Title

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Abstract As countries around the world formulate policies to mitigate greenhouse gas (GHG) emissions, policymakers must weigh the merits of implementing an emissions tax or a cap-and-trade system. A primary barrier to the adoption of a cap-and-trade system is the idea that variability and uncertainty in the permit price (and hence a firm's emissions cost) has an adverse impact on domestic manufacturing firms. An emissions tax, on the other hand, can establish a fixed, certain emissions cost. Analysis in this chapter, however, suggests that variability in the emissions cost under a cap-and-trade system is beneficial, stimulating domestic manufacturing, compared to a mean-equivalent emissions tax. Hence, if emissions intensity among foreign competitors located in the region without climate policy is high, then variability in the emissions cost decreases expected emissions from production. Although global emissions may increase after a region initiates climate policy, due to a shift in manufacturing to a region without climate policy and increased transportation, that leakage phenomenon might be mitigated by adopting a cap-and-trade system, compared to a mean-equivalent tax.

1 Introduction

In the absence of a global climate policy, a state may act alone to reduce greenhouse gas (GHG) emissions by imposing a tax on emissions or a cap-and-trade system.

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For example, in July 2012, Australia introduced an emissions tax of $23AUD per tonne of carbon dioxide equivalent emissions (Australian Government Clean Energy Regulator, 2014), but repealed that tax in July 2014 (Hannam, 2014). The European Union (E.U.) has operated a cap-and-trade system since 2005, and the state of California has done so since 2012. A cap-and-trade system limits the total amount of GHG emissions. Government issues a corresponding number of permits for emissions, which may be auctioned or given away. Businesses buy and sell permits as needed, allowing market forces to distribute and price the permits. In contrast to a fixed tax on emissions, a cap-and-trade system introduces *variability* and *uncertainty* in the cost of emissions. For example, the price of a permit in the E.U. has varied substantially, from a peak of €32 in April 2006 to below €3 per tonne of carbon dioxide equivalent in January 2013 (The Guardian, 2013).

Policymakers need to assess the economic and environmental consequences of such unilateral action. A primary barrier to the adoption of either an emissions tax or cap-and-trade system is the concern that manufacturing will shift to a region with no climate policy, thereby increasing GHG emissions in that region. A related barrier to adoption of a cap-and-trade system is the concern that variability in the cost of emissions is undesirable for firms, and so might exacerbate the shift in manufacturing.

This chapter aims to provide guidance to policymakers and helps to bridge and extend the literatures on climate policy and on facility location by answering the following questions: How does instituting a climate policy (emissions tax versus a cap-and-trade system) affect the equilibrium number of manufacturers that choose to locate in the region with climate policy (and the region without climate policy) and their production and export quantities? What are the implications for global GHG emissions? The most important contribution is to show that increased variance in the cost of emissions can cause more firms to locate in the region with climate policy and increase production therein.

The operations management literature on facility location contains few papers that address cost variability or uncertainty. In Snyder's 2006 survey of 152 papers on facility location under uncertainty, only eight papers consider either production cost or transportation cost uncertainty. Only one of those eight papers incorporates uncertainty in both transportation costs and production costs, and it is not representative of emissions cost uncertainty (Jornsten and Bjorndal, 1994). Melo et al. (2009) review the facility location literature in the supply chain context and note that papers integrating stochasticity into this literature are still scarce. The sources of uncertainty covered in this literature include customer demand, exchange rate, travel time, amount of returns in reverse logistics, supply lead time, transportation cost, and holding cost (Melo et al., 2009, Table 1). Chen et al. (2014) review the literature on the interface of facility location and sustainability. The review includes papers which consider climate change performance as a factor when choosing the location of manufacturing facilities (Chen et al., 2014, Table 5). Other recent papers, which incorporate carbon emissions concerns into the supply chain design problems, include (Diabat and Simchi-Levi, 2010; Benjaafar et al., 2013; Jin et al., 2014). However, these papers do not focus on the variability in permit prices under the cap-and-trade system; they assume the permit price is relatively stable over the firm's planning horizon and is exogenous from the viewpoint of individual firms.

In climate policy literature on whether an emissions tax or a cap-and-trade system is socially optimal, the seminal paper by Weitzman (1974) focuses on how society is affected by uncertainty in emissions quantity versus emissions cost. If the expected social cost of uncertainty in emissions quantity and the resulting environmental damage is higher, then a cap-and-trade system (fixing the amount of emissions) is optimal. If the expected social cost of uncertainty in the emissions cost is higher, then an emissions tax is optimal. Nordhaus (2007) adopts the latter, pro-tax view, emphasizing the adverse economic impacts of variability and uncertainty in the permit price under a cap-and-trade system. Goulder and Schein (2013) provide a broad overview of the equivalences and trade-offs in adopting a tax versus cap-and-trade system. In particular, like Nordhaus (2007), Goulder and Schein (2013) emphasize the adverse economic impacts of variability and uncertainty in the permit price under a cap-and-trade system, and observe that some business groups abhor that uncertainty. To reduce that variability and uncertainty, Goulder and Schein (2013) recommend imposing a floor and ceiling on the permit price, and Weber and Neuhoff (2010) provide theoretical support for doing so.

Conventional wisdom in policy circles also supports the idea that variability in the emissions cost is undesirable. William D. Nordhaus states that: "The high level of volatility is economically costly and provides inconsistent signals to private-sector decision makers. Clearly, a carbon tax would provide consistent signals and would not vary so widely from year to year, or even day to day" (Nordhaus, 2009, Pg. 6). Janet E. Milne also emphasizes the complexity that the volatility of permit prices under a cap-and-trade system adds: "The straightforwardness of carbon taxes makes them economically efficient, as the Congressional Budget Office has recognized. ... Cap-and-trade proposals can build in features that limit the price exposure and allow flexibility in annual compliance, but add more layers of complexity (Milne, 2008)." Shapiro (2009) notes that the variability in energy prices can result in under-investment in climate-friendly fuels and the volatility in permit prices would attract financial speculation.

The potential to influence GHG emissions through facility location and inter-regional trade is substantial. Transportation of manufactured goods currently contributes nearly 10% of global carbon dioxide (CO_2) emissions and, absent climate change policy, is expected to grow 3% per annum through 2030 due to increased consumption and lengthening of supply chains (McKinnon, 2008). Manufacturing contributes more than 30% of global greenhouse gas emissions (Bernstein et al., 2007). The emission-intensity of manufacturing differs around the world. Therefore, shifting of manufacturing from a region with climate policy to a region without climate policy might substantially increase emissions from manufacturing and transportation.

An extensive literature, surveyed in (Condon and Ignaciuk, 2013), examines the impact of a unilateral climate policy in shifting manufacturing and GHG emissions to a region without climate policy. Much of that literature does not address variability in the emissions cost. Furthermore, much of that literature is based on computable general equilibrium models of the entire economy, which assume perfect competition. However, the papers most closely related to this chapter restrict attention to a single industry, in order to deal with the complexity of imperfect competition. In modeling a cap-and-trade system, the single-industry papers and this chapter assume that firms in the industry are price-takers in the market for emissions permits, which spans many industries (Fowlie et al., 2014); in other words, the emissions cost is a model parameter. Among single-industry papers, for example, Fowlie et al. (2014) empirically estimate a model of how cement manufacturers dynamically adjust their capacities and choose production quantities over time. Mathiesen and Maestad (2004), Demailly and Quirion (2008), and Lanz et al. (2013) use partial equilibrium models to measure the impact of sub-global climate policies on the emissions from the steel, cement and copper industries, respectively.

In the operations management literature, Drake (2015) studies the effect of regionally asymmetric emissions regulations in models of imperfect competition. Drake (2015) does so with a focus on discrete technology choice and border adjustment without uncertainty while Drake et al. (2015) investigate the impact of emissions price uncertainty on the expected profit of a single firm with a discrete technology choice and variable capacity costs. This chapter focuses on the impact of emissions price uncertainty on the facility location and trade decisions of firms in an imperfect competition model.

This chapter incorporates an emissions cost (which is a random variable in the cap-and-trade scenario, and is a constant in the tax scenario) into Venables' widely used model of international trade for a single product (Venables, 1985). Region 1 has climate policy and Region 2 does not. Each region has a variable cost of production, emissions intensity of production, and demand function. There is a unit cost to transport goods between the regions. Initially, all firms know the distribution of the emissions cost, which will effectively increase the unit cost of production in Region 1. A firm may establish a production facility in Region 1 or 2, and incurs a fixed cost (potentially different in different regions) to do so. Then, all firms realize the emissions cost and choose quantities to produce and export in a Cournot equilibrium. The equilibrium number of firms building production facilities in each region is uniquely determined by each having net zero expected profit.

Section 2 describes our two-region, single-product model of facility location under uncertain production costs and the equilibrium number of firms in each region, optimal domestic sales and exports of each firm. We present several analytical results in Section 3 where we discuss the behavior of several key attributes of interest with respect to the magnitude and uncertainty of the emissions cost. In Section 4, we provide the outcome of several numerical experiments where we extend the problem to the asymmetric limited capacity case, followed by the conclusions in Section 5.

2 Model Formulation

In our model, we consider two regions producing and trading a commodity. Region 1 adopts a climate policy. Each firm in Region 1 incurs a cost per unit GHG emissions related to the production and shipment of a commodity, T. Let e_i denote the emissions intensity of production, emissions per unit of production, in region $i = 1,2$ and let e_s denote the emission intensity of shipping, emissions per unit shipped from one region to the other. A firm in Region 1 pays e_1T per unit produced and e_sT per unit shipped to Region 2. T is an almost surely strictly positive random variable with mean μ and variance σ^2. Note that, in the emissions tax setup, we have no variability in the emission cost, implying $\mathrm{T} = \mu$ almost surely ($\sigma^2 = 0$) whereas in a cap-and-trade system $\sigma^2 > 0$ due to the uncertainty induced by the free market pricing. Region 2 has no climate policy.

