Carbon leakage under incomplete environmental regulation: An industry-level approach

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Abstract

Carbon leakage is a major concern for policymakers involved with environmental initiatives such as the European Union's emissions trading scheme and similar cap-and-trade proposals in the United States, Australia, and elsewhere. This paper provides a framework for understanding the drivers underlying carbon leakage at the level of an individual sector in which only a subset of firms is covered by such regulation. It provides simple formulae to estimate leakage rates using information on industry characteristics that is typically available to the analyst. Illustrative estimates for the steel industry in the EU ETS suggest carbon leakage of 25–30% or (much) higher—unless environmental-efficiency improvements by regulated firms are substantial.

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1 Introduction

Economic policy towards climate change is a key item on policymakers' agendas, with Stern (2007) referring to climate change as "the greatest market failure the world has ever seen." Tackling climate change represents a major challenge because of the global nature of the problem and the international cooperation that many solutions require.

We are currently witnessing a major push towards market-based mechanisms for addressing environmental issues, with several emerging regional initiatives. For example, the European Union's emissions trading scheme (EU ETS) that was introduced in 2005 covers emissions-intensive industries such as electricity, cement and steel, with further sectors such as aluminium and aviation due to join the scheme. In the United States, legislation for a similar cap-and-trade scheme for greenhouse gas emissions at the federal level is currently being discussed, and other countries including Australia and New Zealand are in the process of designing and implementing multi-sector carbon trading schemes.[1]

A major concern of policymakers involved with each of these initiatives is that emissions reductions achieved by the firms covered in their scheme will be counteracted by emissions increases by firms located elsewhere—a phenomenon usually referred to as carbon leakage.[2] Leakage issues are potentially relevant to a wide range of emissions-intensive industries in which firms compete internationally and where only a subset of firms experiences (tightened) environmental regulation.[3] The absence of a level playing field amongst firms can substantially undermine the effectiveness of such "incomplete" regulation. Indeed, *global* emissions could even rise as a result of the policy if the emissions increases by unregulated firms are sufficiently pronounced.

By contrast, the basic mechanism underlying "complete" environmental regulation of all firms in a particular sector is relatively well-understood and compelling. Then climate policy in form of a carbon tax or a cap-and-trade scheme leads to an increase in *each* firm's unit costs of production to reflect the price of carbon. Much of this cost increase is typically passed on to consumers in form of higher market prices. Moreover, all firms in the sector have incentives to improve their environmental efficiency by using cleaner production technologies. Under relatively mild conditions, industry output and consumption fall, and the policy succeeds in reducing emissions.[4]

[1] A number of state-based initiatives are also emerging in the United States, including the Regional Greenhouse Gas Initiative (RGGI) for the power sector in ten Northeastern and Mid-Atlantic states with a first compliance period that began in January 2009.

[2] For example, carbon leakage has emerged as one of the key issues in the design of the EU ETS, notably for its third phase beginning in 2013. Similarly, Australia's Carbon Pollution Reduction Scheme (CPRS) and recent cap-and-trade proposals in the United States pay particular attention to trade-exposed sectors and carbon leakage.

[3] The main exception concerns markets in which competition is geographically limited due to transport issues or other regulatory restrictions (such as the electricity sector in the EU ETS).

[4] Market-based mechanisms typically also have desirable properties in that emissions reductions are

The implications of "incomplete" environmental regulation that covers only a *subset* of firms in a sector are much less clear-cut.[5] Define carbon leakage (denoted by L throughout) as the proportion of the emissions reductions (denoted by $-\Delta E_I$) by "inside" firms that leaks out in form of emissions increases (denoted ΔE_O) by "outside" firms that are not covered by the policy, that is

$$L = \frac{\Delta E_O}{-\Delta E_I}. \tag{1}$$

As before, marginal costs for inside firms increase to reflect the price of carbon, but they do not increase for the unregulated, outside firms. While inside firms decrease output and emissions (so $-\Delta E_I > 0$), outside firms typically benefit from the cost advantage by gaining market share and increasing their emissions (so $\Delta E_O > 0$). So some of the emissions reductions achieved by the policy leak out ($L > 0$), and global carbon emissions increase by less. In the extreme case with $L \geq 1$ global emissions would be lower *without* incomplete regulation than with such regulation.

Carbon leakage, therefore, is potentially critical for evaluating the properties of current market-based environmental initiatives. This leads to a number of important questions: What are the drivers underlying carbon leakage for a particular industry? Under which circumstances is carbon leakage likely to be high? How can leakage rates be estimated for a sector (to be) included in a cap-and-trade scheme or covered by a carbon tax?

This paper addresses these questions by taking an industry-level approach that models the impact of climate policy on a particular emissions-intensive sector that is characterized by an imperfectly competitive market structure. This is an appropriate assumption for many of the industries that are likely to be covered by market-based climate policy, such as electricity, cement or steel. Moreover, firms are assumed to act as carbon price-takers. This approach seems a reasonable approximation for cap-and-trade schemes that include firms from many different sectors (such as the EU ETS or proposed schemes in the United States and Australia), and is clearly appropriate for the case of carbon taxes.[6] With these assumptions, my results apply equally to a cap-and-trade scheme that covers only a subset of firms in a sector or to a carbon tax imposed only on these firms.

Section 2 introduces a simple "ABC" decomposition of carbon leakage (see Lemma 1) into three channels: (A) the emissions intensity (that is, emissions per unit of output) of unregulated firms relative to regulated firms (*before* the policy is implemented), (B) the leakage of output (and hence market share) from inside to outside firms, and, finally, (C) the impact of environmental-efficiency improvements by inside firms (that is, reductions

achieved at least cost (since regulated firms' marginal abatement costs are equalized).

[5] This paper does not attempt to explain why environmental regulation may be incomplete, but rather focuses on the implications of incompleteness in terms of carbon leakage.

[6] There is an important literature beginning with Hahn (1984) that examines the incentives of firms with market power to manipulate permit prices in cap-and-trade schemes.

in emissions intensities). All else equal, carbon leakage tends to be higher when output leakage is higher, outside firms are relatively dirtier (so their output gains translate into high emissions increases), and when inside firms have fewer profitable opportunities to switch to cleaner production technologies. Thereby, output leakage is particularly important in the following sense: carbon leakage is positive if and only if output leakage is positive. This decomposition presents a useful, model-independent way to think about carbon leakage.[7]

The main analysis focuses on characterizing the equilibrium impact of channels B and C, with the particular objective of obtaining simple formulae to calculate carbon leakage using parameters that are observable to the analyst (or can at least be estimated with reasonable accuracy). Section 3 sets up the benchmark Cournot-Nash model with (a fixed number of) asymmetric firms and a general demand function.[8] The inside firms experience an increase in their unit costs of production, while the outside firms' costs remain unchanged. However, the policy also induces the regulated firms to engage in abatement, and they can switch to cleaner production technologies (with lower emissions intensities) at some cost. Thereby, my analysis places no significant *a priori* restrictions on carbon leakage: depending on parameter values, the leakage rate for a sector could be significantly negative, far above 100%, or anything in between.[9]

Section 4 provides a simple formula to calculate equilibrium output leakage (channel B), showing that it is higher when there are more unregulated firms in the market and when the demand curve is more concave. I also show that this corresponds to a lower rate of pass-through of carbon costs to price (see Propositions 1–3). Moreover, under fairly weak conditions output leakage exceeds 50%—so over half of the emissions reduction achieved by way of output cuts by inside firms are offset by output gains by unregulated firms (see Propositions 2 and 3 for sufficient conditions).[10] These results suggest that carbon leakage may be rather high for industries in which there is limited scope for reducing the emissions intensity of production at the prevailing carbon price.

