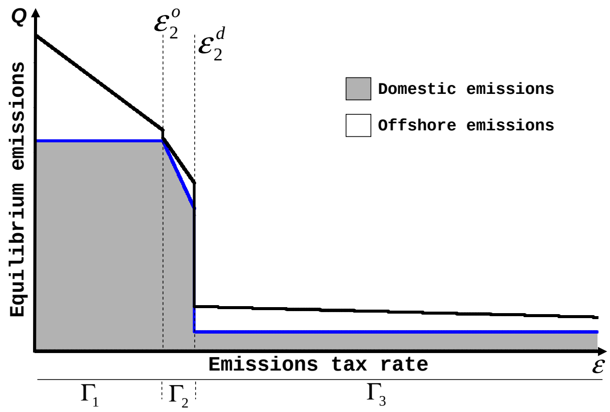
Proposition 7. *Assume $\beta_k = \alpha_k \varepsilon$, $\forall k \in \mathcal{K}$ and $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_k^d)$. Global emissions strictly* decrease *in ε as a result of increasing entry if $\alpha_\tau\left(\alpha_{k-1}-\alpha_k\right) < \left(\alpha_{k-1}-\alpha_k\right)^2 + \frac{\alpha_k(\alpha_k+\alpha_\tau)}{n_d}$, $\forall k \in \{2, \ldots, k_o\}$, and increase in ε otherwise.*

From Lemma 1 and Proposition 5, it is evident that foreign entry with a border adjustment can only occur over emissions price intervals where foreign firms operate cleaner technology – i.e., when $\varepsilon \in [\tilde{\varepsilon}_k^o, \tilde{\varepsilon}_l^d]$. Accounting for volume effects on total offshore and domestic production, a shift from domestic toward cleaner offshore production overcomes the impact of additional transport emissions when the inequality within Proposition 7 holds. This results in a decrease in global emissions. The potential for global emissions improvement due to increased foreign entry under a border adjustment differs notably from the case with no border adjustment, where global emissions strictly increase within incremental entry.

Further, at the emissions price threshold $\tilde{\varepsilon}^o = \tilde{\varepsilon}^d_{k^o}$, global emissions decrease due to offshoring if $\alpha_{k^o} - \alpha_{k^o} > \alpha_\tau$, but otherwise increase. Therefore, 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. Figures 4a and 4b illustrate these decision and performance results.



(a) Equilibrium quantities under BAM



(b) Equilibrium emissions under BAM

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 interval Γ_1, with foreign entry decreasing over that range and domestic production constant, per Propositions 5 and 6. At point ε_2^o, offshore production adopts technology 2 (at a lower emissions price than domestic adoption, per Lemma 1). Therefore, over interval Γ_2 offshore production utilizes cleaner technology than domestic production and, as a consequence (given that $\frac{\alpha_{k-1}}{\alpha_k} \geq 1 + \frac{1}{n_d}$ in this example), entry increases and domestic production decreases in ε over interval Γ_2 per Propositions 5 and 6. In Γ_2, if $\frac{\alpha_{k-1}}{\alpha_k} < 1 + \frac{1}{n_d}$, then both domestic and offshore production would decrease, but offshore production would decline at a lesser rate. Finally, at point ε_2^d, domestic production also adopts cleaner technology, and again domestic production is fixed while offshore production decreases. Per Corollary 3, total production decreases strictly in ε over all intervals.

As illustrated in Figure 4b, increases in ε do not impact domestic emissions in intervals Γ_1 and Γ_3 where domestic and foreign firms operate the same technology. This is a consequence of fixed domestic output over Γ_1 and Γ_3 as discussed above. As a result, a regulator's ability to impact domestic emissions is limited, potentially creating challenges in meeting its emissions targets.

5.4. Discussion and summary

Unlike the setting without border adjustment, when emissions regulation is paired with border adjustment its ability to impact global emissions and technology choice is not bounded at the threshold where domestic firms would opt to offshore, or at any other threshold. Further, under a border adjustment, technology choice plays a defining role in determining the nature of competition. Domestic production offshores only to adopt technology strictly cleaner than that utilized domestically. Further, offshore production adopts clean technologies at a lower emissions price than domestic production when it incurs a border adjustment. As a consequence, in addition to mitigating leakage, when leakage does occur (whether due to entry or offshoring), it can lead to a global reduction in emissions. This differs markedly from the setting without border adjustment where leakage leads to a strict increase in global emissions.

The above are clear advantages resulting from border adjustment. However, there are also potential drawbacks. While the ultimate goal of emissions regulation is to reduce global emissions, the reality is that there can be costs associated with the failure 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 emissions price when domestic and offshore production utilize the same technology – i.e., when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$. As a consequence, the domestic regulator may become more reliant on Joint Implementation or Clean Development Mechanism allowances, which can be subject to a long and uncertain review process. Further, foreign entry conditionally decreases in emissions price when foreign firms operate cleaner technology than domestic firms – when $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$ – and strictly decreases in emissions price when domestic and foreign firms operate similar technology – when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$. This lends credence to the anti-competitive potential of border adjustments which has thus far stymied proposals for such a mechanism. These results are summarized below in Figure 5.