Let n_i denote the number of firms that incur a fixed cost f_i to establish the capability to produce in region i. After doing so, each firm realizes the demand for this commodity in both regions and the permit price $\mathrm{T} = \tau$. Each firm decides how much to produce: The variable cost per unit production in Region 2 is c_2, and the effective variable cost per unit production in Region 1 is $c_1 = \underline{c_1} + \tau$, the sum of per unit production cost and the permit price, respectively. The cost to ship a unit from one region to the other is s. The selling price per unit in region $i \in \{1,2\}$ is:

$$p_i \ = D_i - Q_i, \tag{1}$$

where Q_i is the total quantity sold in region i. We assume that the uncertainty in demand is represented by D_i which embodies the effects of all factors other than price that affect demand. D_i is an almost surely strictly positive random variable, and d_i represents the corresponding realization. The supply-demand equation is:

$$Q_i = n_i y_i + n_j x_j \text{ for } i,j = 1,2,\ i \neq j, \tag{2}$$

wherein y_i represents a firm's sales in its domestic market and x_i represents its export quantity, both chosen to maximize each firm's profit operating in region i, Π_i, according to

$$\begin{aligned} \Pi_1 = \max_{y_1, x_1 \geq 0} \ & \{(p_1 - c_1)y_1 + (p_2 - c_1 - s)x_1 - f_1\} \\ & \text{with } p_1 = d_1 - y_1 - Q_1^- \text{ and } p_2 = d_2 - x_1 - Q_2^- \end{aligned} \tag{3}$$

$$\begin{aligned} \Pi_2 = \max_{y_2, x_2 \geq 0} \ & \{(p_2 - c_2)y_2 + (p_1 - c_2 - s)x_2 - f_2\} \\ & \text{with } p_2 = d_2 - y_2 - Q_2^- \text{ and } p_1 = d_1 - x_2 - Q_1^-, \end{aligned} \tag{4}$$

with Q_i^- denoting the aggregate quantity supplied by other firms to region $i = 1,2$.

In equilibrium, active firms have non-negative expected profit, but the entry of an additional firm would reduce expected profit below zero. This equilibrium condition will be expressed by setting $E[\Pi_i] = 0$ if the number of active firms n_i is strictly positive, and $E[\Pi_i] < 0$ if n_i is zero,[1] for each region $i = 1,2$. Doing so ignores the fact that the number of active firms should take only integer values but, as noted by Venables (1985), provides a good approximation when the number of firms is large.

In Section 3, we present analytical results for two scenarios. In the first scenario, we consider "imperfect competition," where $f_i > 0$ for $i = 1,2$, and, following Venables (1985), we assume existence of an equilibrium with a strictly positive number of firms active in each region, which supply both their domestic and export markets.[2] We also assume, for analytic tractability, that the regions are differentiated only in that Region 1 has climate policy, i.e., $D_1 = D_2 = D$ almost surely, $f_1 = f_2 = f$, $c_2 = c$ and $c_1 = c + \tau$.[3] Finally, we assume that the variance of $D + \mathrm{T}$ is not less than the variance of D.

In the second scenario, we consider the case of "perfect competition," where the fixed costs $f_i \to 0$ for $i = 1,2$. Hence, in equilibrium, each region is supplied only from the region with the lowest variable cost to do so, at a price corresponding to that variable cost. In a knife-edge case, in which the variable cost of Region 1 production is identical to the variable cost of Region 2 production and shipping, we focus on the equilibrium with only local production. For brevity of exposition, we also make the plausible assumption that D_1 and D_2 are sufficiently large with high probability, such that consumption occurs in each region with strictly positive probability.

3 Analytical Results

Throughout this section, we use the terms "domestic" and "foreign" to refer to Region 1 (with climate policy) and Region 2 (without climate policy), respectively.

Lemma 1. *Consider imperfect competition.*
(a) *For any given $n_1 > 0$, $n_2 > 0$, the optimal sales quantities for each firm in Region 1 and 2 are*

$$y_1^* = \frac{d_1 - c - (1+n_2)\tau + n_2 s}{n_1 + n_2 + 1}, \tag{5}$$

$$x_1^* = \frac{d_2 - c - (1+n_2)(\tau + s)}{n_1 + n_2 + 1}, \tag{6}$$

$$y_2^* = \frac{d_2 - c + n_1(s + \tau)}{n_1 + n_2 + 1}, \tag{7}$$

$$x_2^* = \frac{d_1 - c + n_1\tau - (1+n_1)s}{n_1 + n_2 + 1}, \tag{8}$$

[1] Expectation is over the joint uncertainty induced by T and $\{D_i\}$.

[2] This assertion can be justified under some mild technical assumptions; see Lemma 1 in Section 3 for further details.

[3] Whenever a result is valid without this assumption, we differentiate these parameters and random variables by specifying the corresponding region index i.

provided that $y_i^* > 0$, $x_i^* > 0$, $i = 1,2$. The corresponding prices are

$$p_1^* = \frac{d_1 + n_1(c+\tau) + n_2(c+s)}{n_1 + n_2 + 1}, \tag{9}$$

$$p_2^* = \frac{d_2 + n_1(c+\tau+s) + n_2 c}{n_1 + n_2 + 1}. \tag{10}$$

For $D_1 = D_2 = D$ a.s., a necessary and sufficient condition for strict positivity of y_i^*, x_i^*, and p_i^* for $i = 1,2$ is $\underline{\tau} < \tau < \overline{\tau}$, where $\underline{\tau} = -\frac{d-c}{n_1} + \frac{n_1+1}{n_1}s$ and $\overline{\tau} = \frac{d-c}{1+n_2} - s$.
***(b)** Assuming $\tau \in (\underline{\tau}, \overline{\tau})$, and D_1 and D_2 are equal to a deterministic value d with probability 1, the number of firms at equilibrium is unique and given by:*

$$n_1^* = \frac{1}{2}\left(\sqrt{\frac{4(d-c)[(d-c-s)(s^2+\sigma^2) - \mu s^2] + s^2[(\mu+s)^2 + 2\sigma^2]}{(2f - s^2 - \mu^2 - \sigma^2)(s^2+\mu^2+\sigma^2)}} - \frac{\mu[2(d-c)-s] + s^2}{s^2+\mu^2+\sigma^2}\right), \tag{11}$$

$$n_2^* = n_1^* + \frac{\mu[2(d-c)-s] - \mu^2 - \sigma^2}{s^2+\mu^2+\sigma^2}, \tag{12}$$

provided that $n_1^* > 0$ and $n_2^* > 0$.

Remark 1. Both n_1^* and n_2^* are monotonic decreasing in f. Therefore, there exists an upper bound $\overline{f}$, such that the condition of $f < \overline{f}$ implies positivity of n_1^* and n_2^*.

3.1 The Impact of Instituting a Climate Policy

We say that a climate policy is introduced in a region if an emissions tax ($T = \mu$) or a cap-and-trade system (T is a random variable with mean μ and variance σ^2) is imposed on the firms in that region. We next quantify the impact of introducing such policies on firms.

First, we consider the case of fixed number of firms, n_1 and n_2. Examining Lemma 1(a), it is easy to see that instituting a climate policy in Region 1 reduces the domestic sales and the exports of each firm in Region 1, y_1 and x_1, and increases the respective quantities in Region 2, y_2 and x_2. Therefore, the total domestic production, $n_1(x_1+y_1)$, decreases and the total foreign production, $n_2(x_2+y_2)$, increases with a climate policy. The total production $n_1(x_1+y_1) + n_2(x_2+y_2)$ and the total shipping quantity $n_1x_1 + n_2x_2$ decrease with a climate policy. This implies that the total emissions, $e_1[n_1(x_1+y_1)] + e_2[n_2(x_2+y_2)] + e_s[n_1x_1+n_2x_2]$, decreases with climate policy provided that the emissions intensity in Region 2, e_2, is not too large compared to the emissions intensity in Region 1, e_1. However, if production in Region 2 is much more emissions intensive compared to Region 1, introducing a climate policy in Region 1 can increase the total emissions. Also, as one would expect, a climate policy in Region 1 reduces consumer surplus in Region 1 and 2, $(d_i - p_i)^2/2$ for $i = 1,2$, and raises government revenue, $\tau n_1(x_1+y_1)$, (which can increase social welfare by reducing the need for other taxes that distort the economy). Firms have zero expected profits in equilibrium. Hence the climate policy will increase social welfare in Region 1 to the extent that tax revenue is valuable and (in the aforementioned parameter region in which the climate policy reduces GHG emissions) the social cost of GHG emissions is high.

Next, we investigate the effects of imposing a climate policy on the number of firms and production quantities in each region. Note that, the result reported in Proposition 1 holds for both an emissions tax (i.e., $\mu > 0$ and $\sigma = 0$) and a cap-and-trade system (i.e., $\mu > 0$ and $\sigma > 0$).

Proposition 1. ***(a)*** *Under imperfect competition, instituting a climate policy decreases the number of firms in Region 1 and increases the number of firms in Region 2 (where at least one of the changes is strict). Moreover, the expected domestic production* $n_1 E[x_1 + y_1]$ *strictly decreases and expected foreign production* $n_2 E[x_2 + y_2]$ *strictly increases.*
(b) *Under perfect competition, instituting a climate policy decreases the total domestic production and increases the total foreign production, almost surely.*

The above results imply that instituting either type of climate policy in Region 1 can increase total expected emissions from the industry. A climate policy shifts production from Region 1 to Region 2, so an increase in expected emissions occurs when emissions intensity is high in Region 2. Indeed, concern that a climate policy will cause production to move offshore is a primary impediment to its adoption. Conventional wisdom is that uncertainty in the emissions cost, inherent in a cap-and-trade system, will increase the offshoring. We will explore this effect in the next subsection.