Section 5 explores the impact of regulated firms adopting cleaner production technologies (channel C). Intuitively, such efficiency improvements can reduce carbon leakage for

[7] A simplifying assumption needed to obtain a decomposition of this form is that emissions intensities are uniform across regulated and unregulated firms respectively. Most of the existing literature on carbon leakage (implicitly) makes the same assumption as it treats industries only at an aggregated level. See also the end of this introduction (on the related literature) and Section 6 for further discussion.

[8] Cournot-based modelling provides a natural starting point for the kinds of industries likely to be covered by market-based climate policy. It has been employed (in different contexts) for emissions-intensive sectors such as electricity (see, e.g., Borenstein and Bushnell, 1999), aviation (see, e.g., Brander and Zhang, 1990), steel (see, e.g., Demailly and Quirion, 2008), pulp and paper (see, e.g., Pesendorfer, 2003), and others. I discuss the robustness of the results to other models of competition in Section 5.

[9] This is principally because I do not impose any restrictions on the curvature of the demand function (and thus also not on the rate of cost pass-through).

[10] For example, output leakage always exceeds 50% with a linear or concave demand curve.

two reasons: first, lower emissions intensities reduce the cost impact of regulation, so inside firms optimally cut output by less, and, second, lower emissions intensities also mean that a given output cut leads to a larger emissions reduction by insiders. From the ABC decomposition, the impact of these is driven by two factors, the percentage reduction in inside firms' emissions intensities and the percentage reduction in their output. Proposition 4 provides a simple formula to estimate the regulated firms' output cut. Proposition 5 shows that it is ambiguous whether a higher carbon price increases or decreases leakage, and that much depends on the details of how easily the regulated firms' production technologies admit environmental-efficiency improvements and at what cost. In light of this, I then provide a method that yields bounds on the overall rate of carbon leakage for any given equilibrium efficiency improvement, without relying on functional form assumptions on firms' abatement costs.

Section 6 pursues a number of natural variations on the benchmark Cournot-Nash model to show that the 50% benchmark on output leakage applies much more generally, and that carbon leakage tends to be higher in more competitive markets (for example, when firms compete in prices or have market share objectives). However, leakage rates can also be much lower if firms' products are strongly differentiated or if the regulated firms achieve substantial environmental-efficiency improvements (as in the benchmark model).

Section 7 ties together all the main results with an illustrative empirical implementation to the steel industry that has been covered by the EU ETS since 2005, specifically to the market for cold-rolled sheet steel. The results suggest significant carbon leakage unless rather substantial reductions in the emissions intensities of regulated firms are achieved. For example, as long as such reductions are less than 20%, equilibrium rates of carbon leakage are around 25–30% or (much) higher. In the absence of such efficiency gains, all emissions reductions come via output cuts and carbon leakage is around 75%.

I discuss several extensions to the basic modelling framework in Section 8: (I) estimating carbon leakage in the presence of other existing environmental regulation; (II) welfare implications in terms of consumer surplus, "profit leakage", and global emissions; (III) the impact of abatement via end-of-pipe technologies; and (IV) the role of free permit allocations (in cap-and-trade schemes) and relocation of regulated firms' production facilities. Section 9 offers concluding remarks and discusses some policy implications on how to evaluate whether a particular sector is "at risk" of significant carbon leakage.

My analysis is related to several strands of the literature. In an important paper, Hoel (1991) emphasized free-riding effects in showing that unilateral climate policy can lead to carbon leakage and increases in global emissions. A number of subsequent papers have estimated carbon leakage rates under the Kyoto Protocol, typically using complex computable general equilibrium (CGE) modelling approaches with multiple regions and (highly aggregated) industries. While these have obtained a wide range of leakage estimates, most of these are fairly low and lie within the range 5–40%.[11] There are two main sources of leakage in these models: First, via the goods market, where regulated firms reduce production, so the market price increases and unregulated firms produce more. Second, via factor markets, where inside firms' energy demand decreases, so energy prices fall and outside firms may switch to dirtier production technologies. Thereby, much of the existing literature makes the simplifying assumption of perfect competition in product markets, combined with an Armington elasticity structure that governs substitution patterns between domestic production and imports. Partly as a result of such assumptions, climate policy induces a "macro" adjustment *between countries*, rather than leading to a "micro" adjustment *within industries.* The present paper complements this literature by exploring the industrial economics of the first of these two sources, while abstracting from the general-equilibrium effects associated with the second source (which tend to increase leakage).[12] This approach sheds new light on the drivers underlying carbon leakage at the industry level, and also yields simple formulae that can be used to estimate leakage rates.

Babiker (2005) considers a CGE model with imperfect competition in product markets and free entry and exit of firms. He shows that the relocation of energy-intensive production facilities away from OECD countries can lead to significantly higher carbon leakage rates of 50–130% in CGE modelling. Fowlie (2009) examines carbon leakage in a partial-equilibrium, Cournot-Nash model that is simulated to analyze the impact of state-level environmental regulation on the Californian electricity industry.[13] She also argues that carbon leakage can significantly undermine climate policy effectiveness, and also shows that incomplete regulation can lead to an increase in global emissions (only) if unregulated firms are sufficiently dirtier than regulated firms.[14] However, her model assumes that regulated firms cannot reduce their emissions intensities by using cleaner production technologies. This means that channel C of my decomposition is switched off, with the implication that all emissions reductions by regulated firms must come via output cuts. While this may be a reasonable approximation in some cases, it seems potentially restrictive as a general assumption and is relaxed in the following analysis.

[11] See the 1999 Kyoto Protocol special issue of the *Energy Journal* for an overview of this literature.

[12] But see also Copeland and Taylor (2005) who argue that incorporating international trade in goods between countries has important implications for the evaluation of unilateral climate policy, and show that it may substantially reduce carbon leakage in such perfect-competition, general-equilibrium models.

[13] I thank Robert Hahn for drawing my attention to this reference.

[14] The modelling approaches differ in that Fowlie (2009) assumes linear demand (implying that output and carbon leakage must be positive), but allows firms to differ in their emissions intensities, while this paper uses a general demand function, but assumes that inside and outside firms each have uniform emissions intensities. Fowlie (2009) also presents results for the different counterfactual of how emissions under incomplete regulation compare with the hypothetical scenario where all firms are regulated.

2 ABC decomposition

Before modelling the equilibrium impact of incomplete environmental regulation, I present an "ABC" decomposition of carbon leakage into three channels that help understand its underlying drivers. To obtain a simple decomposition of this form, I assume that all inside firms have the same emissions intensity of production (that is, emissions per unit of output), and that all outside firms do too. Moreover, while the regulated firms have incentives to reduce their emissions intensities, the emissions intensities of outside firms remain unchanged with the introduction of the policy.