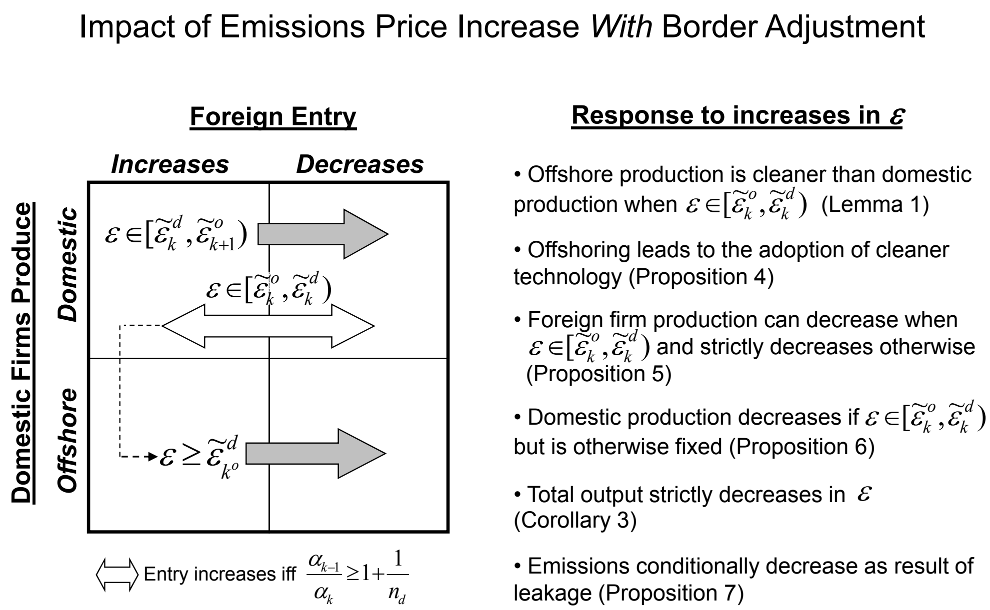


Figure 5 **Entry and offshoring paths and results under increasing emissions price with border adjustment.**

6. Implications, Conclusions and Future Research

This research explores the impact of carbon tariffs – i.e., border adjustments – on firms' technology choice, regional competitiveness, and global emissions. This paper is the first to analytically research the impact of border adjustments when technology choice is treated as endogenous to the setting. As such, the results here have implications for each of the primary stakeholders: regulators making the policy decision regarding border adjustments; firms interested in understanding their competitiveness and location strategies under a border adjustment; and technology producers interested in assessing the potential impact of border adjustments on demand for cleaner technologies. Results indicate that while technology choice plays a minor role without a border adjustment, it fundamentally defines the nature of competitiveness when border adjustments are implemented. In border-adjusted settings where foreign firms utilize cleaner technology, increases in emissions price favor entry, while emissions price increases favor domestic producers when firms operate similar technologies (Propositions 5 and 6). Further, the offshoring of domestic production under border adjustment only occurs when domestic firms adopt a technology cleaner than it would utilize locally, implying that offshored production is strictly cleaner than production undertaken domestically (Proposition 4).

The implementation of border adjustments significantly impacts regulators' ability to influence both emissions and technology choice, and has important implications for regional competitiveness. Without a border adjustment, regulators' ability to influence firms' technology decisions as well as global emissions is limited by the emissions price threshold at which domestic production would offshore (Corollary 2) – a threshold that can occur at emissions prices sufficiently low to be of practical concern (e.g., Boston Consulting Group 2008). Under such a circumstance (i.e., $\varepsilon > \varepsilon^o$), domestic emissions would be eliminated while global emissions increase as a consequence of carbon leakage due to offshoring (Remark 3). The regulator can reduce domestic emissions without a border adjustment by increasing emissions price over the interval $\varepsilon \in [\varepsilon^e, \varepsilon^o)$, with increased foreign entry under such circumstances displacing domestic production while total production remains constant (Proposition 3). However, global emissions under such conditions strictly increase (Remark 4). Therefore, the regulator can only reduce global emissions without a border adjustment in sectors where there is a domestic oligopoly – i.e., when $\varepsilon \in (0, \varepsilon^e)$. Clearly, this limits the regulation's ability to achieve its intent: the abatement of global emissions to mitigate the effects of climate change.

All production serving the carbon-regulated market, whether located domestically or offshore, incurs carbon costs under a policy that includes border adjustment. Counter to intuition, when imported goods incur the same carbon costs as they would if produced domestically, offshore production adopts clean technologies at lower emissions prices than domestic production (Lemma 1). Further, domestic production adopts cleaner technology when it offshores than it would utilize domestically (Proposition 4). As a result, carbon leakage under a border adjustment – whether due to entry or offshoring – can lead to a reduction in global emissions rather than the strict increase resulting from leakage without a border adjustment (Proposition 7). That said, the regulator's ability to reduce domestic emissions can be limited, as domestic production is insensitive to emissions price changes when it utilizes the same technology as offshore production (Proposition 6) – i.e., when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$. Further, as emissions price could conditionally be employed as a lever to reduce foreign entry under border adjustment (Propositions 5 and 6), the debate related to such a mechanism as potentially anti-competitive is likely to continue.

6.1. Future research

Promising directions for future work include exploring the perspectives of each of the primary stakeholders involved – capacity owners, technology producers, and the policy maker. From the capacity owners' perspective, considering the middle-term problem would be of great interest. Today, emissions regulation exists without border adjustment, but there is ongoing debate on the issue, with such adjustments possible in the future. Given that uncertainty and a dynamic setting, addressing the question of capacity pre-commitment could provide interesting insights. There is some urgency for foreign firms to "plant their flag" and strategically commit to the regulated market as the equilibrium number of entrants is limited. To the extent that production processes can be decoupled into carbon intensive and finishing stages (as in the cement sector with clinker production versus grinding/blending), this presents firms with a real option. Understanding the value of that option and its impact on the equilibria in both markets would be an interesting direction for further study.