Proposition 2 shows that instituting an "emissions tax" (changing the emissions cost from $\mathrm{T} = 0$ to $\mathrm{T} = \mu > 0$) can increase total expected emissions from the industry by increasing the expected number of units that are shipped. This perverse outcome tends to occur when the tax and the emissions intensity of shipping are large.

Proposition 2. ***(a)*** *Under imperfect competition and an emissions tax (i.e.,* $\mathrm{T} = \mu > 0$ *and* $\sigma = 0$*), total shipments* $n_1 x_1 + n_2 x_2$ *are strictly convex in the emissions tax* μ*. There exists a threshold* $\overline{\mu} \in (0, (\sqrt{2}-1)s)$ *such that total shipments, when compared to the case of no emissions tax, are lower if and only if the emissions tax is sufficiently small, i.e.,*

$$n_1 x_1 + n_2 x_2|_{\mu \in (0,\overline{\mu})} < n_1 x_1 + n_2 x_2|_{\mu = 0} < n_1 x_1 + n_2 x_2|_{\mu \in (\overline{\mu},(\sqrt{2}-1)s)}. \tag{13}$$

(b) *In the scenario of part (a), for any* $\varepsilon \in (0, \overline{\mu})$, $\mu_l \in (\varepsilon, \overline{\mu})$, *and* $\mu_h \in (\overline{\mu}, (\sqrt{2}-1)s)$, *there exists a threshold* $\overline{e}_s \in [0, \infty)$ *such that if the emissions intensity per unit shipped* $e_s > \overline{e}_s$, *then total emissions* $\mathscr{E}$, *when compared to the case of no emissions tax, are lower if the emissions tax is small and are higher if the emissions tax is large.*

$$\mathscr{E}|_{\mu \in (\varepsilon, \mu_l)} < \mathscr{E}|_{\mu = 0} < \mathscr{E}|_{\mu \in (\mu_h, (\sqrt{2}-1)s)}. \tag{14}$$

(c) *Under perfect competition, instituting a large emissions tax* $(\mu > \underline{\mu} = c_2 - c_1 - s)$ *strictly increases total expected shipments if and only if* $\underline{\mu} > 0$, $\mu > c_2 - c_1 + s$, *and*

$E[D_1 - c_2 - s]^+ > E[D_2 - c_1 - s]^{+4}$. *Instituting a small emissions tax* $\mu \in (0, \underline{\mu})$ *strictly reduces total expected shipments.*

The intuition for Proposition 2 is that by making production in Region 1 less attractive, a emissions tax reduces exports from Region 1 and increases exports from Region 2. Because the emissions tax has a direct impact on Region 1 exports, and only an indirect impact on Region 2 exports, it is natural that the export-reduction effect in Region 1 would outweigh the export-increase effect in Region 2. This result and intuition hold when the emissions tax is small. However, it is reversed when the emissions tax is large. Under imperfect competition, the effect of a large emissions tax is to sharply curtail production in Region 1. The vast majority of Region 1's demand is filled by exports from Region 2, and this leads to an increase in total exports.

In the scenario with perfect competition, shipping occurs in only one direction, if at all. Suppose that $\underline{\mu} = c_2 - c_1 - s > 0$, meaning that Region 1 exports to Region 2 in the absence of the emissions tax. A small emissions tax $\mu \in (0, \underline{\mu})$ reduces exports from Region 1, and hence total shipping. A large emissions tax $\mu > \underline{\mu}$ prevents exports from Region 1, and it causes Region 2 to export to Region 1 if and only if $\mu > c_2 - c_1 + s$. Then, the inequality $E[D_1 - c_2 - s]^+ > E[D_2 - c_1 - s]^+$ means that expected exports from Region 2 (the exports turned on by the emissions tax) exceed the expected exports from Region 1 that were turned off by the emissions tax. Hence total expected shipping increases.

In short, in both scenarios, a small emissions tax reduces shipping by reducing exports from Region 1 (and having relatively little or no effect on exports from Region 2) whereas a large emissions tax increases shipping by increasing exports from Region 2 by more than it reduces exports from Region 1.

3.2 The Impact of Variability in Emissions Cost

The propositions in this section suggest that a cap-and-trade system generates more domestic competition, production, and consumer surplus compared to a emissions tax with the same mean cost of emissions, i.e, a mean-equivalent emissions tax, under the assumptions specified at the beginning of this section.

Formally, propositions in this section examine impacts of increasing the standard deviation of the emissions cost, σ. That may be interpreted as an increase in the variability or uncertainty regarding the emissions cost. For brevity, the propositions use only the term "variability".

In Proposition 3 below, we find that the variability in the permit prices under a cap-and-trade system increases the number of firms in the region with climate policy.

[4] The shorthand $[\cdot]^+$ refers to capping the input by 0 from below, i.e., $\forall x \in \mathbb{R}$, $[x]^+ = \max(x, 0)$.

Proposition 3. *Under imperfect competition, the number of active firms in the region with climate policy, n_1, is strictly increasing in the variability in the emissions cost, σ.*

Corollary 1. *Under imperfect competition, the number of active firms in the region with climate policy is strictly greater under a cap-and-trade system than a mean-equivalent emissions tax.*

The intuition is that, for a given number of active firms in each region, a firm's profit from producing in Region 1 is a convex function of the realized emissions cost τ. Hence variance in τ increases the expected profit of a firm in Region 1, which pushes more firms to enter Region 1. The countervailing indirect force is that, for a given number of active firms in each region, variance in τ also increases the expected profit of a firm in Region 2, which tends to push more firms to enter Region 2 and decrease the expected profit of a firm in Region 1. However, the direct benefit of variance to a firm in Region 1 dominates the indirect effect and hence, the variance increases the number of firms in Region 1. The proposition below shows that variance in the emissions cost can also increase the expected production in Region 1.

Proposition 4. *Under imperfect competition, there exists $\overline{\sigma} > 0$ such that as the variability in the emissions cost, σ, increases on $\sigma \in (0, \overline{\sigma}]$, total expected production in Region 1, $n_1 E[x_1 + y_1]$, strictly increases and total expected production in Region 2, $n_2 E[x_2 + y_2]$, strictly decreases.*

An immediate interpretation of Proposition 4 is that, within the imperfect competition setup, domestic expected production is strictly higher and foreign expected production is strictly lower under a cap-and-trade system than their mean-equivalent emissions tax counterparts, provided that the variance of the emissions cost is not too large.

In the scenario with perfect competition, a firm always has zero profit, so does not benefit from the variability in emissions cost inherent in a cap-and-trade system. Nevertheless, a cap-and-trade system may result in greater expected domestic production.

Proposition 5. *Under perfect competition, domestic expected production is higher and foreign expected production is lower under a cap-and-trade system than a mean-equivalent emissions tax if $\mu > s + c_2 - c_1$.*

The logic is simple. A high emissions tax $\mu > s + c_2 - c_1$ shuts down domestic production, whereas a mean-equivalent cap-and-trade system allows for domestic production to occur (which also reduces imports and hence foreign production) at low realizations of the emissions cost.

In addition to increasing expected domestic production, a cap-and-trade policy results in strictly higher overall expected production than a mean-equivalent emissions tax.

Proposition 6. ***(a)*** *Under imperfect competition, total expected production* $n_1E[x_1 + y_1] + n_2E[x_2 + y_2]$ *increases in* σ.
(b) *Under imperfect and perfect competition, total industry expected production is greater under a cap-and-trade system than a mean-equivalent emissions tax.*

To understand the implication for emissions, consider the simple case in which emission-intensity is homogeneous ($e_1 = e_2$) and large relative to the emissions intensity of shipping e_s. Increasing overall production increases emissions. Hence Proposition 6(b) suggests that an emissions tax must be lower than the mean permit price in a cap-and-trade system in order to achieve the same emissions as the cap-and-trade system. With an emissions tax exactly equal to the mean permit price, emissions will be lower with the tax than in the cap-and-trade system.

One might think that expected government revenue would be relatively high under the cap-and-trade system because of the increase in domestic expected production. That is true in the scenario with perfect competition under the condition $\mu > s + c_2 - c_1$ (by logic similar to the proof of Proposition 5). It is not necessarily true in the scenario with imperfect competition because when the realized emissions cost is high, domestic production and associated emissions are relatively low, and revenue is the product of the two.

The proposition below shows that variability in the emission cost can benefit the consumers in the region with climate policy.

Proposition 7. *Under imperfect competition, given a sufficiently small mean emissions tax,* $\mu \leq s$, *domestic expected consumer surplus is increasing in the variability of the emissions cost* σ.

An immediate corollary of Proposition 7 is that, for imperfect competition, as long as mean permit price is not too high, domestic expected consumer surplus is higher under a cap-and-trade system than a mean-equivalent emissions tax setup.

4 Numerical Analysis for the U.S. Southwest Cement Industry

In a numerical example motivated by the U.S. Southwest cement industry, this section incorporates capacity constraints and the potential for a permit price spike under a cap-and-trade system, because such price spikes are seen as a particularly pernicious form of variability (Goulder, 2013). An extreme price spike, modeled in the numerical example, compels cement manufacturers to idle their production facilities, thus preventing them from recovering sunk costs of capacity. Nevertheless, in the numerical example, consistent with the results in the previous section for the simpler model without capacity constraints, a cap-and-trade system with price spikes induces more firms to locate in the region with climate policy than does a mean-equivalent emissions tax.

Policy analysts are concerned about price spikes because various existing cap-and-trade systems have exhibited extreme price spikes. For example, permit prices under the RECLAIM program for nitrogen oxides (NO_x) rose from an average of \$4,284 per ton in 1999 to almost \$45,000 per ton, contributing to the disruptive price spike in the California wholesale electricity spot market in 2000 (Ellerman et al., 2003).