The basic idea is straightforward: inside firms can cut their emissions either by producing less output or by producing cleaner output. In particular, the change in the inside firms' emissions $\Delta E_I = \omega_I \Delta X_I + \Delta\omega_I (X_I + \Delta X_I) < 0$, where ω_I is their initial emissions intensity, $\Delta\omega_I \leq 0$ is the change in emissions intensity due to the policy, and X_I and $\Delta X_I < 0$ are the inside firms' initial output and change in output respectively. Similarly, the change in the outside firms' emissions $\Delta E_O = \omega_O \Delta X_O$ as their emissions intensity remains unchanged. Using these expressions in the definition of carbon leakage and some rearranging yields the following result:

Lemma 1 *The rate of carbon leakage can be expressed as*

$$L = \frac{\left(\frac{\omega_O}{\omega_I}\right)\left(\frac{\Delta X_O}{-\Delta X_I}\right)}{\left[1 + \frac{\Delta\omega_I}{\omega_I}\left(\frac{X_I}{\Delta X_I} + 1\right)\right]}.$$

Carbon leakage can thus be decomposed into three channels: (A) the outside firms' emissions intensity relative to inside firms *before* the policy is implemented—all else equal, carbon leakage is higher when outside firms are relatively dirtier (so ω_O/ω_I is higher); (B) the rate of leakage of *output* from inside to outside firms—all else equal, higher output leakage (higher $-\Delta X_O/\Delta X_I$) implies higher carbon leakage; (C) the impact of efficiency improvements by inside firms—all else equal, greater intensity reductions (higher $-\Delta\omega_I/\omega_I$) and smaller output contraction by inside firms (smaller $-\Delta X_I/X_I$) reduce the rate of carbon leakage.

All three of these channels can play quantitatively important roles in determining the rate of carbon leakage in an industry. However, output leakage plays a crucial role in the following sense: *carbon leakage is positive if and only if output leakage is positive.*

It is also useful to highlight the two limiting cases in terms of inside firms' efficiency improvements. First, suppose that inside firms do not reduce their emissions intensities in response to the policy—perhaps because such efficiency improvements are technologically infeasible, or because they are not profitable at the prevailing carbon price.

Then carbon leakage is determined solely by the first two of the above channels, and so $L = (\omega_O/\omega_I)\,[\Delta X_O/(-\Delta X_I)]$. Second, at the opposite extreme, suppose that, at some cost, the regulated firms' production becomes "zero-emissions", so $\omega_I + \Delta\omega_I = 0$. Then the expression for carbon leakage becomes $L = (\omega_O/\omega_I)\,(\Delta X_O/\Delta X_I)\,(\Delta X_I/X_I)$, as the third channel reduces to the (percentage) contraction in inside firms' output. Somewhat loosely, these last two expressions can be thought of as upper and lower bounds on the rate of carbon leakage (whenever it is positive).

The ABC decomposition provides a useful, model-independent way of thinking about carbon leakage. I now turn to modelling the equilibrium impact of channels B and C.[15]

3 Benchmark model

An industry with $N_I + N_O$ profit-maximizing firms produces a homogeneous good, where $N_I \geq 1$ is the number of inside firms to be covered by environmental regulation and $N_O \geq 1$ is the number of outside firms that are not covered. Let the total output by insiders $X_I = \sum_{j=1}^{N_I} x_I^j$, total output by outsiders $X_O = \sum_{i=1}^{N_O} x_O^i$, and total industry output $X = X_I + X_O$, so the market share of all inside firms $\sigma_I = X_I/X$ and, similarly, $\sigma_O = X_O/X$. The firms face a downward-sloping (inverse) demand curve $p = f(X)$, and the Cournot-Nash equilibrium is assumed to be unique and stable. Let the total emissions of inside and outside firms $E_I = \sum_{j=1}^{N_I} e_I^j$ and $E_O = \sum_{i=1}^{N_O} e_O^i$ respectively.

Before the introduction of climate policy (when carbon is still unpriced, $t = 0$), inside firm j's unit cost of production is $c_I^j(0)$ and that of outside firm i is $c_O^i(0)$. Now consider the introduction of an emissions trading scheme or a carbon tax with a price $t > 0$ per unit of emissions. This increases the production costs (only) of the regulated firms, but also gives them incentives to engage in abatement and to use cleaner production technologies in order to minimize costs. Inside firm j's unit cost of production becomes $c_I^j(t) = c_I^j(0) + t\omega_I^j(t) + \varphi^j(t)$, where $\omega_I^j(t) = e_I^j(t)/x_I^j(t)$ is its optimally chosen emissions intensity (that is, emissions per unit of output at carbon price t) and $\varphi^j(t)$ represents its abatement costs (per unit of output).[16] Revealed preference arguments guarantee that $\Delta\omega_I^j(t) = \omega_I^j(t) - \omega_I^j(0) \leq 0$ and $\varphi^j(t) \geq 0$. In other words, a regulated firm (weakly) improves its environmental efficiency by decreasing its emissions intensity and this comes at a non-negative cost of abatement. By the envelope theorem, $dc_I^j(t)/dt = \omega_I^j(t)$, so a higher carbon price leads to higher (minimized) carbon costs. If the production technology

[15] Since channel A refers to relative emissions intensities *before* regulation, it can typically be estimated for an industry independently of the equilibrium analysis that follows.

[16] Note that my formulation in terms of emissions intensity is equivalent to a firm optimally choosing its output and emissions. All the main results also go through if there is (additive) uncertainty on the market price, a firm's production costs, or on the carbon price. So, in particular, the results go through for a cap-and-trade scheme to which firms adjust according to the *expected* carbon price.

is such that abatement is non-optimal or impossible, then the firm's emissions intensity remains unchanged, so $k^*(t) = t\omega_I^*(0)$. Assume that inside firms' emissions intensities and abatement costs are uniform in that $\omega_I^j(t) = \omega_I(t)$ and $\varphi^j(t) = \varphi(t)$, and that the emissions intensity of outside firms remains constant, so $\omega_O^i(t) = \omega_O(0)$.

Let $k(t)$ denote the total increase in an inside firm's unit cost, and note that, in equilibrium,

$$k^*(t) = t\omega_I^*(t) + \varphi^*(t), \tag{2}$$

where $k^*(0) = 0$.[17]

Although the above formulation is more general, it is helpful to bear in mind two particular forms of abatement. First, a firm may have access to a technology that reduces its emissions intensity by ζ at a cost of $g(\zeta)$. Then its unit cost of production $c_I^j(t) = \min_{\zeta \geq 0} \left[c_I^j(0) + t\left(\omega_I^*(0) - \zeta\right) + g(\zeta)\right]$. Denoting the cost-minimizing value as $\zeta^*(t)$, it follows that $\omega_I^*(t) = \omega_I^*(0) - \zeta^*(t)$ with an abatement cost (per unit of output) of $g(\zeta^*)$. Second, a firm may have a choice between two discrete production methods: the status quo with low marginal cost but high emissions intensity, and an alternative technology with higher marginal cost yet lower emissions intensity. It is profitable for regulated firms to change to the cleaner technology if $t \geq \underline{t}$, say, and remain with the dirtier technology otherwise. An example is fuel switching: for a sufficiently high carbon price, it may become optimal for a firm to switch some of its production, say, from coal to gas (which is significantly less carbon-intensive).

In the next two sections, I first characterize output leakage within this benchmark model, and then turn to the impact of efficiency improvements by the regulated firms.