From the perspective of technology producers, adoption of clean technologies is incentivized through regulation only within the domestic market when no border adjustment is employed. Border adjustments extend the market for clean technology to offshore production that serves the emissions-regulated region. As a result, economies of scale and the degree of learning-by-doing with respect to cost and performance improvements would differ between the two settings, as would technology pricing. All of this points to important second order effects resulting from the border adjustment decision that are worthy of further exploration. Finally, the regulator's problem is complex, involving discontinuities with respect to global emissions, a social welfare incentive to reduce global emissions and a potentially competing financial incentive to reduce domestic emissions. Added to the traditional challenges of managing firm profits and consumer surplus, the challenge of targeting a single emissions price across a heterogenous set of sectors under emissions regulation provides several facets for future study from the perspective of the policy maker.

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Appendix

Proof of Proposition 1. In order to prove Proposition 1, the following Lemma must be established:

LEMMA 2. *Firms will only produce with the lowest cost technology available to them, k_d^* for domestic firms, and k_o^* for offshore firms.*

Proof of Lemma 2. For domestic firm technology choice, note that $c_{k',l}(\varepsilon,\beta_k) \geq \hat{c}_{i,k_d^*}(\varepsilon,\hat{\beta}_d)$, $\forall k' \in \mathcal{K} \backslash k_d^*$, $\forall l \in \mathcal{L}$ by the definition of k_d^*. Assume that the total quantity produced at location l by firm i is $X_{i,l} = \sum_{k=1}^m x_{i,k,l}$. Then $\sum_{k=1}^m (c_{k,d}(\varepsilon,\beta_k)x_{i,k,d} + c_{k,o}(\varepsilon,\beta_k)x_{i,k,o}) \geq \sum_{k=1}^m \hat{c}_{i,k_d^*}(\varepsilon,\hat{\beta}_d)(X_{i,d} + X_{i,o})$. As a consequence, firm i minimizes its costs and maximizes profits defined in Equation (1), by producing only with k_d^*.

A symmetric argument holds for offshore firms as $c_{k',o}(\varepsilon,\beta_k) \geq \hat{c}_{i,k_o^*}(\varepsilon,\hat{\beta}_o)$, $\forall k' \in \mathcal{K} \backslash k_d^*$ by the definition of k_o^*. ■

Then, equilibrium quantities under free entry are required to prove Proposition 1, and are defined by the following Lemma:

LEMMA 3. *Under free entry (i.e., $F = 0$), domestic firms produce at equilibrium quantities*

$$x_{i,k_d^*,r}^*\left(\varepsilon,\hat{\beta}_d,\hat{\beta}_o\right) = \frac{A - \hat{c}_{i,k_d^*}\left(\varepsilon,\hat{\beta}_d\right)}{b\left(n_d + n_o + 1\right)} + \frac{n_o\left(\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right) - \hat{c}_{i,k_d^*}\left(\varepsilon,\hat{\beta}_d\right)\right)}{b\left(n_d + n_o + 1\right)},$$

$$x_{i,k,r}^*\left(\varepsilon,\hat{\beta}_d\right) = 0,\ \forall k \in \mathcal{K}\backslash k_d^* \quad \text{and} \quad x_{i,k,-r}^*\left(\varepsilon,\hat{\beta}_d\right) = 0,\ \forall k \in \mathcal{K}, \quad \forall i \in \mathcal{N}_d,$$

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

$$y_{j,k_o^*}^*\left(\varepsilon,\hat{\beta}_d,\hat{\beta}_o\right) = \frac{A - \hat{c}_{j,k_o^*}\left(\varepsilon,\hat{\beta}_o\right)}{b\left(n_d + n_o + 1\right)} - \frac{n_d\left(\hat{c}_{j,k_o^*}\left(\varepsilon,\hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)\right)}{b\left(n_d + n_o + 1\right)},$$

$$\text{and} \quad y_{j,k}^*\left(\varepsilon,\hat{\beta}_o\right) = 0,\ \forall k \in \mathcal{K}\backslash k_o^*, \quad \forall j \in \mathcal{N}_o.$$

Proof of Lemma 3. Following directly from Lemma 2, it is clear that all quantities produced from technologies aside from a firm's preferred technology option are zero. Therefore, consider the equilibrium resulting from quantities $x_{i,k_d^*,r}$ and y_{j,k_o^*}, $\forall i \in \mathcal{N}_d$ and $\forall j \in \mathcal{N}_o$.

First order conditions for firm $i \in \mathcal{N}_d$ and firm $j \in \mathcal{N}_o$ are then

$$\frac{\partial \pi_i\left(X_d, X_o, Y\right)}{\partial x_{i,k_d^*,r}(\varepsilon,\beta_k)} = A - b(X_o + X_d + Y) - bx_{i,k_d^*,r}(\varepsilon,\beta_k) - \hat{c}_{i,k_d^*}(\varepsilon,\beta_k) = 0, \quad \forall i \in \mathcal{N}_d, \tag{14}$$

and

$$\frac{\partial \pi_j\left(X_d, X_o, Y\right)}{\partial y_{j,k_o^*}(\varepsilon,\beta_k)} = A - b(X_o + X_d + Y) - by_{j,k_o^*}(\varepsilon,\beta_k) - \hat{c}_{j,k_o^*}(\varepsilon,\beta_k) = 0, \quad \forall j \in \mathcal{N}_o. \tag{15}$$

Since the problem is symmetric for all domestic firms and is likewise symmetric for all offshore firms, Equations (14) and (15) can be rewritten as

$$\frac{\partial \pi_i\left(X_d, X_o, Y\right)}{\partial x_{i,k_d^*,r}(\varepsilon,\beta_k)} = A - b(n_d x_{i,k_d^*,r} + n_o y_{j,k_o^*}) - bx_{i,k_d^*,r}(\varepsilon,\beta_k) - \hat{c}_{i,k_d^*}(\varepsilon,\beta_k) = 0, \quad \forall i \in \mathcal{N}_d,, \tag{16}$$

and

$$\frac{\partial \pi_j\left(X_d, X_o, Y\right)}{\partial y_{j,k_o^*}(\varepsilon,\beta_k)} = A - b(n_d x_{i,k_d^*,r} + n_o y_{j,k_o^*}) - by_{j,k_o^*}(\varepsilon,\beta_k) - \hat{c}_{j,k_o^*}(\varepsilon,\beta_k) = 0, \quad \forall j \in \mathcal{N}_o., \tag{17}$$

respectively.