In addition to incorporating capacity constraints and the potential for a permit price spike, this section eliminates assumptions made in the previous analysis that firms are symmetric and their equilibrium production quantities are characterized by an interior solution. Instead, a firm may produce zero quantity or produce at the capacity constraint.

This section focuses on production and trade of cement within the U.S. Southwest, i.e., California, Arizona and Nevada. This is motivated by the observation that the U.S. Southwest imports at most negligible amounts of cement from other U.S. states, according to Miller and Osborne (2014). Imports to the U.S. Southwest cement market from other countries also are very small.[5] Region 1 corresponds to the state of California, which introduced a cap-and-trade system in November 2012, and Region 2 represents Arizona and Nevada, which have no emissions tax or cap-and-trade system.

We fit a linear demand function for each region i, $Q_i = D_i - a_i p_i$ for $i = 1,2$. We assume that the average capacity of a plant in California, Nevada and Arizona is equal to the average clinker capacity of an active plant in the U.S., $K_1 = K_2 = 1,104,167$ metric tons per year (Van Oss, 2013, Table 5). The variable investment cost of such a new state-of-the-art conventional cement plant was approximately \$236.7 per metric ton in 2011 dollars and the fixed capacity investment is $F_1 = F_2 = \$261,378,850$. The details of the above calculations can be found in the Appendix.

We assume the useful life of a cement plant is 30 years and the cost of capital is 8%. At time zero, the firms in each region will decide whether to enter the market. If a firm chooses to enter the market, they will build a cement plant with an average capacity of 1,104,167 metric tons per year. Then, for 30 years, at the start of each year the permit price is realized and the firm decides how much to produce. We assume the distribution of the permit price is stationary.

Operations and maintenance (O&M) costs for a typical existing plant were approximately \$46 per metric ton in 2011 (International Energy Agency Energy Technology Systems Analysis Programme, 2010)[6]. We assume that O&M costs are the same in California, Arizona, and Nevada, and represent the variable production cost ($c_1 = c_2 = \$46$ per metric ton).

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[5] In 2010, as opposed to the 6.6 million metric tons of clinker produced in California, 242,000 metric tons of hydraulic cement and clinker were imported to California ports in Los Angeles, San Diego, and San Francisco from other countries (Van Oss, 2012, Tables 5 and 18); in 2011, as opposed to the 7,193,000 metric tons of clinker produced in California, the foreign imports accounted for only 121,000 metric tons. The Nogales customs district in Arizona had a negligible amount of clinker import in 2010 and 2011 from Mexico.

[6] The O&M cost includes labor, power, and fuel costs but no depreciation. The O&M cost in 2007 Euros was converted to 2011 U.S. dollars by using a 2007 average exchange rate of \$1 = €0.76, and 2007 and 2011 average consumer price indices of 207.342 and 224.939, respectively (U.S. Department Of Labor, Bureau of Labor Statistics, 2013).

In 2011, around 97% of the Portland cement shipments to the customers were made by truck (Van Oss, 2013, Table 10). The average emissions intensity of trucking is 50 grams of CO_2 per metric ton of cement per kilometer (Schipper et al., 2011). Assuming an average shipping distance of 196.34 kilometers (122 miles) as estimated in Miller and Osborne (2014), the emissions intensity of shipping one metric ton of clinker between California and other states is 0.01 metric tons of CO_2. A crude estimate of the shipping cost of cement is $18 in 2011 dollars (Van Oss, 2004, p. 16.5).[7]

In 2010, the average emissions intensity of cement manufacturing in the United States was approximately 0.89 metric tons of CO_2 per metric ton of clinker (Van Oss, 2013, pp. 16.1,16.2) excluding very minor carbon dioxide equivalent emissions of methane and nitrous oxide (N_2O). We will use this as the emissions intensity of cement plants in California, Arizona and Nevada. The California Air Resources Board provides 0.786 metric tons of CO_2 worth of free allowances per metric ton of adjusted clinker and mineral additives produced. Then, a cement plant manufacturing one metric ton of clinker will pay $0.89 - 0.786 = 0.104$ times the permit price.

The 2013 reserve price in auctions for permits in the California cap-and-trade system is $10.71. We assume if there is no price spike, the permit price under the cap-and-trade system is $10.71 per tonne of carbon dioxide equivalent. Motivated by the examples of extreme price spikes in cap-and-trade systems provided by Nordhaus (2007) and Goulder and Schein (2013), we assume that the permit price will increase to $100 per tonne of emissions if there is a price spike.

Varying the probability of a price spike from zero to one, we calculate n_1, the equilibrium number of firms that establish production facilities in Region 1 (California) under the cap-and-trade system and under a mean-equivalent tax on emissions. That number n_1 is greater under the cap-and-trade system than under the mean-equivalent tax on emissions for all levels of the probability of a price spike. That number n_1 is strictly greater under the cap-and-trade system than under the mean-equivalent tax when the probability of a price spike is between 0.1 and 0.5.

In summary, the numerical example suggests that with capacity constraints and the threat of an extreme price spike under a cap-and-trade system, a cap-and-trade system can attract more firms to locate production facilities in the region with climate policy than a mean-equivalent tax would.

5 Conclusion

This chapter discusses the impact of adopting regional climate policies, in particular, a cap-and-trade system versus an emissions tax, to reduce the GHG emissions in energy-intensive industries. Instituting a climate policy increases the production cost in the region with the climate policy, and hence reduces the total production

[7] 2004 and 2011 annual average consumer price indices as given by U.S. Department Of Labor, Bureau of Labor Statistics (2013) are 188.9 and 224.939, respectively.

and competition among firms. On the other hand, the production and competition in the region without the climate policy increase. The models including the facility location, production and shipping decisions of firms show that instituting a regional climate policy increases total emissions when the emissions intensity in the region without climate policy is high, or when the emissions intensity of shipping is high and the emissions tax is moderate. In contrast to conventional wisdom in some academic and policy circles, these models indicate that the emissions cost variability and uncertainty inherent in a cap-and-trade system can encourage competition among firms and increase production relative to a mean-equivalent emissions tax. In particular, the equilibrium number of firms that locate production facilities in the region with climate policy, expected consumer surplus in the region with climate policy, and the total number of firms increase in the variability of the emissions cost. Moreover, variability in the permit price decreases expected production in the region without climate policy. This implies that if emissions intensity in the region without climate policy is high, then variability in the permit price decreases expected emissions from production. Hence a cap-and-trade system might be preferable for a region planning to adopt a climate policy.

Appendix

Proof of Lemma 1. **(a)** In this proof, we assume that $n_1 > 0$ and $n_2 > 0$, $c_1 = c + \tau$, and $c_2 = c$. The first-order conditions for (3, 4) yield:

$$FOC_{y_i}: \; y_i = p_i - c_i \geq 0, \tag{15}$$
$$FOC_{x_i}: \; x_i = p_j - c_i - s \geq 0 \tag{16}$$

for $i, j = 1, 2$, $i \neq j$.

Using (1) and (2), we obtain:

$$d_1 - p_1 = n_1 y_1 + n_2 x_2, \tag{17}$$
$$d_2 - p_2 = n_2 y_2 + n_1 x_1. \tag{18}$$

Using (15) for $i = 1$, (16) for $i = 2$ and (17), we can solve for the optimal price in Region 1, given by (9). Following a similar procedure, the optimal price in Region 2 is given by (10). By the equalities in (15) and (16), the optimal sales quantities for each firm in Region 1 and 2 are given by (5, 6, 7, 8), respectively.

Next, for $D_1 = D_2 = D$ a.s., we derive the conditions that ensure positivity of y_i^* and x_i^*, $i = 1, 2$. Note that

$$x_1^* = y_1^* - \frac{(1 + 2n_2)s}{n_1 + n_2 + 1},$$
$$x_2^* = y_2^* - \frac{(1 + 2n_1)s}{n_1 + n_2 + 1}.$$

Given that the transportation cost is strictly positive ($s > 0$), and the number of firms in each region are non-negative ($n_1 \geq 0$ and $n_2 \geq 0$), we have $x_1^* < y_1^*$ and $x_2^* < y_2^*$. This, in turn, implies that it suffices to identify the necessary and sufficient conditions on τ for x_1^* and x_2^* to be strictly positive:

$$x_1^* > 0 \Leftrightarrow d - c - (1+n_2)(s+\tau) > 0,$$
$$\Leftrightarrow \tau < \frac{d-c}{1+n_2} - s.$$

Hence, the upper bound on τ is $\overline{\tau} = \frac{d-c}{1+n_2} - s$.

$$x_2^* > 0 \Leftrightarrow d - c + n_1\tau - (1+n_1)s > 0,$$
$$\Leftrightarrow \tau > -\frac{d-c}{n_1} + \frac{n_1+1}{n1}s.$$

Hence, the lower bound on τ is $\underline{\tau} = -\frac{d-c}{n_1} + \frac{n_1+1}{n1}s$. For a given (n_1, n_2) pair, $x_i^* > 0$ and $y_i^* > 0$ for $i = 1,2$ if and only if $\tau \in (\underline{\tau}, \overline{\tau})$. This completes the proof of part (a) of the claim. Next, we proceed with deriving the number of firms at equilibrium.