4 Output leakage

The basic effect of environmental policy in the model is that the inside firms cut their equilibrium output X_I^* and emissions E_I^* in response to the increase in their costs of production. This effect is amplified when they have higher emissions intensities or the carbon price is higher. Typically, the firms not covered by the regulation react by increasing their equilibrium output X_O^* (and hence emissions) to "fill the gap" in the market. Total industry output X^*, however, is lower and the market price of the good, $p^*(t)$ is higher (both by stability). The relative emissions intensity (pre-regulation) of outside firms compared to inside firms ω_O/ω_I (channel A of the decomposition) then determines the mapping from output leakage to carbon leakage.

[17] This does not explicitly capture the *indirect* carbon costs that regulated firms may face due to concomitant increases in electricity prices if that sector is also covered by the policy. However, such costs could easily be incorporated into $k^*(t)$, at the expense of additional notation and without changing the main conclusions of the analysis.

□ **Characterizing output leakage.** Determining the rate of leakage more formally requires a comparison of the industry equilibrium before the introduction of climate policy with that after it has been implemented. In general, performing this comparison is hard as it involves dealing with some complicated expressions for which closed-form expressions are usually not available, thus making them hard to interpret.

To overcome this difficulty, I analyze a first-order approximation of firms' output responses that effectively linearizes around the initial, pre-policy equilibrium. This approach yields simple, easily interpretable formulae to estimate leakage that have the additional advantage that they can be empirically implemented using data that can be observed (or at least estimated) by the analyst. As will become clear, only little accuracy is lost with this approximation if the demand curve is not too non-linear *or* if the carbon price (and hence carbon costs) is not too large—indeed, it yields exact results for the case when demand is linear.[18]

The details of the output adjustments are governed by the strategic properties of the interaction between the regulated and unregulated firms in the market. In a Cournot-Nash setting, these can usefully be summarized by

$$\lambda_I = N_I + \sigma_I^* \frac{f''(X^*)X^*}{f'(X^*)} \text{ and } \lambda_O = N_O + \sigma_O^* \frac{f''(X^*)X^*}{f'(X^*)} \tag{3}$$

for the insiders and outsiders respectively. If demand is linear, the two strategic effects are equal to the number of firms, $\lambda_I = N_I$ and $\lambda_O = N_O$, but more generally they also depend on market shares and the curvature of the demand function, $f''(X^*)X^*/f'(X^*)$.[19] The strategic effects evaluated at the initial equilibrium when carbon remains unpriced (that is, at $t = 0$) will be an important determinant of carbon leakage in what follows. (Loosely put, the reason the first-order approach is exact for linear demand is that the strategic effects are then both constants.)

The economic interpretation of the strategic effect for the outside firms is given by

$$\lambda_O = \sum_{i=1}^{N_O} \left[\frac{\text{slope of outside firm } i\text{'s marginal revenue curve}}{\text{slope of inverse demand curve}} - 1 \right], \tag{4}$$

so it is stronger when firms' marginal revenue curves are steeper relative to demand (as

[18] The "large" adjustment from the old equilibrium to the new equilibrium (with environmental regulation) can be thought of as the integral of a sequence of "small" adjustments as the carbon price (and carbon costs) increases from zero. However, this yields only little additional insight, as these integrals are hard to simplify and interpret—except when demand is linear.

[19] Demand curvature $f''(X^*)X^*/f'(X^*)$ measures the elasticity of the slope of the inverse demand curve $f(X)$ evaluated at X^*, akin to the coefficient of relative risk aversion in utility theory. Note that it has no tight relationship with the standard price elasticity of demand—except in cases where demand is iso-elastic. See also the empirical illustration in Section 7, especially note 39, for further discussion.

is the case for more concave demand curves). With linear demand, a firm's marginal revenue curve is always twice as steep as the inverse demand curve, so $\lambda_O = N_O$ as expected. More generally, a *sufficient* condition for both strategic effects to be positive is that each firms' marginal revenue curve is steeper than demand. This corresponds to a Cournot-Nash equilibrium involving competition in strategic substitutes (that is, all firms have downward-sloping best response curves).

Using the first-order approach, I obtain the following key result for output leakage.

Proposition 1 *The equilibrium rate of output leakage satisfies*

$$\frac{\Delta X_O^*}{-\Delta X_I^*} = \frac{\lambda_O}{(\lambda_O + 1)},$$

where $(\lambda_O + 1) > 0$ *by stability.*

The result shows that output leakage (via the outsiders' strategic effect) depends on three parameters: the number of outside firms N_O, their market share *before* the policy is implemented σ_O^*, as well as demand curvature $f''(X^*)X^*/f'(X^*)$.

(All proofs are collected in the Appendix.)

To understand the result, it is useful to begin building some intuition for the special case when the demand curve is linear, and so output leakage $-\Delta X_O^*/\Delta X_I^* = N_O/(N_O+1)$. With linear demand, therefore, output leakage *always* exceeds 50%—regardless of the further details of the industry structure. It is higher the more outside firms in the market, and tends to 100% as their number grows large. The intuition is that the degree of output leakage is importantly determined by the number of "business stealing" effects by outside firms: a large number of outside firms fills almost the entire "gap" in the market that arises due to the output contraction of the regulated firms.

Recalling the ABC decomposition, this result already leads to two important insights regarding carbon leakage. If outside firms are (initially) no cleaner than inside firms (so $\omega_O \geq \omega_I$) and any environmental-efficiency improvements $(-\Delta\omega_I/\omega_I)$ by insiders are sufficiently small, then carbon leakage exceeds 50% with linear demand. Furthermore, if the number of outside firms is large (so output leakage tends to 100%), then carbon leakage can easily exceed 100% if outside firms have sufficiently higher emissions intensities than insiders. This implies that incomplete environmental regulation actually leads to an *increase* in global emissions.[20]

With linear demand, output leakage does not depend on the number of inside firms or on the distribution of market shares in the industry. The reason is that, while a larger

[20] Using different modelling approaches, this result has also been obtained by Hoel (1991), Babiker (2005), and others. Note also that output leakage itself cannot exceed 100% (by stability), so it is necessary for the result that outside firms have higher emissions intensities than regulated firms. Fowlie (2009) makes a similar point in a Cournot-Nash model with linear demand.

number of inside firms means a larger output reduction, the *proportion* of this reduction that leaks to outside firms only depends on their number. Moreover, since the slopes of firms' marginal revenue curves are constant (and identical) with linear demand, the (absolute) output adjustment required in response to the cost increase does not depend on a firm's relative size (i.e., its market share).[21]

With non-linear demand, however, the slopes of firms' marginal revenue curves differ, which leads to the additional terms in the expression for output leakage from Proposition 1. Firms' best response curves are relatively steeper (that is, more negatively sloped) when demand is more concave, so output leakage tends to be higher as the (negative) interdependence between the inside and outside firms is stronger. Finally, with concave demand ($f''(X^*) < 0$), output leakage is higher if the market share of the unregulated firms σ_O^* is higher, as this also corresponds to steeper best response curves and a stronger strategic effect (higher λ_O), while the opposite conclusion holds for convex demand ($f''(X^*) > 0$).

□ **50% benchmark.** Although the linear case is a special one, the two main insights—that *output leakage is importantly driven by the number of "business stealing" effects by outside firms, and often exceeds a 50% benchmark*—hold much more generally. Indeed, from Proposition 1, output leakage exceeds 50% whenever the outside strategic effect $\lambda_O \geq 1$. The following result translates this condition into a set of more easily interpretable *sufficient* conditions.