Solving Equation (17) for y_{j,k_o^*} yields

$$y^*_{j,k_o^*}\left(\varepsilon, \hat{\beta}_d, \hat{\beta}_o, x_{i,k,l}\right) = \frac{A - \hat{c}_{j,k_o^*}(\varepsilon,\hat{\beta}_o) - bn_d x_{i,k,l}}{b(n_o+1)}, \quad \forall j \in \mathcal{N}_o. \tag{18}$$

Substituting (18) for y_{j,k_o^*} within Equation (16) and then solving for $x_{i,k_d^*,r}$ yields

$$x^*_{i,k_d^*,r}\left(\varepsilon,\hat{\beta}_d\right) = \frac{A - \hat{c}_{i,k_d^*}\left(\varepsilon,\hat{\beta}_d\right)}{b\left(n_d+n_o+1\right)} + \frac{n_o\left(\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right) - \hat{c}_{i,k_d^*}\left(\varepsilon,\hat{\beta}_d\right)\right)}{b\left(n_d+n_o+1\right)}, \quad \forall i \in \mathcal{N}_d,$$

which, by substituting into Equation (18) yields

$$y^*_{j,k_o^*}\left(\varepsilon,\hat{\beta}_d,\hat{\beta}_o\right) = \frac{A - \hat{c}_{j,k_o^*}\left(\varepsilon,\hat{\beta}_o\right)}{b\left(n_d+n_o+1\right)} - \frac{n_d\left(\hat{c}_{j,k_o^*}\left(\varepsilon,\hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)\right)}{b\left(n_d+n_o+1\right)}, \quad \forall j \in \mathcal{N}_o.$$

■

The number of offshore entrants follows directly from its definition,

$$\max_{y_{j,k},\forall k} \pi_j\left(X_d, X_o, Y\right) = \max_{y_{j,k},\forall k} \sum_{k\in\mathcal{K}} \left[P\left(X_d,X_o,Y\right)y_{j,k} - c_{k,o}\left(\varepsilon,\beta_k\right)y_{j,k}\right] = F, \quad \forall j \in \mathcal{N}_o.$$

$$\Rightarrow \left[A - b\left(n_d x^*_{i,k_d^*,r}(\varepsilon,\hat{\beta}_d) + n_o y_{j,k_o^*}(\varepsilon,\hat{\beta}_o)\right)\right] y_{j,k_o^*}(\varepsilon,\hat{\beta}_o) - \hat{c}_{j,k_o^*}(\varepsilon,\hat{\beta}_o) y_{j,k_o^*}(\varepsilon,\hat{\beta}_o) = F, \quad \forall j \in \mathcal{N}_o.$$

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

$$n_o^* = \max\left\{0, \frac{A - \hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) - n_d\left(\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)\right)}{\sqrt{Fb}} - n_d - 1\right\}. \quad \square$$

Proof of Proposition 2. The condition $\hat{c}_{k_o^*}(\cdot) + n_d\left(\hat{c}_{k_o^*}(\cdot) - \hat{c}_{k_d^*}(\cdot)\right) + \sqrt{Fb}(n_d+1) < A$ implies $n_o^* > 0$ by Proposition 1, insuring an interior solution. Therefore, also by Proposition 1,

$$n_o^* = \frac{A - \hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) - n_d\left(\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) - \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)\right)}{\sqrt{Fb}} - n_d - 1. \tag{19}$$

The result follows directly by substituting (19) into the free entry solutions for $x_{i,k_d^*,r}(\varepsilon, \hat{\beta}_d)$ and $y_{j,k_o^*}(\varepsilon, \hat{\beta}_o)$ from Lemma 3. $\square$

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

$$H(\pi) = \begin{bmatrix} \frac{\partial^2 \pi_1(\cdot)}{\partial x^2_{1,k_d^*,r}(\cdot)} & \cdots & \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,k_d^*,r}(\cdot)\partial x_{n_d,k_d^*,r}(\cdot)} & \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,k_d^*,r}(\cdot)\partial y_{1,k_o^*}(\cdot)} & \cdots & \frac{\partial^2 \pi_1(\cdot)}{\partial x_{1,k_d^*,r}(\cdot)\partial y_{n_o,k_o^*}(\cdot)} \\ \vdots & \ddots & & & & \\ \frac{\partial^2 \pi_{n_d}(\cdot)}{\partial x_{n_d,k_d^*,r}(\cdot)\partial x_{1,k_d^*,r}(\cdot)} & & \frac{\partial^2 \pi_{n_d}(\cdot)}{\partial x^2_{n_d,k_d^*,r}(\cdot)} & & & \\ \frac{\partial^2 \pi_1(\cdot)}{\partial y_{1,k_o^*}(\cdot)\partial x_{1,k_d^*,r}(\cdot)} & & & \frac{\partial^2 \pi_1(\cdot)}{\partial y^2_{1,k_o^*,r}(\cdot)} & & \\ \vdots & & & & \ddots & \\ \frac{\partial^2 \pi_{n_o}(\cdot)}{\partial y_{n_o,k_o^*}(\cdot)\partial x_{1,k_d^*,r}(\cdot)} & & & & & \frac{\partial^2 \pi_{n_o}(\cdot)}{\partial y^2_{n_o,k_o^*,r}(\cdot)} \end{bmatrix},$$