(b) We assume that the optimal sales quantities for the problem in (3,4) are given by (5) through (8) provided that $y_i^* > 0$ and $x_i^* > 0$ for $i = 1,2$. By inserting the optimal sales quantities into the objective function in (3,4), we find the optimal objective function value for each individual firm in Region 1 and 2, respectively:

$$\Pi_1 = (n_1+n_2+1)^{-2}\left\{[d_1 - c - (1+n_2)\tau + n_2 s]^2 + [d_2 - c - (1+n_2)(\tau+s)]^2\right\} - f_1, \quad (19)$$
$$\Pi_2 = (n_1+n_2+1)^{-2}\left\{[d_2 - c + n_1(s+\tau)]^2 + [d_1 - c + n_1\tau - (1+n_1)s]^2\right\} - f_2. \quad (20)$$

Then, assuming D_1 and D_2 are equal to a deterministic value d with probability 1 and $f_1 = f_2 = f$, the expected profit of a firm in each region before observing the permit price $\mathrm{T} = \tau$ is:

$$\begin{aligned} E\Pi_1 = {} & (n_1+n_2+1)^{-2}\left\{2(d-c)(d-c-s) + (1+2n_2+2n_2^2)t^2 \right. \\ & \left. -2[2(d-c)-s](1+n_2)\mu + 2(1+n_2)^2(\mu^2+\sigma^2)\right\} - f, \\ E\Pi_2 = {} & (n_1+n_2+1)^{-2}\left\{2(d-c)(d-c-s) + (1+2n_1+2n_1^2)t^2 \right. \\ & \left. +2[2(d-c)-s]n_1\mu + 2n_1^2(\mu^2+\sigma^2)\right\} - f. \end{aligned} \quad (21)$$

Note that this is an unconditional expectation over τ due to the assumption that $y_i^* > 0$ and $x_i^* > 0$ for $i = 1,2$ or according to part (a) of the lemma, $\tau \in (\underline{\tau}, \overline{\tau})$. Solving for the equilibrium number of firms (n_1^*, n_2^*) by equating $E\Pi_1$ and $E\Pi_2$ to zero, we get the expressions in (11) and (12). We assume that τ only needs to be in $(\underline{\tau}, \overline{\tau})$ when $(n_1, n_2) = (n_1^*, n_2^*)$, i.e., $\tau \in (\underline{\tau}(n_1^*), \overline{\tau}(n_2^*))$. Finally, conditions $n_1^* > 0$ and $n_2^* > 0$ need to be satisfied. □

Proof of Proposition 1. **(a)** We begin with the case of imperfect competition. We first show that instituting climate policy regulation (i.e., either a emissions tax or cap-and-trade) decreases n_1 and increases n_2. It is straightforward to verify that for an interior solution, the expected profit of a firm in Region i, $E\Pi_i$, is strictly decreasing in n_1 and n_2 for $i \in \{1,2\}$. Further, for fixed n_1 and n_2, instituting climate policy regulation decreases the expected profit of a Region 1 firm

$$E\Pi_1|_{\mu>0,\ \sigma\geq 0} < E\Pi_1|_{\mu=0,\ \sigma=0}$$

and increases the expected profit of a Region 2 firm

$$E\Pi_2|_{\mu>0,\ \sigma\geq 0} > E\Pi_2|_{\mu=0,\ \sigma=0}.$$

We first establish that instituting climate policy regulation cannot either (i) increase both n_1 and n_2 or (ii) decrease both n_1 and n_2. The proof is by contradiction. Let n_i^r denote the equilibrium number of firms under climate policy regulation and n_i^o denote the equilibrium number of firms under no climate policy regulation for $i \in \{1,2\}$. Suppose $n_1^r \geq n_1^o$ and $n_2^r \geq n_2^o$. Then,

$$\begin{aligned}0 &= E\Pi_1|_{n_1=n_1^r,\ n_2=n_2^r,\ \mu>0,\ \sigma\geq 0}\\ &\leq E\Pi_1|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu>0,\ \sigma\geq 0} < E\Pi_1|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu=0,\ \sigma=0} = 0.\end{aligned}$$

a contradiction. So it cannot be that $n_1^r \geq n_1^o$ and $n_2^r \geq n_2^o$. Similarly, if $n_1^r \leq n_1^o$ and $n_2^r \leq n_2^o$, then

$$\begin{aligned}0 &= E\Pi_2|_{n_1=n_1^r,\ n_2=n_2^r,\ \mu>0,\ \sigma\geq 0}\\ &\geq E\Pi_2|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu>0,\ \sigma\geq 0} > E\Pi_2|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu=0,\ \sigma=0} = 0.\end{aligned}$$

a contradiction. So it cannot be that $n_1^r \leq n_1^o$ and $n_2^r \leq n_2^o$. This implies that one of the following holds:

$$n_1^r \geq n_1^o \text{ and } n_2^r \leq n_2^o, \text{ where at least one of the equalities is strict} \tag{22}$$

$$n_1^r \leq n_1^o \text{ and } n_2^r \geq n_2^o, \text{ where at least one of the equalities is strict.} \tag{23}$$

Observe from equation (12) that $n_1^r < n_2^r$ if and only if

$$\sigma^2 < \mu[2(d-c)-s-\mu]. \tag{24}$$

The condition for the interior solution, $x_1^* > 0$ holds for all τ, implies $\tau \leq d-c-s$. This implies that $\int_0^{d-c-s}(d-c-s-\tau)\phi(\tau)d\tau \geq 0$. This implies $E[\tau^2]-E[\tau]^2 \leq E[\tau](d-c-s)-E[\tau]^2$, or equivalently, $\sigma^2 \leq \mu(d-c-s-\mu)$. This implies (24). Therefore, $n_1^r - n_2^r < 0 = n_1^o - n_2^o$, which implies $n_1^o - n_1^r > n_2^o - n_2^r$. If (22) holds, then $0 \geq n_1^o - n_1^r > n_2^o - n_2^r \geq 0$, a contradiction. We conclude that (23) holds.

Second, we show that instituting climate policy regulation increases $n_1E[y_1]$ and $n_1E[x_1]$ and decreases $n_2E[y_2]$ and $n_2E[x_2]$. Equalities (5)-(8) denote the optimal sales quantities for each firm in Region 1 and Region 2, when there are n_1 firms in Region 1, n_2 firms in Region 2, and the realized permit price is τ. To make this dependence explicit, we write $y_1(n_1,n_2,\tau)$ to denote y_1^* in equation (5). Define $x_1(n_1,n_2,\tau)$, $y_2(n_1,n_2,\tau)$, and $x_1(n_1,n_2,\tau)$ analogously. Let x_i^o denote the export quantity of a firm in Region i under no climate policy regulation, and let

x_i^r denote the export quantity of a firm in Region i under climate policy regulation and permit price $\tau \geq 0$, for $i \in \{1,2\}$. Let y_i^o and y_i^r denote the analogous domestic production quantities for $i \in \{1,2\}$. It is straightforward to show that $(\partial/\partial n_i)[n_i y_i(n_1,n_2,\tau)] > 0$, $(\partial/\partial n_i)[n_i x_i(n_1,n_2,\tau)] > 0$, $(\partial/\partial n_j) y_i(n_1,n_2,\tau) < 0$, and $(\partial/\partial n_j) x_i(n_1,n_2,\tau) < 0$ for $i \in \{1,2\}$ and $j \neq i$. Then, because $n_1^r \leq n_1^o$ and $n_2^r \geq n_2^o$,

$$n_1^r x_1^r = n_1^r x_1(n_1^r,n_2^r,\tau) \leq n_1^o x_1(n_1^o,n_2^r,\tau) \leq n_1^o x_1(n_1^o,n_2^o,\tau) \leq n_1^o x_1(n_1^o,n_2^o,0) = n_1^o x_1^o, \tag{25}$$

where the last inequality is strict if $\tau > 0$. Because (25) holds when x is replaced by y, it follows that $n_1^r y_1^r \leq n_1^o y_1^o$, where the equality is strict if $\tau > 0$. Similarly,

$$n_2^r x_2^r = n_2^r x_2(n_1^r,n_2^r,\tau) \geq n_2^o x_2(n_1^r,n_2^o,\tau) \geq n_2^o x_2(n_1^o,n_2^o,\tau) \geq n_2^o x_2(n_1^o,n_2^o,0) = n_2^o x_2^o, \tag{26}$$

where the equality is strict if $\tau > 0$. By similar argument, $n_2^r y_2^r \geq n_2^o y_2^o$, where the equality is strict if $\tau > 0$. Because under climate policy regulation (i.e., $\mu > 0$ and $\sigma \geq 0$), $\tau > 0$ with positive probability, (25) implies that $n_1^r E[x_1^r] < n_1^o x_1^o$, where the expectation is taken over τ. Similarly, $n_1^r E[y_1^r] < n_1^o y_1^o$, $n_2^r E[x_2^r] > n_2^o x_2^o$, and $n_2^r E[y_2^r] > n_2^o y_2^o$. □

□

Proof of Proposition 2. We first provide Lemma 2, which characterizes some properties of an interior solution under a emissions tax. The Lemma is useful in the proof of Proposition 2.

Lemma 2. *Under $\sigma = 0$, an interior solution satisfies the following:*

$$\mu < (\sqrt{2}-1)s, \tag{27}$$

$$f > (s^2+\mu^2)^2/(s-\mu)^2, \tag{28}$$

$$D-c > s(s^2-\mu^2)/(s^2-2t\mu-\mu^2). \tag{29}$$

Proof. Suppose $\sigma = 0$. Because an interior solution has $x_1 > 0$, it has

$$D-c-(1+n_2)(s+\mu) > 0. \tag{30}$$

It follows from (11)-(12) that n_2 is decreasing in f and that (30) holds if and only if (27). An interior solution has $n_1 > 0$, which from (11), holds if and only if

$$f < \overline{f} = [2(D-c)(D-c-s)+s^2](s^2+\mu^2)^2/([2(D-c)-s]\mu+s^2)^2. \tag{31}$$

Together, (28) and (31) imply $(D-c-s)(s^2-\mu^2)-2(D-c)s\mu > 0$, which holds if and only if (27) and (29) hold. □

Next, we proceed with the proof of Proposition 2.