Proposition 2 *The equilibrium rate of output leakage exceeds 50% if any of the following conditions holds:*
(i) the demand curve $f(X^*)$ is concave or linear;
(ii) the direct demand curve $f^{-1}(p^*)$ is log-concave and $N_O \geq 2$;
(iii) industry marginal revenue for $f(X^*)$ is downward-sloping and $N_O \geq 3$;
(iv) the elasticity of the slope of $f(X^*)$ is bounded below and the number of outside firms N_O is sufficiently large.

The basic message from this result is that only fairly weak conditions on the demand curve are needed for output leakage to exceed 50%. This conclusion applies whenever demand is not too convex *or* as long as there are sufficiently many outside firms in the industry (as already suggested by the case with linear demand).[22] For instance, it always

[21] For similar reasons, the rate of output leakage also does not depend on the inside firms' carbon costs $k^*(t)$. Put differently, with linear demand, the insiders' output reduction increases linearly with their carbon costs, as does the outsiders' output increase (since best-response curves are also linear), so their ratio, and hence output leakage, is independent of carbon costs. To first order, the same conclusion also goes through for non-linear demand. In general, of course, carbon costs do matter for determining the rate of carbon leakage, and I turn to their effects when analyzing environmental-efficiency improvements by regulated firms in the next section.

[22] Klemperer and Padilla (1997) identify a set of conditions with a similar flavour for circumstances under which firms in Cournot markets have incentives to offer a socially excessive number of products.

holds if the demand curve is concave or linear since even a single outside firm then is sufficiently aggressive in capturing output from the insiders, and also holds under the common assumption that (direct) demand is log-concave as long as there are at least two outside firms.[23] So Proposition 2 shows that *output and carbon leakage can be substantial even if only relatively few firms in the industry do not face regulation.*[24]

Nevertheless, it is also worth pointing out that output leakage can be lower, and indeed negative, in some settings. The latter can only occur when the outside firms, *on average*, do not consider their rivals' outputs as a strategic substitute, that is, when $\lambda_O < 0$. Although not impossible, the case of strategic complements is typically considered unusual in Cournot-Nash equilibrium—and it is clear from Proposition 2 that it is (easily) ruled out by plausible configurations for demand conditions and market structure. To see a counterexample, let $N_O = 1$ and the single outside firm's market share $\sigma_O^* = 40\%$, and suppose that the price elasticity of demand is low and constant at 1/2, so demand curvature $f''(X^*)X^*/f'(X^*) = -3$. Then the outside strategic effect $\lambda_O = -1/5$, so the rate of output leakage $-\Delta X_O/\Delta X_I = 25\%$ and so carbon leakage must also be negative (recalling Lemma 1).[25] (In this example, all else equal, output leakage would certainly be positive if $N_O \geq 3$, and would exceed the 50% benchmark if $N_O \geq 4$.)

□ **Cost pass-through.** Much of the recent policy discussion surrounding the design of cap-and-trade schemes for greenhouse gas emissions has focused on the question of cost pass-through—namely the extent to which regulated firms are able to (respectively, have incentives to) pass cost increases on to customers in form of higher prices. I now show that cost pass-through indeed provides another natural way to understand what drives leakage.

[23] In terms of demand, my setup is equivalent to one in which a large number of customers purchases one unit of the product if and only if their reservation value exceeds its price. Then market demand is proportional to $y = 1 - G(p)$, where $G(p)$ is the distribution of reservation values. A sufficient condition for (direct) demand to be log-concave is that the density of reservation values $g(p)$ is log-concave, which holds for many familiar densities (see, e.g., Bagnoli and Bergstrom, 2005).

[24] These sufficient conditions do not depend on the first-order approximation employed to obtain Proposition 1. The exact output responses can be written as $\Delta X_I^* = \int_{z=0}^{k^*(t)} [(\lambda_O + 1)/(\lambda_I + \lambda_O + 1)f'(X^*)]\, dz$ and $\Delta X_O^* = \int_{z=0}^{k^*(t)} [\lambda_O/(\lambda_I + \lambda_O + 1)f'(X^*)]\, dz$ respectively (see also note 18). So output leakage $-\Delta X_O^*/\Delta X_I^* \geq \frac{1}{2}$ is satisfied whenever $\int_{z=0}^{k^*(t)} [(\lambda_O - 1)/(\lambda_I + \lambda_O + 1)f'(X^*)]\, dz \leq 0$. Since $f'(X^*) < 0$ and $(\lambda_I + \lambda_O + 1) > 0$ (by stability), a *sufficient* condition is that $\lambda_O \geq 1$ for all $z \in [0, k^*(t)]$. It is easy to check that the conditions of Proposition 2 also apply here, so output leakage exceeds 50% if any of them is satisfied for all $z \in [0, k^*(t)]$, that is, along the entire adjustment path from the the old to the new equilibrium with the policy implemented.

[25] The possibility of negative carbon leakage has also been pointed out by Copeland and Taylor (2005) who show that inside and outside emissions can be strategic complements in certain settings. My result shows that the trade channels they emphasize are not actually necessary to generate a negative leakage rate, but rather that this can obtain solely because of the wedge between price and marginal revenue under imperfect competition. Furthermore, I show in Section 6 that *competition* in strategic complements (e.g., price competition), in general, does not imply negative leakage rates, and indeed that output and carbon leakage can be positive and large under such circumstances.

In Cournot-Nash equilibrium, a small increase in the costs of a subset of firms (i.e., the regulated firms) leads to a rate of cost pass-through

$$\rho^* = \frac{N_I}{(\lambda_I + \lambda_O + 1)}, \tag{5}$$

where $(\lambda_I + \lambda_O + 1) > 0$ by stability. Cost pass-through is always positive, though it is lower the more outside firms N_O in the market (who are not directly affected by the cost change), and the more concave the demand curve (as this increases the strategic effects λ_I and λ_O).[26]

So there clearly is a sense in which lower rates of cost pass-through are associated with higher rates of leakage. More formally, observe that, for a given market structure (that is, a given number of firms and market shares), there is a "duality" between the rate of cost pass-through and demand curvature in that $f''(X^*)X^*/f'(X^*) = N_I/\rho^* - (N_I + N_O + 1)$. Using this to express things in terms of pass-through rates yields the following result.

Proposition 3 *In equilibrium, for any given market structure:*
(i) a lower rate of cost pass-through implies a higher rate of output leakage;
(ii) if the rate of cost pass-through $\rho^* \leq N_I/(N_I + 2) \equiv \overline{\rho}$, then the rate of output leakage exceeds 50%.

The intuition for the first part of the result is straightforward: if a given output reduction by inside firms leads to a smaller increase in price, then this means that the outside firms must have expanded their output by more, so output leakage must be higher. The second part of the result is the analogue to Proposition 2, and gives a precise sense in which the 50% benchmark for output leakage must be satisfied if cost pass-through is sufficiently low.

Indeed, note that $\overline{\rho} \geq \frac{1}{3}$, so output leakage must exceed 50% if demand conditions mean that cost pass-through is less than $33\frac{1}{3}\%$—again regardless of the further details of the market structure. More generally, $\overline{\rho} \to 1$ as the number of inside firms N_I grows large, so *even relatively high rates of cost pass-through can be consistent with substantial leakage.* Note also that pass-through much below 100%—despite a large number of inside firms experiencing the cost change—means that either demand is rather concave or that there is also a large number of outside firms. This corresponds exactly to the sufficient conditions from Proposition 2 for output leakage to exceed 50%.