Based on the FOCs given by Equations (14) and (15), it is clear that the second derivative of domestic and offshore objectives are

$$\frac{\partial^2 \pi_i(\cdot)}{\partial x^2_{i,k_d^*,r}(\cdot)} = -2b, \ \ \forall i \in \mathcal{N}_d, \qquad \text{and} \qquad \frac{\partial^2 \pi_j(\cdot)}{\partial y^2_{j,k_o^*,r}(\cdot)} = -2b, \ \ \forall i \in \mathcal{N}_d, \ \ \forall j \in \mathcal{N}_o,$$

while the cross-partials are

$$\frac{\partial^2 \pi_i(\cdot)}{\partial x_{i,k_d^*,r}(\cdot)\partial y_{j,k_o^*}(\cdot)} = -b, \qquad \frac{\partial^2 \pi_j(\cdot)}{\partial y_{j,k_o^*}(\cdot)\partial x_{i,k_d^*,r}(\cdot)} = -b, \ \ \forall i \in \mathcal{N}_d, \ \ \forall j \in \mathcal{N}_o,$$

$$\frac{\partial^2 \pi_i(\cdot)}{\partial x_{i,k_d^*,r}(\cdot)\partial x_{-i,k_d^*,l}(\cdot)}, \ \ \forall i \in \mathcal{N}_d, \ \ \forall l \in \mathcal{L}, \quad \text{and} \quad \frac{\partial^2 \pi_j(\cdot)}{\partial y_{j,k_o^*}(\cdot)\partial y_{-j,k_o^*}(\cdot)}, \ \ \forall j \in \mathcal{N}_o.$$

From these second derivatives and cross partials, it is clear that the main diagonal of the Hessian will be composed of elements equal to $-2b$ while all other elements will be 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. The condition $\hat{c}_{k_o^*}(\cdot)+n_d\Big(\hat{c}_{k_o^*}(\cdot)-\hat{c}_{k_d^*}(\cdot)\Big)+\sqrt{Fb}(n_d+1)\geq A$ implies $n_o^*=0$ by Proposition 1. Therefore $y_{j,k}=0$, $\forall j\in\mathcal{N}_o$ and $\forall k\in\mathcal{K}$. Quantities for domestic firms then follow from the following FOC derived from Equation (1),

$$\frac{\partial\pi_i\left(X_d,X_o,0\right)}{\partial x_{i,k_d^*,r}(\varepsilon,\beta_k)}=A-b(X_o+X_d)-bx_{i,k_d^*,r}(\varepsilon,\beta_k)-\hat{c}_{i,k_d^*}(\varepsilon,\beta_k)=0,\ \ \forall i\in\mathcal{N}_d. \tag{20}$$

Due to symmetry, Equation (20) can be re-written as

$$\frac{\partial\pi_i\left(X_d,X_o,0\right)}{\partial x_{i,k_d^*,r}(\varepsilon,\beta_k)}=A-b(n_dx_{i,k_d^*,r}(\varepsilon,\beta_k))-bx_{i,k_d^*,r}(\varepsilon,\beta_k)-\hat{c}_{i,k_d^*}(\varepsilon,\beta_k)=0,\ \ \forall i\in\mathcal{N}_d, \tag{21}$$

with the result following directly from standard algebra. $\square$

Proof of Proposition 3. By definition, $\varepsilon>\varepsilon^e$ implies offshore and domestic firms compete and therefore $n_o^*>0$. Under such conditions, from Proposition 1,

$$\frac{\mathrm{d}\,n_o^*}{\mathrm{d}\,\varepsilon}=\frac{n_d\hat{\alpha}_d}{\sqrt{Fb}},$$

therefore, total offshore production $Y=n_o^*y_{j,k_o^*}^*$ increases in ε by

$$\frac{\mathrm{d}\,Y}{\mathrm{d}\,\varepsilon}=\left(\frac{n_d\hat{\alpha}_d}{\sqrt{Fb}}\right)\left(\frac{\sqrt{FB}}{b}\right)=\frac{n_d\hat{\alpha}_d}{b}.$$

From Proposition 2,

$$\frac{\mathrm{d}\,x_{i,k_d^*,r}^*}{\mathrm{d}\,\varepsilon}=-\frac{\hat{\alpha}_d}{b},$$

therefore total production by domestic firms $X_d+X_o=n_dx_{i,k_d^*,r}^*$ increases in ε when $n_o^*>0$ by

$$\frac{\mathrm{d}\,X_d+X_o}{\mathrm{d}\,\varepsilon}=-\frac{n_d\hat{\alpha}_d}{b}.$$

Production increases in ε by offshore firms when $\varepsilon>\varepsilon^e$ exactly offset production decreases in ε when $\varepsilon>\varepsilon^e$. As a consequence, total output is fixed in ε when $\varepsilon>\varepsilon^e$. $\square$

Proof of Corollary 2. By the definition of $\hat{c}_{k_d^*}(\varepsilon, \hat{\beta}_d)$, $\varepsilon > \varepsilon^o$ implies that $\hat{c}_{k_d^*}(\varepsilon, \hat{\beta}_d) = \hat{c}_{k_o^*}(\varepsilon, \hat{\beta}_o)$. There are two cases to consider; the case when offshore firms have entered (i.e., $\varepsilon > \varepsilon^o$ and $\varepsilon > \varepsilon^e$), and the case when there is a domestic oligopoly (i.e., $\varepsilon \in (\varepsilon^o, \varepsilon^e)$.