(a) First, we show that total shipments $n_1x_1+n_2x_2$ are continuous and strictly convex in μ for an interior solution. Continuity follows from the fact that n_1, n_2, x_1 and x_2 are continuous in μ. With the change of variable $M = D-c$

$$(\partial^2/\partial\mu^2)[n_1x_1+n_2x_2] = f(2f-s^2-\mu^2)^{-5/2}(s^2+\mu^2)^{-7/2}\beta(f,M,s,\mu), \quad (32)$$

where

$$\begin{aligned}\beta(f,M,s,\mu) &= 2M\tau(f,s,\mu)-4f^2s(s^4+6s^3\mu-10s^2\mu^2-9s\mu^3+4\mu^4)\\ &\quad+2f(3s^7+15s^6\mu-20s^5\mu^2-5s^4\mu^3-13s^3\mu^4-19s^2\mu^5+10s\mu^6+\mu^7)\\ &\quad-(s^2+\mu^2)^2(2s^5+9s^4\mu-16s^3\mu^2-14s^2\mu^3+6s\mu^4+\mu^5) \quad (33)\\ \tau(f,s,\mu) &= 4f^2(2s^4-11s^2\mu^2+4\mu^4)-2f(5s^6-21s^4\mu^2-21s^2\mu^4+5\mu^6)\\ &\quad+3(s^2+\mu^2)^2(s^4-6s^2\mu^2+\mu^4). \quad (34)\end{aligned}$$

We next observe that $\tau(f,s,\mu)>0$ for (28) and (27); this follows because under (27), $\tau(f,s,\mu)$ is strictly convex in f, $\lim_{f\to(s^2+\mu^2)^2/(s^2-\mu^2)}(\partial/\partial\mu)\tau(f,s,\mu)>0$ and $\lim_{f\to(s^2+\mu^2)^2/(s^2-\mu^2)}\tau(f,s,\mu)>0$. Therefore, $\beta(f,M,s,\mu)$ is increasing in M. Therefore, under (29),

$$\begin{aligned}\beta(f,M,s,\mu) &> \beta(f,s(s^2-\mu^2)/(s^2-2s\mu-\mu^2),s,\mu)\\ &= \psi(f,s,\mu)(s^2-\mu^2)/(s^2-2s\mu-\mu^2), \quad (35)\end{aligned}$$

where

$$\begin{aligned}\psi(f,s,\mu) &= 4f^2s^2(3s^3-4s^2\mu-6s\mu^2-\mu^3)\\ &\quad-2f(7s^7-9s^6\mu-6s^5\mu^2-11s^4\mu^3-11s^3\mu^4-s^2\mu^5+2s\mu^6+\mu^7)\\ &\quad+(s^2+\mu^2)^2(4s^5-5s^4\mu-10s^3\mu^2-4s^2\mu^3+2s\mu^4+\mu^5). \quad (36)\end{aligned}$$

We next observe that

$$\psi(f,s,\mu)>0 \quad (37)$$

for (27) and (28); this follows because under (27), $\psi(f,s,\mu)$ is strictly convex in f, $\lim_{f\to(s^2+\mu^2)^2/(s^2-\mu^2)}(\partial/\partial\mu)\psi(f,s,\mu)>0$ and $\lim_{f\to(s^2+\mu^2)^2/(s^2-\mu^2)}\psi(f,s,\mu)>0$. It follows from (32), (35), (37) and Lemma 2 that $n_1x_1+n_2x_2$ is strictly convex in μ for an interior solution.

Second, we show that there exists $\overline{\mu}>0$ such that the first inequality in (13) holds. Because an interior solution satisfies (27) and (28), it satisfies $f>s^2$. Observe that $\lim_{\mu\to 0}(\partial/\partial\mu)[n_1x_1+n_2x_2] = \left(s\Big/\sqrt{2f-s^2}-1\right)\Big/2<0$, where the inequality holds because $f>s^2$. This, together with the observation that $n_1x_1+n_2x_2$ is continuous and strictly convex in μ, implies that there exists $\overline{\mu}>0$ such that the first inequality in (13) holds.

Third, we show that total shipments are higher under a large emissions tax than they are under no emissions tax

$$n_1x_1+n_2x_2|_{\mu=0} < n_1x_1+n_2x_2|_{\mu\in[s/3,\sqrt{2}-1)s)}. \quad (38)$$

From (38), Step One and Step Two, it follows that there exists $\overline{\mu}\in(0,(\sqrt{2}-1)s)$ such that (13) holds.

(b) Let

$$\overline{e}_{s,1} = \max\left(0, \frac{\max_{\mu\in(\varepsilon,\mu_l)}[e_1n_1(x_1+y_1)+e_2n_2(x_2+y_2)] - [e_1n_1(x_1+y_1)+e_2[n_2(x_2+y_2)]|_{\mu=0}}{[n_1x_1+n_2x_2]|_{\mu=0} - [n_1x_1+n_2x_2]|_{\mu=\varepsilon}}\right).$$

Because $\mu_l < \overline{\mu}$, by part (a),

$$n_1x_1+n_2x_2|_{\mu\in(\varepsilon,\mu_l)} < n_1x_1+n_2x_2|_{\mu=\varepsilon} < n_1x_1+n_2x_2|_{\mu=0}.$$

Therefore, if $e_s > \overline{e}_{s,1}$, then $\mathscr{E}|_{\mu\in(\varepsilon,\mu_l)} < \mathscr{E}|_{\mu=0}$. Let

$$\overline{e}_{s,2} = \max\left(0, \frac{[e_1n_1(x_1+y_1)+e_2n_2(x_2+y_2)]|_{\mu=0} - \min_{\mu\in(\mu_h,\sqrt{2}-1)s)}[e_1n_1(x_1+y_1)+e_2n_2(x_2+y_2)]|}{[n_1x_1+n_2x_2]|_{\mu=\mu_h} - [n_1x_1+n_2x_2]|_{\mu=0}}\right).$$

Because $\mu_h \in (\overline{\mu},(\sqrt{2}-1)s)$, by part (a),

$$n_1x_1+n_2x_2|_{\mu=0} < n_1x_1+n_2x_2|_{\mu=\mu_h} < n_1x_1+n_2x_2|_{\mu\in(\mu_h,\sqrt{2}-1)s)}$$

Therefore, if $e_s > \overline{e}_{s,2}$, then $\mathscr{E}|_{\mu=0} < \mathscr{E}|_{\mu\in(\mu_h,\sqrt{2}-1)s)}$. The result holds with $\overline{e}_s = \max(\overline{e}_{s,1},\overline{e}_{s,2})$.

(c) In the scenario with perfect competition, the total quantity shipped under an emissions tax (T $= \mu > 0$) or in the absence of climate policy (T $= \mu = 0$) is

$$[D_2-c_1-s-\mu]^+1\{c_1+s+\mu<c_2\}+[D_1-c_2-s]^+1\{c_1+\mu>c_2+s\}, \quad (39)$$

wherein the first term represents Region 1 exports (to Region 2) and the second term represents Region 2 exports (to Region 1). When $\mu \in (0,\underline{\mu})$, $\underline{\mu} = c_2-c_1-s > 0$ which implies that Region 2 does not produce, and Region 1 exports the quantity $[D_2-c_1-s-\mu]^+$ which strictly decreases due to the emissions tax in the event that $D_2-c_1-s>0$. Our assumption that consumption occurs in Region 2 with strictly positive probability implies that $D_2-c_1-s>0$ with strictly positive probability, so $E[D_2-c_1-s-\mu]^+$ strictly decreases due to the emissions tax. A large emissions tax $\mu > \underline{\mu}$ prevents exports from Region 1, and it causes Region 2 to export to Region 1 if and only if $\mu > c_2-c_1+s$. Region 2 does not export in the absence of the emissions tax if and only if $c_2-c_1-s>0$. When $c_2-c_1-s>0$, the increase in total expected shipments caused by the large emissions tax is $E[D_1-c_2-s]^+ - E[D_2-c_1-s]^+$. Hence the large emissions tax $\mu > \underline{\mu}$ strictly increases total expected shipping if and only if $\mu > c_2-c_1+s$, $c_2-c_1-s>0$, and $E[D_1-c_2-s]^+ > E[D_2-c_1-s]^+$.

□

Proof of Proposition 3. **Lemma 3.** *n_1+n_2 is strictly increasing in σ.*

Proof. We denote:

$$\begin{aligned} A &= n_1+n_2+1 \\ &= \sqrt{\frac{4(D-c)[(D-c-s)(s^2+\sigma^2)-\mu s^2]+s^2[(\mu+s)^2+2\sigma^2]}{(2f-s^2-\mu^2-\sigma^2)(s^2+\mu^2+\sigma^2)}}. \end{aligned} \quad (40)$$

To prove the above lemma is equivalent to show that A is strictly increasing in σ. The sufficient conditions for $\frac{\partial A}{\partial \sigma} > 0$ to hold are:

$$\frac{\partial}{\partial \sigma}\left(\frac{4(D-c)[(D-c-s)(s^2+\sigma^2)-\mu s^2]}{(2f-s^2-\mu^2-\sigma^2)(s^2+\mu^2+\sigma^2)}\right) > 0, \tag{41}$$

and

$$\frac{\partial}{\partial \sigma}\left(\frac{s^2[(\mu+s)^2+2\sigma^2]}{(2f-s^2-\mu^2-\sigma^2)(s^2+\mu^2+\sigma^2)}\right) > 0. \tag{42}$$

We will first prove that (41) holds. Given the expression for x_1^* in (6) and the condition for an interior solution, $x_1^* > 0$ at $\tau = \mu$, imply that:

$$\begin{aligned} & D-c-s-\mu > 0, \\ \Rightarrow\ & (D-c-s)(s^2+\sigma^2)-\mu s^2 > 0. \end{aligned} \tag{43}$$

(43) implies that for $A = n_1 + n_2 + 1$ in (40) to be positive at an interior solution, the following condition should hold:

$$2f-s^2-\mu^2-\sigma^2 > 0. \tag{44}$$

Combining (43) and (44) with the facts:

$$\frac{\partial}{\partial \sigma}(2f-s^2-\mu^2-\sigma^2) < 0$$

and

$$\frac{\partial}{\partial \sigma}\frac{[(D-c-s)(s^2+\sigma^2)-\mu s^2]}{(s^2+\mu^2+\sigma^2)} = \frac{2\mu\sigma[(D-c-s)\mu+s^2]}{(s^2+\mu^2+\sigma^2)^2} > 0$$

shows that (41) holds.