Although the details of market structure and demand conditions are clearly important, these results suggest that output leakage is significant for most industries, and may

[26] Slightly abusing notation, note that $\rho^*(N_I) = [N_I/(N_I + N_O)]\,\rho^*(0) < \rho^*(N_I + N_O)$, where $\rho^*(N_I + N_O) = (N_I + N_O)/(\lambda_I + \lambda_O + 1)$ is equilibrium cost pass-through if all $N_I + N_O$ firms are affected by a cost change. So cost pass-through under incomplete regulation equals cost pass-through under complete regulation times the proportion of firms that are covered.

often exceed a 50% benchmark. In the absence of significant efficiency improvements by regulated firms, carbon leakage is at least this high whenever $\omega_O \geq \omega_I$ (from channel A).

5 Efficiency improvements

By putting a price on carbon, environmental regulation in form of emissions trading or a carbon tax creates incentives for regulated firms to adopt cleaner production technologies. In terms of carbon leakage, such environmental-efficiency improvements can have a two-fold benefit. First, a reduction in emissions intensities mitigates the cost impact of the regulation, so inside firms optimally cut output by less. Second, a reduction in the emissions intensities of regulated firms also means that a given contraction in their output translates into a greater reduction in their emissions. These forces can substantially reduce carbon leakage (assuming output leakage is positive).

However, such efficiency improvements also cannot *fully* eliminate leakage. The reason is that, although a reduction of its emissions intensity may be a cost-minimizing strategy for an inside firm, such a clean-up of production involves abatement costs. So firms always experience *some* cost increase at the margin, which leads to *some* output contraction—which in turn leads to carbon leakage (via the output leakage channel).

□ **Quantifying output reductions.** From the ABC decomposition, the two relevant variables for quantifying the impact of efficiency improvements on leakage are the percentage change in inside firms' emissions intensity $\Delta\omega_I/\omega_I$, and the corresponding percentage change in the inside firms' production level $\Delta X_I/X_I$. This section characterizes this efficiency effect based on the inside firms' cost-minimizing choice of inputs (including emissions) using the first-order approach outlined in the previous section. Once again, not much is lost if the demand curve is not too non-linear *or* the carbon price is not too large, and the results are exact for the special case with linear demand.

The following proposition presents a simple formula to quantify how much inside firms reduce output in response to carbon costs.

Proposition 4 *The equilibrium reduction in the inside firms' output in response to a cost increase $k^*(t)$ is given by*

$$\frac{-\Delta X_I^*}{X_I^*} = \frac{k^*(t)}{\bar{\mu}_I^*(0)} \left(\frac{\lambda_O + 1}{\lambda_I + \lambda_O + 1} \right),$$

where $\bar{\mu}_I^*(0) \equiv \frac{1}{N_I} \sum_{j=1}^{N_I} \left[p^*(0) - c_I^j \right]$ is the average operating profit margin of the inside firms when carbon is unpriced, and $(\lambda_O + 1) > 0$ and $(\lambda_I + \lambda_O + 1) > 0$ by stability.

The regulated firms' output reduction is driven by two components: first, a carbon-cost-to-profitability ratio that captures how large the inside firms' (minimized) carbon costs are relative to their average operating profit margin *before* introduction of the regulation (both measured in dollars), and, second, a composite strategic effect that depends on the numbers of inside and outside firms, their market shares (again, before introduction of regulation), and demand curvature.

The percentage output reduction is larger if carbon costs are larger and also if, on average, the regulated firms have lower operating profit margins. A simple condition guarantees that the carbon-cost to profitability ratio forms an upper bound; in particular, note that $-\Delta X_I^*/X_I^* \leq k^*(t)/\bar{\mu}_I^*(0)$ if (and only if) $\lambda_I \geq 0$. This corresponds to the inside firms regarding competition as being in strategic substitutes (again, on average), which, as noted above, is typically thought to be the usual case in Cournot-Nash settings.

To gain a better understanding of the formula, and the composite strategic effect in particular, it is again useful to consider the special case of linear demand (for which $\lambda_I = N_I$ and $\lambda_O = N_O$) in some detail. Recalling the formulae for cost pass-through, observe that one can also write

$$\frac{-\Delta X_I^*}{X_I^*} = \frac{k^*(t)}{\bar{\mu}_I^*(0)}(1-\rho^*). \tag{6}$$

With linear demand, the percentage output reduction by regulated firms (exactly) equals the cost-profitability ratio times the proportion of carbon costs that is *not* passed on.[27] All else equal, higher cost pass-through therefore implies a lower output reduction—corresponding to either fewer outside rivals or more numerous inside firms. Indeed, the rate of cost pass-through here exceeds 50% whenever inside firms make up the strict majority of firms in the market, that is $N_I \geq N_O + 1$. This puts a tighter upper bound of 50%, on the (composite) strategic effect, and hence also on the output reduction by the regulated firms.[28]

With non-linear demand, the above expression of the output reduction in terms of cost pass-through also *roughly* applies whenever the number of firms N_I and N_O dominate the calculations. In such cases, cost pass-through is approximately equal to the proportion of firms affected by regulation, that is $\rho^* \approx N_I/(N_I + N_O)$. Also, analogously to output leakage (Proposition 1), the composite strategic effect is more pronounced (so output cuts are larger) if the market share of outside firms is higher whenever demand is concave, and less pronounced when demand is convex.

[27] It turns out that this reformulation using cost pass-through applies quite generally in models with linear-symmetric demand structures (see also the discussion in Section 6).

[28] Of course, it is worth bearing in mind that carbon-costs-to-profitability ratio is itself endogenous; with a larger number of firms in the market, the inside firms' average profitability will typically decrease, which, all else equal, means that their percentage output reduction will tend to be greater.

The formula from Proposition 4 can be implemented empirically using data on market structure and demand conditions for an industry, combined with information on firm profitability and carbon costs. The general flavour of the results is similar to those for output leakage: regulated firms are typically in a better position if there is less "business stealing" by outside rivals—this is associated with a smaller reduction in output, a lower rate of output leakage and a higher rate of cost pass-through to market prices.

□ **Carbon price effects.** In contrast to output leakage, the impact of inside firms' efficiency improvements on the rate of carbon leakage depends *directly* on the carbon price. There are two opposing forces at work. First, a higher carbon price increases inside firms' carbon costs. All else equal, this leads to a larger reduction in their output—which in turn lessens the beneficial impact of any efficiency improvements. Second, however, a higher carbon price increases the returns to such efficiency improvements. This can lead to a larger reduction in inside firms' emissions intensities—which in turn strengthens the efficiency effect and so decreases the rate of carbon leakage.

The following result provides a condition for which of the two effects is more important.

Proposition 5 *A higher carbon price leads to a higher equilibrium rate of carbon leakage* $\partial L^*/\partial t \geq 0$ *if and only if*

$$\epsilon_X \geq \epsilon_\omega \left(1 + \frac{\Delta X_I^*}{X_I^*}\right),$$

where $\epsilon_\omega \equiv d\log(-\Delta\omega_I)/d\log t$ *and* $\epsilon_X \equiv d\log(-\Delta X_I)/d\log t$.