CASE 1: $\varepsilon > \varepsilon^o$ and $\varepsilon > \varepsilon^e$

By the definition of $\hat{c}_{k_d^*}(\varepsilon, \hat{\beta}_d)$, $\varepsilon > \varepsilon^o$ implies that $\hat{c}_{k_d^*}(\varepsilon, \hat{\beta}_d) = \hat{c}_{k_o^*}(\varepsilon, \hat{\beta}_o)$. Therefore, conditional on foreign entry, $\varepsilon > \varepsilon^o$ implies that entry is such that

$$n_o^* = \frac{A - \hat{c}_{k_o^*}(\varepsilon, \hat{\beta}_o)}{\sqrt{FB}} - n_d - 1. \tag{22}$$

With no border adjustment, $\hat{\beta}_o$, Equation (22) does not depend on ε, and therefore $\frac{\mathrm{d}\, n_o^*}{\mathrm{d}\,\varepsilon} = 0$.

Domestic firms produce at quantities

$$x^*_{i,k_d^*,o}\left(\varepsilon, \hat{\beta}_d\right) = \frac{\sqrt{FB}}{b},$$

which also does not depend on ε, and as a consequence $\frac{\mathrm{d}\, x^*_{i,k_d^*,o}(\cdot)}{\mathrm{d}\,\varepsilon} = 0$. Therefore, the result holds when $\varepsilon > \varepsilon^o$ and $\varepsilon > \varepsilon^e$.

CASE 2: $\varepsilon \in (\varepsilon^o, \varepsilon^e)$ By the definition of $\hat{c}_{k_d^*}(\varepsilon, \hat{\beta}_d)$, when $\varepsilon > \varepsilon^o$, $\hat{c}_{k_d^*}(\varepsilon, \hat{\beta}_d) = \hat{\gamma}_d + \hat{\beta}_d$. When there is no border adjustment, $\hat{\beta}_d = 0$. Therefore, quantities under a domestic-owned oligopoly are

$$x_{i,k_d^*,o}\left(\varepsilon, \hat{\beta}_d\right) = \frac{A - \hat{\gamma}_d}{b(n_d + 1)},$$

which do not depend on ε, and as a consequence $\frac{\mathrm{d}\, x^*_{i,k_d^*,o}(\cdot)}{\mathrm{d}\,\varepsilon} = 0$. Therefore the result holds when $\varepsilon \in (\varepsilon^o, \varepsilon^e)$. □

Proof of Lemma 1. Offshore firms prefer technology k to technology $k-1$ when $c_{k,o}(\varepsilon, \beta_k) \leq c_{k-1,o}(\varepsilon, \beta_{k-1})$. Under a border adjustment such that $\beta_k = \alpha_k \varepsilon$, this implies that the lowest emissions price at which offshore producers prefer technology k to technology $k-1$ is $\tilde{\varepsilon}_k^o = \delta\left(\frac{\gamma_k - \gamma_{k-1}}{\alpha_{k-1} - \alpha_k}\right)$, which follows from the definition of $c_{k,o}(\varepsilon, \beta_k)$ and the ordering $\alpha_1 < \ldots < \alpha_m$.

By a similar argument, the lowest price at which domestic firms prefer technology k to technology $k-1$ is when $c_{k,d}(\varepsilon, \beta_k) = c_{k-1,d}(\varepsilon, \beta_{k-1})$ at $\tilde{\varepsilon}_k^d = \frac{\gamma_k - \gamma_{k-1}}{\alpha_{k-1} - \alpha_k}$.

By assumption, $\delta \in (0,1)$, i.e., offshore production has an operating and capital recovery cost advantage. That $\delta < 1$ implies $\tilde{\varepsilon}_k^o < \tilde{\varepsilon}_k^d$ at emissions prices such that domestic firms produce locally (i.e., until domestic firms adopt offshore economics at $\tilde{\varepsilon}_{k^o}^d$). $\square$

Proof of Proposition 4. Domestic firms offshore when $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right) \geq \hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_d\right)$ by the definition of $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)$ and $\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right)$. Therefore, the lowest emissions price at which domestic production will offshore is $\tilde{\varepsilon}^o | \min_{k \in \mathcal{K}} c_{k,d}\left(\varepsilon, \beta_k\right) = \min_{k \in \mathcal{K}} c_{k,o}\left(\varepsilon, \beta_k\right)$.

There are three cases to consider: when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$ and when $\varepsilon < \varepsilon_2^o$ under which conditions domestic and offshore firms operate identical technology; and when $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$ under which conditions offshore firms operate cleaner technology than domestic firms.

CASE 1: $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$

Domestic and offshore firms utilize the same technology (with domestic firms producing locally) when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$. As a consequence, within these intervals of emissions prices, $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right) = \gamma_k + \alpha_k \varepsilon$ and $\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right) = \delta\gamma_k + \alpha_k \varepsilon + \tau$ by the definition of $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)$ and $\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right)$ and a border adjustment such that $\beta_k = \alpha_k \varepsilon$. Therefore, $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)$ and $\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right)$ increase equally in ε with

$$\frac{\mathrm{d}\, \hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)}{\mathrm{d}\, \varepsilon} = -\alpha_k \quad \text{and} \quad \frac{\mathrm{d}\, \hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_d\right)}{\mathrm{d}\, \varepsilon} = -\alpha_k$$

when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$.