(42) is equivalent to:

$$\frac{2s^2[(s-\mu)^2 f+(2\mu s+\sigma^2)(2f-s^2-\mu^2-\sigma^2)]}{(2f-s^2-\mu^2-\sigma^2)^2(s^2+\mu^2+\sigma^2)^2} > 0.$$

Given (44), the above inequality holds. □

Lemma 4. *$n_1 - n_2$ is strictly increasing in σ.*

Proof. By the expression for n_1 and n_2 in (11) and (12):

$$n_1 - n_2 = \frac{\mu^2+\sigma^2-\mu[2(D-c)-s]}{s^2+\mu^2+\sigma^2}.$$

Thus, the derivative of $n_1 - n_2$ with respect to σ is:

$$\frac{\partial}{\partial \sigma}(n_1-n_2) = \frac{\partial}{\partial \sigma}\frac{\mu^2+\sigma^2-\mu[2(D-c)-s]}{s^2+\mu^2+\sigma^2} = \frac{2\sigma(s^2+\mu[2(D-c)-s])}{s^2+\mu^2+\sigma^2} > 0$$

where the inequality follows as $D-c-s > 0$ holds at an interior solution. □

Proposition 3 follows directly from Lemmata 3 and 4.

□

Proof of Proposition 4. We first show that there exists $\overline{\sigma} > 0$ such that as σ increases on $\sigma \in (0, \overline{\sigma}]$, $n_2 E[x_2 + y_2]$ strictly decreases. Note that

$$\frac{d}{d\sigma} n_2 E[x_2 + y_2] = \frac{\sigma}{2(t^2 + \mu^2 + \sigma^2)^3 A} B, \tag{45}$$

where A is given by (40) and B is a lengthy expression satisfying $\lim_{\sigma \to 0} B = -2C/[(2f - s^2 - \mu^2)^2(2[D-c] - s - \mu)]$, where

$$\begin{aligned} C = {} & 8(D-c)^3 f\mu[2f(2s^2-\mu^2) - 3s^4 - 2s^2\mu^2 + \mu^4] + 2(D-c)^2[4f^2(s-\mu)(2s^3 - 4s^2\mu - 7s\mu^2 - 4\mu^3) \\ & -2f(s^2+\mu^2)(5s^4 - 9s^3\mu + 3s\mu^3 + 7\mu^4) + 3(s^2+\mu^2)^4] \\ & -2(D-c)[2f^2(4s^5 - 3s^4\mu - 6s^3\mu^2 + s^2\mu^3 + 8s\mu^4 + 4\mu^5) \\ & -2f(s^2+\mu^2)(5s^5 - s^4\mu + 3s^3\mu^2 + 7s\mu^4 + 4\mu^5) + (3s+2\mu)(s^2+\mu^2)^4] \\ & +s[2f^2(s-\mu)(s^4 + 2s^3\mu - 3s^2\mu^2 - 4s\mu^3 - 4\mu^4) \\ & -f(s^2+\mu^2)(3s^5 + 4s^4\mu - 4s^3\mu^2 + 4s^2\mu^3 + s\mu^4 + 8\mu^5) + (s+2\mu)(s^2+\mu^2)^4]. \end{aligned} \tag{46}$$

Because an interior solution satisfies (28), to show that $C > 0$, it is sufficient to show that C is convex in f for an interior solution, $\lim_{f \to (s^2+\mu^2)^2/(s-\mu)^2} (d/df)C > 0$ and $C|_{f=(s^2+\mu^2)^2/(s-\mu)^2} > 0$. Note that $(d^2/df^2)C = G$, where

$$\begin{aligned} G = {} & 32(D-c)^3\mu(2s^2-\mu^2) \\ & +16(D-c)^2(s-\mu)(2s^3 - 4s^2\mu - 7s\mu^2 - 4\mu^3) \\ & -8(D-c)(4s^5 - 3s^4\mu - 6s^3\mu^2 + s^2\mu^3 + 8s\mu^4 + 4\mu^5) \\ & +4s(s-\mu)(s^4 + 2s^3\mu - 3s^2\mu^2 - 4s\mu^3 - 4\mu^4). \end{aligned} \tag{47}$$

With the change of variable $M = D - c$, and using the fact that an interior solution satisfies (27) and (29), it is straightforward to show that G is convex in M on $M \geq s(s^2-\mu^2)/(s^2 - 2s\mu - \mu^2)$, $\lim_{M \to s(s^2-\mu^2)/(s^2-2s\mu-\mu^2)} (d/dM)G > 0$ and $G|_{M=s(s^2-\mu^2)/(s^2-2s\mu-\mu^2)} > 0$. Because an interior solution satisfies (27), this implies that $G > 0$, which implies that C is convex in f for an interior solution. A parallel argument establishes that $\lim_{f \to (s^2+\mu^2)^2/(s-\mu)^2} (d/df)C > 0$ and $C|_{f=(s^2+\mu^2)^2/(s-\mu)^2} > 0$. We conclude that for an interior solution, $C > 0$. Because the constraints for an interior solution are continuous in σ, from (45), $C > 0$ implies that there exists $\overline{\sigma} > 0$ such that as σ increases on $\sigma \in (0, \overline{\sigma}]$, $n_2 E[x_2 + y_2]$ strictly decreases. This in conjunction with part (a) of Proposition 6 implies that as σ increases on $\sigma \in (0, \overline{\sigma}]$, $n_1 E[x_1 + y_1]$ strictly increases. □

Proof of Proposition 5. In the scenario with perfect competition, domestic production is

$$[D_1 - c_1 - \mathrm{T}]^+ 1\{c_1 + \mathrm{T} \leq c_2 + s\} + [D_2 - c_1 - \mathrm{T} - s]^+ 1\{c_1 + \mathrm{T} + s < c_2\} \tag{48}$$

where the first term represents production for the domestic market and the second term represents exports. Under an emissions tax $\mathrm{T} = \mu > s + c_2 - c_1$, (48) is zero.

It is strictly positive for realizations of the emissions cost $\mathrm{T} < \min[s + c_2 - c_1,\, D_1 - c_1]$ and zero for $\mathrm{T} \geq \min[s + c_2 - c_1,\, D_1 - c_1]$, so domestic expected production is greater under the cap & trade system. A similar argument establishes the result regarding foreign expected production. □

Proof of Proposition 6. **(a)** First, observe that because an interior solution has $n_1 > 0$, an interior solution has

$$f < [2(D-c)(D-c-s)+s^2](s^2+\mu^2+\sigma^2)^2/[(2(D-c)-s)\mu+s^2]^2. \tag{49}$$

Note that

$$(\partial/\partial\sigma)(n_1 E[x_1+y_1]+n_2 E[x_2+y_2]) = \frac{\sigma B(f)}{(2f-s^2-\mu^2-\sigma^2)^2(s^2+\mu^2+\sigma^2)^3 A^3}, \tag{50}$$

where

$$\begin{aligned} B(f) &= (s^2+\mu^2+\sigma^2)([2(D-c)-s-\mu]s^2 \\ &\quad +[2(D-c)-s]\sigma^2)(4(D-c)[(D2-c-s)(s^2+\sigma^2)-\mu s^2] \\ &\quad +s^2[(\mu+s)^2+2\sigma^2])+(2f-s^2-\mu^2-\sigma^2)[(2(D-c)-s)\mu+s^2]G, \\ G &= [2(D-c)-s](s^2+\sigma^2)s^2-\mu([2(D-c)-s]^2(s^2+\sigma^2) \\ &\quad -s^2[6(D-c)\mu-2\mu^2-2\sigma^2-3s\mu-s^2]). \end{aligned}$$

and A is given by (40). If $G \geq 0$, then the result holds. Suppose $G < 0$. Then, because $B(f)$ is decreasing in f and inequality (49) holds, for an interior solution,

$$\begin{aligned} B(f) &> B([2(D-c)(D-c-s)+s^2](s^2+\mu^2+\sigma^2)^2/[(2(D-c)-s)\mu+s^2]^2) && (51)\\ &= 2s^2[2(D-c)-s-\mu](s^2+\mu^2+\sigma^2)^2(4(D-c)[(D-c-s)(s^2+\sigma^2)-\mu s^2] && (52)\\ &\quad +s^2[(\mu+s)^2+2\sigma^2])/([2(D-c)-s]\mu+s^2) && (53)\\ &> 0. && (54) \end{aligned}$$

This, together with (50) implies the result.

(b) The claim that corresponds to the imperfect competition case is a direct consequence of part (a). For the case of perfect competition, we proceed with the following argument. In the scenario with perfect competition, production to serve Region 1 is

$$[D_1-c_1-\mathrm{T}]^+ 1\{c_1+\mathrm{T} \leq c_2+s\} + [D_1-c_2-s]^+ 1\{c_1+\mathrm{T} > c_2+s\}, \tag{55}$$

where the first term represents local production and the second term represents exports from Region 2. This is a convex function of T for $\mathrm{T} \geq 0$, so by Jensen's inequality, changing the cost of emissions T from a constant μ (an emissions tax) to a random variable with mean μ (a mean-equivalent cap-and-trade system) increases the expected value of (55). The same arguments hold regarding production to serve Region 2,

$$[D_2-c_2]^+ 1\{c_1+\mathrm{T}+s \geq c_2\} + [D_2-c_1-\mathrm{T}-s]^+ 1\{c_1+\mathrm{T}+s < c_2\}. \tag{56}$$

Therefore, total industry production, the sum of (55) and (56), is greater in expectation under a cap-and-trade system than a mean-equivalent emissions tax.