Basically, a higher carbon price increases the leakage rate if the output reduction by regulated firms is sufficiently sensitive to the carbon price compared to the magnitude of their efficiency improvements. Carbon leakage certainly increases if the elasticity of the output reduction is no less than that of the efficiency improvements, so $\epsilon_X \geq \epsilon_\omega$. However, if the latter is sufficiently higher, then the rate of carbon leakage may well decrease.[29] So *it is not necessarily correct that a higher carbon price results in greater leakage*—as sometimes seems to be presumed in policy discussions.

To illustrate, it is useful to consider the example in which regulated firms can choose between two discrete technologies: the status quo with low marginal cost and high emissions intensity, and an alternative technology with higher marginal cost yet lower emissions intensity. It is profitable for inside firms to change to the cleaner technology if (and only if) the carbon price $t \geq \underline{t}$, say—which might, for instance, represent fuel switching from coal to gas. Now consider the thought experiment of a carbon price starting at zero, and

[29] Note that channel A (relative intensities) is independent of the carbon price and that channel B (output leakage), to first order, also does not depend on it. Therefore, leakage does not vary with the carbon price in the absence of any efficiency improvements by inside firms.

then gradually increasing it to its actual level $t \geq \underline{t}$. For a sufficiently small carbon price, inside firms stick with their status quo technology and do not experience any efficiency improvements—and so the rate of carbon leakage remains constant (as determined by the first two channels of leakage). However, when the carbon price reaches t^*, it becomes optimal for the inside firms to switch to the cleaner technology. Around this point, the rate of carbon leakage falls discontinuously as the insiders' emissions intensities are extremely sensitive to the carbon price around the kink. Thereafter, however, no further efficiency improvements are possible (since the insiders have already switched to the cleanest technology available), and so a higher carbon price again leads to greater output contractions—and a higher rate of carbon leakage.

□ **Deriving bounds on carbon leakage.** In general, therefore, there is no unambiguous relationship between the carbon price and carbon leakage: much depends on the details of how easily the regulated firms' production technologies admit environmental efficiency improvements, in particular on the shape of their abatement costs $\varphi(t)$. Similarly, to complete the calculation of equilibrium carbon leakage, an important challenge is that typically only little is known to the analyst about the functional form of these abatement costs for a particular industry—while any such assumption effectively also determines the equilibrium efficiency improvement $\Delta\omega_I^*/\omega_I$.

Nevertheless, it is possible to use the techniques developed to estimate rates of carbon leakage for an industry with reasonable accuracy, whilst making only minimal assumptions on the abatement costs of regulated firms. In particular, note the following bounds on the implied carbon costs $k^*(t)$ incurred by an inside firm: if an emissions intensity reduction of $-\Delta\omega_I^*/\omega_I$ is the *optimal* choice for a firm, then (i) carbon costs must be at least $t\omega_I\,(1 + \Delta\omega_I^*/\omega_I)$ since the abatement costs incurred must be non-negative (that is, $\varphi^*(t) \geq 0$), and (ii) carbon costs must be no more than they would have been without any abatement, namely $t\omega_I$. It follows that inside firms' carbon costs can be bounded by

$$t\omega_I \left(1 + \frac{\Delta\omega_I^*}{\omega_I}\right) \leq k^*(t) \leq t\omega_I. \tag{7}$$

Note especially that this also places bounds on the rate of output contraction $-\Delta X_I^*/X_I^*$ by inside firms from Proposition 5 as a function of equilibrium efficiency improvements $\Delta\omega_I^*/\omega_I$.

Channel A of the decomposition is determined by relative emissions intensities in the industry *before* the policy implemented, and Channel B on output leakage can be estimated using Proposition 1. Combining the three channels then allows me to calculate bounds on the overall equilibrium rate of carbon leakage L^* for any given $\Delta\omega_I^*/\omega_I$, without relying on functional form assumptions on firms' abatement costs. Moreover, in many cases, these bounds on leakage are perhaps surprisingly tight.

I illustrate this technique in Section 7 by tying together the results on output leakage and the impact of efficiency improvements in an empirical application to the steel industry in the EU ETS. Before this, however, the next section discusses the robustness of these results to different forms of competition. (This robustness analysis can be skipped to go directly to the empirical application without any loss of continuity.)

6 Robustness

The benchmark Cournot-Nash model offers a simple way to replicate any observed distribution of market shares for an imperfectly competitive industry. This section shows that its main insights on the impact of incomplete environmental regulation—in particular, output leakage and the impact of efficiency improvements—are quite robust to different forms of competition.[30] For simplicity, and to obtain exact results that are easily comparable to those from the benchmark model, I assume that the respective demand structures are linear in most of what follows.

□ **Conjectural variations.** An alternative, more general formulation of imperfect competition assumes that each inside firm conjectures that (all of) its rivals will adjust their output choice according to $d(X - x_I^j)/dx_I^j = \theta \geq -1$ (for all j) in response to a change in its own output choice, and similarly $d(X - x_O^i)/dx_O^i = \theta$ (for all i). The Cournot-Nash equilibrium is nested where $\theta = 0$, and industry conduct is more (less) competitive whenever $\theta < 0$ ($\theta > 0$).[31]

With a linear demand curve, the (exact) rate of output leakage $-\Delta X_O^*/X_I^* = N_O/(N_O + 1 + \theta)$, so the more competitive the industry (i.e., the lower θ), the higher the rate of output leakage, as outside firms are more aggressive in "filling the gap" in the market that is left by the insiders' output contraction. In the limit, *output leakage tends to 100% as the industry becomes perfectly competitive.* Conversely, output leakage is lower in industries that are "more collusive" than in a Cournot-Nash equilibrium.

There are two opposing effects with respect to the output contraction by regulated firms. For any given operating costs, tougher competition implies lower profit margins, but *higher* cost pass-through. However, it can be shown that the former effect outweighs, and so, as expected, the output contraction by insiders is more pronounced the more

[30] Note that the regulated firms' (minimized) carbon costs $k^*(t)$ are not affected by the form of competition given the setup of the model.

[31] The conjectural variations model is known to be logically flawed, but can nevertheless be useful as a reduced-form way of representing alternative theories of imperfectly competitive firm behaviour.

competitive the industry.[32] In sum, therefore, competition that is tougher than Cournot-Nash leads to a higher degree of output leakage, and a greater contraction by inside firms—both of which imply higher rates of carbon leakage.

The conjectural-variations model with $\theta < 0$ can also be seen as a reduced form for other models of competition for which outcomes typically lie between perfect competition and Cournot-Nash. For example, the same conclusions also hold if firms (or their managers) for strategic reasons pursue objectives such as sales revenue or market share (see, e.g., Fershtman and Judd (1987) and Ritz (2008) respectively) in addition to profits.

□ **Price competition.** Carbon leakage also tends to be higher when firms instead engage in (undifferentiated) price competition. Suppose there are $N_I + N_O$ firms that initially have identical marginal cost c, and symmetric market shares of $1/(N_I + N_O)$ each before the introduction of incomplete environmental regulation. The initial equilibrium market price is at marginal cost, $p^*(0) = c$. If there are at least two outside firms (so $N_O \geq 2$), the equilibrium price under regulation is still at marginal cost, so $p^*(t) = c$, and the market is split equally amongst the two outside firms (since the regulated firms can no longer produce profitably). It follows that the rate of output leakage is 100%, and that carbon leakage exceeds 100% (so global emissions increase) if the outside firms are more emissions-intensive than the inside firms, $\omega_O \geq \omega_I$. (Note also that cost pass-through is zero in this setting.)