Therefore, $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right)$ and $\hat{c}_{k_o^*}\left(\varepsilon, \hat{\beta}_o\right)$ cannot intersect when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$. As a consequence, $\tilde{\varepsilon}^o \notin [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$, $\forall k \in \{2, ..., m\}$.

CASE 2: $\varepsilon < \varepsilon_2^o$

When $\varepsilon < \varepsilon_2^o$ with a border adjustment, domestic and offshore firms both operate the dirtiest technology 1 with domestic firms producing locally. As a consequence of arguments symmetric to that in Case 1, $\tilde{\varepsilon}^o \notin [0, \varepsilon_2^o)$.

CASE 3: $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$

Offshore firms utilize cleaner technology than domestic firms when $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$. When $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$, total domestic and offshore costs are $\hat{c}_{k_d^*}\left(\varepsilon, \hat{\beta}_d\right) = \gamma_{k-1} + \alpha_{k-1}\varepsilon$

and $\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right)=\delta\gamma_k+\alpha_k\varepsilon+\tau$. Therefore, $\hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)$ increases in ε at a greater rate than $\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right)$, with

$$\frac{\mathrm{d}\,\hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)}{\mathrm{d}\,\varepsilon}=-\alpha_{k-1} \qquad \text{and} \qquad \frac{\mathrm{d}\,\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_d\right)}{\mathrm{d}\,\varepsilon}=-\alpha_k.$$

Note that $\alpha_{k-1}>\alpha_k$ by definition. Therefore, $\hat{c}_{k_d^*}\left(\varepsilon,\hat{\beta}_d\right)-\hat{c}_{k_o^*}\left(\varepsilon,\hat{\beta}_o\right)$ decreases monotonically in ε when $\varepsilon\in[\varepsilon_k^o,\varepsilon_k^d)$, $\forall k\in\{2,\ldots,k^o\}$.

As a consequence of Case 1, Case 2 and Case 3, if the the domestic firm would choose to offshore at a given emissions price – i.e., if $\tilde{\varepsilon}^o$ exists – then the domestic firm would offshore to adopt a cleaner technology than they operate domestically. $\square$

Proof of Proposition 5. There are two cases to consider: emissions price intervals within which offshore firms operate cleaner technology, which occur when $\varepsilon\in[\varepsilon_k^o,\varepsilon_k^d)$, $\forall k\in\{2,\ldots,k^o\}$; and emissions price intervals within which domestic and offshore firms operate identical technology that occur when $\varepsilon<\tilde{\varepsilon}_2^o$, when $\varepsilon\geq\tilde{\varepsilon}_{k^o}^d$, and when $\varepsilon\in[\varepsilon_k^d,\varepsilon_{k+1}^o)$, $\forall k\in\{2,\ldots,k^o\}$.

CASE 1: $\varepsilon\in[\varepsilon_k^o,\varepsilon_k^d)$, $\forall k\in\{2,\ldots,k^o\}$

By definition, under border adjustment, when $\varepsilon\in[\varepsilon_k^o,\varepsilon_k^d)$, $\forall k\in\{2,\ldots,k^o\}$, offshore production is cleaner than domestic production. When $n_o^*>0$ under such conditions, from Proposition 1,

$$\frac{\mathrm{d}\,n_o^*}{\mathrm{d}\,\varepsilon}=\frac{-\alpha_k+n_d(\alpha_{k-1}-\alpha_k)}{\sqrt{Fb}},\quad \forall k\in\{2,\ldots,k^o\}. \tag{23}$$

Equation (23) is non-negative when $\frac{\alpha_{k-1}}{\alpha_k}\geq 1+\frac{1}{n_d}$, but is strictly negative when $\frac{\alpha_{k-1}}{\alpha_k}<1+\frac{1}{n_d}$.

CASE 2: $\varepsilon<\tilde{\varepsilon}_2^o$, or $\varepsilon\geq\tilde{\varepsilon}_{k^o}^d$, or $\varepsilon\in[\varepsilon_k^d,\varepsilon_{k+1}^o)$, $\forall k\in\{2,\ldots,k^o\}$

When $\varepsilon<\tilde{\varepsilon}_2^o$, domestic and offshore firms both operate technology 1, with domestic firms producing locally. When $\varepsilon\in[\varepsilon_k^d,\varepsilon_{k+1}^o)$, domestic firms operate offshore and produce under the same economics, and therefore the same technologies, as offshore firms. Lastly, over emissions price intervals such that $\varepsilon\in[\varepsilon_k^d,\varepsilon_{k+1}^o)$, $\forall k\in\{2,\ldots,k^o\}$, domestic and offshore firms produce with identical technology, with domestic firms producing locally. Under all such conditions with border adjustment, when $n_0^*>0$, it is clear from Proposition 1 that

$$\frac{\mathrm{d}\,n_o^*}{\mathrm{d}\,\varepsilon}=-\frac{\alpha_k}{\sqrt{Fb}}<0,\quad \forall k\in\mathcal{K}. \quad \square$$

Proof of Proposition 6. Similar to Proposition 5, there are two cases to consider: emissions price intervals within which offshore firms operate cleaner technology that occur when $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$; and emissions price intervals within which domestic and offshore firms operate identical technology that occur when $\varepsilon < \tilde{\varepsilon}_2^o$, when $\varepsilon \geq \tilde{\varepsilon}_{k^o}^d$, and when $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$.