□

Proof of Proposition 7. We define the expected consumer surplus for market 1 as:

$$E[(D-p_1)(n_1y_1+n_2x_2)/2]$$

or given the demand function in (1) and the supply-demand equation in (2),

$$E[(n_1y_1+n_2x_2)^2/2].$$

Using the expressions for y_1 and x_2 in (5) and (8):

$$E[(n_1y_1+n_2x_2)^2] = (1+n_1+n_2)^{-2}[(n_1+n_2)(D-c)-n_1\mu-n_2s]^2+n_1^2\sigma^2;$$

$$\begin{aligned}\frac{dE[(n_1y_1+n_2x_2)^2]}{d\sigma} &= \frac{2[(D-c)(n_1+n_2)-n_1\mu-n_2s]}{n_1+n_2+1} \\ &\quad \cdot\frac{d}{d\sigma}\left[(D-c)-\frac{(D-c)}{n_1+n_2+1}-n_1\mu-n_2s\right]+\frac{d}{d\sigma}\left[\frac{n_1^2\sigma^2}{(n_1+n_2+1)^2}\right] \quad (57)\end{aligned}$$

As $x_1>0$ at an interior solution, $D-c-\mu-s>0$ holds, and by Lemma 1, n_1+n_2 is increasing in σ. Therefore,

$$\frac{dE[(n_1y_1+n_2x_2)^2]}{d\sigma} > \frac{d}{d\sigma}\left[\frac{[(\mu+s)(n_1+n_2)-n_1\mu-n_2s]^2+n_1^2\sigma^2}{(n_1+n_2+1)^2}\right]. \quad (58)$$

Note that $(\mu+s)(n_1+n_2)-n_1\mu-n_2s = n_1s+n_2\mu$. Then, the right hand side of (58):

$$\frac{d}{d\sigma}\left[\frac{(n_1s+n_2\mu)^2+n_1^2\sigma^2}{(n_1+n_2+1)^2}\right] = 2\left(\frac{n_1s+n_2\mu}{n_1+n_2+1}\right)\cdot\frac{d}{d\sigma}\left(\frac{n_1s+n_2\mu}{n_1+n_2+1}\right)+\frac{d}{d\sigma}[(n_1^2\sigma^2)(n_1+n_2+1)^{-2}].$$

Note that

$$\frac{n_1}{n_1+n_2+1} = \frac{\frac{1}{2}\left(A-\frac{s^2+[2(D-c)-s]\mu}{s^2+\mu^2+\sigma^2}\right)}{A} = \frac{1}{2}-\frac{1}{2}\frac{[s^2+[2(D-c)-s]\mu]}{(s^2+\mu^2+\sigma^2)A}.$$

Then, $\frac{d\left(\frac{n_1}{n_1+n_2+1}\right)}{d\sigma} > 0$, as $(s^2+\mu^2+\sigma^2)$ and A are both increasing in σ. Therefore, given $s \geq \mu$,

$$\frac{d}{d\sigma}\left[\frac{(n_1s+n_2\mu)^2+n_1^2\sigma^2}{(n_1+n_2+1)^2}\right] \geq \frac{d}{d\sigma}\left\{(1+n_1+n_2)^{-2}(\mu^2(n_1+n_2)^2+n_1^2\sigma^2)\right\}. \quad (59)$$

We now prove that the RHS of (59) is greater than zero. We split the expression into two terms.
Term 1:

$$\begin{aligned}
&\frac{d}{d\sigma}\left\{(1+n_1+n_2)^{-2}(\mu^2(n_1+n_2)^2)\right\}\\
&=\frac{d}{d(n_1+n_2)}\left\{(1+n_1+n_2)^{-2}\mu^2(n_1+n_2)^2\right\}\frac{d(n_1+n_2)}{d\sigma}\\
&=\frac{\mu^2[2(n_1+n_2)(1+n_1+n_2)^2-2(n_1+n_2+1)(n_1+n_2)^2]}{(n_1+n_2+1)^4}\frac{d(n_1+n_2)}{d\sigma}\\
&=\frac{2\mu^2(n_1+n_2)(n_1+n_2+1)}{(n_1+n_2+1)^4}\frac{d(n_1+n_2)}{d\sigma}>0. \qquad (60)
\end{aligned}$$

Term 2:

$$\begin{aligned}
&\frac{d}{d\sigma}\left\{(1+n_1+n_2)^{-2}n_1^2\sigma^2\right\}\\
&=\frac{(2n_1\frac{dn_1}{d\sigma}\sigma^2+2\sigma n_1^2)(1+n_1+n_2)^2-2(n_1+n_2+1)\left(\frac{dn_1}{d\sigma}+\frac{dn_2}{d\sigma}\right)\sigma^2 n_1}{(n_1+n_2+1)^4}\\
&=\frac{2(n_1+n_2+1)\sigma n_1}{(n_1+n_2+1)^4}\left[\left(\sigma\frac{dn_1}{d\sigma}+n_1\right)(1+n_1+n_2)-\left(\frac{dn_1}{d\sigma}+\frac{dn_2}{d\sigma}\right)\sigma n_1\right]\\
&=\frac{2\sigma n_1}{(n_1+n_2+1)^3}\left[\sigma(n_2+1)\frac{dn_1}{d\sigma}-\sigma n_1\frac{dn_2}{d\sigma}+n_1(1+n_1+n_2)\right]\\
&=\frac{2\sigma n_1}{(n_1+n_2+1)^3}\left[\frac{d\left(\frac{n_1}{n_2+1}\right)}{d\sigma}(n_2+1)^2+n_1(1+n_1+n_2)\right], \qquad (61)
\end{aligned}$$

where the last equality follows from the fact that $\frac{dn_2}{d\sigma}=\frac{d(n_2+1)}{d\sigma}$. To prove the above expression for term 2 is strictly greater than zero, we need to show that $\frac{d\left(\frac{n_1}{n_2+1}\right)}{d\sigma}>0$. By (12), $n_2=n_1+f(\sigma)$ where $f'(\sigma)<0$,

$$\begin{aligned}
\frac{d\left(\frac{n_1}{1+n_1+f(\sigma)}\right)}{d\sigma}&=\frac{\frac{dn_1}{d\sigma}(1+n_1+f(\sigma))-\frac{dn_1}{d\sigma}n_1-f'(\sigma)n_1}{(1+n_1+f(\sigma))^2}\\
&=\frac{\frac{dn_1}{d\sigma}(1+f(\sigma))-f'(\sigma)n_1}{(1+n_1+f(\sigma))^2}>0, \qquad (62)
\end{aligned}$$

where the last inequality follows from Proposition 3 (that n_1 is increasing in σ) and $1+f(\sigma)=\frac{\mu(2(D-c)-s)+s^2}{s^2+\mu^2+\sigma^2}>0$, given $D-c-s>0$ holds at an interior solution.

As given $s\geq\mu$, the first and second terms of the right hand side of (59) are both strictly greater than zero, then the right hand side of (58) is strictly greater than zero. Hence, given $s\geq\mu$, the expected consumer surplus in market 1 is increasing in σ.

□

The Calibration of Parameters for the Numerical Analysis

We fit a linear demand function for each region i, $Q_i=D_i-a_ip_i$ for $i=1,2$. For this, we need the demand and price data for cement. We will use the shipment of Portland cement to a region as a proxy for that region's demand for Portland cement. We will also assume that the demand function did not shift in years 2010 and 2011.

The Portland cement shipments to the final customers in California were 6,218,000 metric tons in 2010 and 6,890,000 metric tons in 2011 (Van Oss, 2013, Table 9). The average value[8] per metric ton of Portland cement reported by California-based entities (not necessarily the location of sales)[9] is \$79 in 2010 and \$75.5 in 2011 (Van Oss, 2013, Table 11). \$79 in 2010 corresponds to \$81.5 in 2011[10].

The Portland cement shipments to the final customers in Arizona and Nevada were 2,374,000 metric tons in 2010 and 2,403,000 metric tons in 2011 (Van Oss, 2013, Table 9). The weighted average mill net value per metric ton of Portland cement sold in the regions including Idaho, Montana, Nevada, Utah, Arizona and New Mexico is \$102 in 2010 and \$94 in 2011. \$102 in 2010 corresponds to \$104.71 in 2011[11].

We have two (Q_i, p_i) pairs for each region $i = 1,2$ as above. We assume a linear demand function $Q_i = D_i - a_i p_i$ for each region i. Then, in Region 1 (California), D_1 is calculated as 15,354,948 and a_1 is 112,118.5. In Region 2 (Arizona and Nevada), D_2 is 2,657,528, and a_2 is 2707.75.

Building a new state-of-the-art conventional plant for a production capacity of 2 and 1 million metric tons per year of clinker costs €130 and €170 per metric ton in 2007 Euros. Assuming a linear relation between the production capacity and unit capacity building cost, for a production capacity of 1,104,167 metric tons, the investment cost is €165.83 per metric ton, or approximately \$236.7 per metric ton in 2011 dollars[12], then the fixed capacity investment is $F_1 = F_2 = \$261,378,850$.

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[9] The mill net values are better viewed as price indices for cement, suitable for crude comparisons among regions and during time.

[10] 2010 and 2011 annual average consumer price indices as given by U.S. Department of Labor, Bureau of Labor Statistics (2013) are 218.056 and 224.939, respectively.

[11] 2010 and 2011 annual average consumer price indices as given by U.S. Department of Labor, Bureau of Labor Statistics (2013) are 218.056 and 224.939, respectively.

[12] The 2007 average exchange rate of Euro and U.S. dollar was \$1 =€0.760 (Internal Revenue Service, 2013). 2007 and 2011 annual average consumer price indices as given by U.S. Department of Labor, Bureau of Labor Statistics (2013) are 207.342 and 224.939, respectively.

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