CASE 1: $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$

Under border adjustment, when $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$, offshore firms operate technology k and domestic firms produce locally with technology $k-1$, which is strictly dirtier than technology k. When $n_o^* > 0$, it is clear from Proposition 2 that under border adjustment total domestic production $X_d + X_d = n_d x_{i,k_d^*,r}^* \left(\varepsilon, \hat{\beta}_d\right)$ decreases in ε

$$\frac{\mathrm{d}\, n_d x_{i,k_d^*,r}(\cdot)}{\mathrm{d}\,\varepsilon} = n_d \left(\frac{\alpha_k - \alpha_{k-1}}{b}\right) < 0, \quad \forall k \in \{2, \ldots, k^o\}.$$

CASE 2: $\varepsilon < \tilde{\varepsilon}_2^o$, or $\varepsilon \geq \tilde{\varepsilon}_{k^o}^d$, or $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$

When $\varepsilon < \tilde{\varepsilon}_2^o$, domestic and offshore firms both operate technology 1, with domestic firms producing locally. When $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, domestic firms operate offshore and produce under the same economics, and therefore the same technologies, as offshore firms. Lastly, over emissions price intervals such that $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$, domestic and offshore firms produce with identical technology, with domestic firms producing locally. Under all such conditions with border adjustment, when $n_0^* > 0$, it is clear from Proposition 2 that total production by domestic firms is fixed in emissions price:

$$\frac{\mathrm{d}\, n_d x_{i,k_d^*,r}(\cdot)}{\mathrm{d}\,\varepsilon} = 0, \quad \forall k \in \mathcal{K}. \quad \square$$

Proof of Corollary 3. There are three cases to consider: a domestic oligopoly when $n_o^* = 0$; competition between offshore and domestic firms when offshore firms operate cleaner technology, which occurs when $n_o^* > 0$ and $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$; and competition between offshore and domestic firms when both sets of firms operate the same technology, which occurs when $n_o^* > 0$ and $\varepsilon < \tilde{\varepsilon}_2^o$, or $\varepsilon \geq \tilde{\varepsilon}_{k^o}^d$, or $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$.

CASE 1: $n_o^* = 0$

Under conditions where $n_o^* = 0$, domestic firms compete amongst themselves in the market. By Corollary 1, it is clear that total production $X_d + X_o + Y = n_d x_{i,k_d^*,r}$ decreases in ε

$$\frac{\mathrm{d}\, X_o + X_d + Y}{\mathrm{d}\, \varepsilon} = -\frac{\hat{\alpha}_d}{b(n_d+1)} < 0.$$

CASE 2: $n_o^* > 0$ and $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$

Conditional on entry – i.e., $n_o^* > 0$ – and border adjustment, when offshore firms operate cleaner technology k and domestic firms operate technology $k-1$, it is evident that total production $X_d + X_o + Y = n_d x_{i,k_d^*,r} + n_o^* y_{j,k_o^*}$ decreases in ε by Proposition 1 and Proposition 2

$$\begin{aligned}\frac{\mathrm{d}\, X_o + X_d + Y}{\mathrm{d}\, \varepsilon} &= n_d \left(\frac{\alpha_k - \alpha_{k-1}}{b} \right) + \left(\frac{-\alpha_k + n_d(\alpha_{k-1} - \alpha_k)}{\sqrt{Fb}} \right) \frac{\sqrt{Fb}}{b} \\ &= -\frac{\alpha_k}{b} < 0, \ \ \forall k \in \{2, \ldots, k^o\}.\end{aligned}$$

CASE 3: $n_o^* > 0$ and $\varepsilon < \tilde{\varepsilon}_2^o$, or $\varepsilon \geq \tilde{\varepsilon}_{k^o}^d$, or $\varepsilon \in [\varepsilon_k^d, \varepsilon_{k+1}^o)$, $\forall k \in \{2, \ldots, k^o\}$

Lastly, conditional on entry – i.e., $n_o^* > 0$ – and border adjustment, when offshore firms and domestic firms both operate technology k, it is also clear that total production $X_d + X_o + Y = n_d x_{i,k_d^*,r} + n_o^* y_{j,k_o^*}$ decreases in ε by Propositions 1 and 2

$$\begin{aligned}\frac{\mathrm{d}\, X_o + X_d + Y}{\mathrm{d}\, \varepsilon} &= 0 - \left(\frac{\alpha_k}{\sqrt{Fb}} \right) \frac{\sqrt{Fb}}{b} \\ &- \frac{\alpha_k}{b} < 0, \ \ \forall k \in \mathcal{K}. \quad \square\end{aligned}$$

Proof of Proposition 7. Under border adjustment and conditional on entry (i.e., $n_o^* > 0$), Proposition 5 shows that foreign entry can only increase in ε if $\varepsilon \in [\varepsilon_k^o, \varepsilon_k^d)$, $\forall k \in \{2, \ldots, k^o\}$ and $\frac{\alpha_{k-1}}{\alpha_k} \geq 1 + \frac{1}{n_d}$. Under these conditions, offshore firms operate technology k and domestic firms produce locally with technology $k-1$. As a consequence, global emissions e^g, which is defined in Equation 10, conditionally decreases in ε, as

$$\frac{\mathrm{d}\, e^g(X_d, X_o, Y)}{\mathrm{d}\, \varepsilon} = -n_d(\alpha_{k-1} - \alpha_k)^2 + n_d \alpha_\tau (\alpha_{k-1} - \alpha_k) - \alpha_k(\alpha_k + \alpha_\tau)$$

is negative if $\alpha_\tau \left(\alpha_{k-1} - \alpha_k\right) < \left(\alpha_{k-1} - \alpha_k\right)^2 + \frac{\alpha_k(\alpha_k + \alpha_\tau)}{n_d}$, $\forall k \in \{2, \ldots, k_o\}$ but is otherwise positive.

$\square$