If there is a single outside firm and M consumers each have a fixed reservation value $R > c$ for one unit of the good, then the rate of output leakage is also 100%, and this again maps into carbon leakage by way of the relative emissions intensity of the outside firm. Note also that any environmental-efficiency improvements by the inside firms do not affect the conclusion: since the their costs must increase at least by abatement costs, they cannot hold onto any market share under price competition (with undifferentiated products).

□ **Product differentiation.** Finally, if firms' products are differentiated, this tends to lead to lower rates of carbon leakage—since firms are effectively less interdependent, and hence strategic effects are less important. Nevertheless, leakage can still be significant and output leakage, in particular, still above the 50% benchmark from Proposition 2. Consider a model of linear product differentiation in which the (inverse) demand curve

[32] Slightly abusing notation, the formula for output reduction with conjectural variations $-\frac{\Delta X_I^*}{X_I^*}(\theta) = [k^*(t)/\bar{\mu}_I^*(\theta)] \cdot [1 - \rho^*(\theta)]$, just as in Cournot-Nash equilibrium. The two opposing effects arise since the average profit margin is increasing in θ, while cost pass-through is decreasing in θ. However, it can be shown that $-\frac{\Delta X_I^*}{X_I^*}(\theta') \geq -\frac{\Delta X_I^*}{X_I^*}(\theta'')$ if any only if $\rho^*(\theta') \geq \rho^*(\theta'')$ if and only if $\theta' \leq \theta''$. As a more competitive industry has a *higher* rate of cost pass-through, using pass-through as a guide to output leakage may be less reliable when applied across different forms of competition.

for inside firm j is given by $p_I^j = \alpha - \beta X_I - \delta X_O$ and that for outside firm i by $p_O^i = \alpha - \beta X_O - \delta X_I$, where $\delta/\beta \in [0,1]$ is a measure of product differentiation. The resulting rate of output leakage $-\Delta X_O^*/X_I^* = (\delta/\beta)\,[N_O/(N_O+1)]$ is a straightforward generalization of Proposition 1 (for linear demand). Evidently, stronger product differentiation reduces leakage, and, in the limit as $\delta/\beta \to 0$, carbon leakage is zero since the inside and outside firms then act independently of each other.[33]

Similarly, the (percentage) output reduction by inside firms is typically lower when products are differentiated than when they are not. Intuitively, the inside firms' (pre-regulation) profit margins are higher and strategic effects are weaker, both of which soften the output responses. Whenever inside firms engage in efficiency improvements, this also reduces the rate of carbon leakage. Nonetheless, it is clear that leakage rates can still be high if the number of outside firms is sufficiently large, and products are not too differentiated.

Leakage rates will also tend to be higher if products are differentiated, but firms compete in prices instead of quantities. To illustrate, consider the duopoly case for which the (dual) direct demand curve for the inside firm $X_I = a - bp_I + dp_O$, and, analogously, $X_O = a - bp_O + dp_I$, so $d/b \in [0,1]$ is the measure of differentiation.[34] In this example, output leakage $-\Delta X_O^*/X_I^* = (d/b)/\left[2-(d/b)\right]^2$ exceeds 50% whenever $d/b \geq \left(\sqrt{3}-1\right) \approx 0.73$. So leakage can be significant even with considerable product differentiation and a single unregulated firm.

All together, these arguments suggest that the results from the benchmark Cournot-Nash model are fairly robust. The 50% benchmark on output leakage applies quite widely under different forms of competition, as long as industry conduct is relatively competitive and products are not too differentiated. These would seem to be the relevant conditions for many of the kinds of emissions-intensive industries that are likely to be covered by environmental regulation. However, efficiency improvements by regulated firms lessen the degree of output contraction and can substantially reduce carbon leakage.

Future research could build on these insights by exploring in more detail the role of heterogeneity in regulated firms' abatement strategies. In many industrial sectors, there is a dominant production technology, so emissions intensities are likely to be comparable across (regulated) firms. However, in other industries, heterogeneity of emissions intensities—as well as of changes in emissions intensities—may be more important, which can lead to additional effects in terms of the interaction between individual firms' output

[33] Babiker (2005) makes a related point by observing that homogeneity of traded products is an important source of carbon leakage across different scenarios of a CGE model. Leakage rates could also be lower if firms' products are *ex post* differentiated because customers incur significant switching costs in their choice of supplier.

[34] The two measures of product differentiation $d/b = \delta/\beta$ due to the duality of the demand structures.

responses and their overall contribution to emissions reductions. In general, such effects are also likely to vary with the degree of competitiveness and demand conditions in the sector—notably demand curvature (or, equivalently, the rate of cost pass-through) in a Cournot-Nash setting.[35]

7 Empirical illustration

Steel production has been included in the EU ETS since its introduction in 2005. However, steel producers located outside the EU have not been affected by comparable environmental regulation. The resulting absence of a "level playing field" has made carbon leakage in this sector (and others) a major concern for policymakers in the EU.

This section illustrates the modelling approach outlined in Sections 2 to 5 with an application to the steel industry in the EU ETS. In particular, I present some indicative figures on carbon leakage for the market for cold-rolled sheet steel, which is used in a variety of end applications, including in cars, machinery, buildings and furniture. This is a capacity-driven market in which firms' products are thought to be close to homogeneous, so the benchmark Cournot-Nash model seems a reasonable initial modelling choice.[36]

Several recent anti-trust cases suggest that the relevant product market definition is European, see, e.g., Usinor/Arbed/Aceralia (COMP/ECSC.1351, 21.11.2001). Market data for 2004 indicate that there were a total of 15 firms supplying cold-rolled sheet steel in Europe, of which $N_I = 12$ were EU firms and $N_O = 3$ firms were located outside the EU, with a market share of $\sigma_O^* = 15\%$.[37] The largest firm had a market share of just over 31% and the Herfindahl-Hirschman index was around 1400, indicating a moderately high degree of concentration.[38]

The price elasticity of demand for steel products is likely to be rather low, estimated,

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[35] Note also that such heterogeneity may only play a limited role if industry conduct is very competitive. For example, in a model of price competition with undifferentiated products (and $N_O \geq 2$), the regulated firms cannot hold on to any market share regardless of the nature of heterogeneity in emissions intensities. So output leakage always equals 100%, and it is easy to show that carbon leakage $L = \bar{\omega}_O/\bar{\omega}_I$ is similar to that in the main text, but now depends on the *average* (pre-policy) emissions intensities, $\bar{\omega}_I \equiv \frac{1}{NI}\sum_{j=1}^{N_I}\omega_I^j$ and $\bar{\omega}_O \equiv \frac{1}{N_O}\sum_{i=1}^{N_O}\omega_O^i$. (Since price remains constant (and industry profits remain zero) throughout, no other firm has increased incentives to enter the incompletely-regulated market either.)

[36] See also Demailly and Quirion (2008) for a numerical model of the impact of the EU ETS on the steel industry as whole (rather than a particular steel product). I am not aware of any *ex post* empirical analysis of carbon leakage for the initial phases of the EU ETS. The shortage of such work may be due to data constraints and difficulties in empirically isolating the impact of environmental regulation on emissions from other effects.

[37] I am very grateful to Eurofer (the European Confederation of Iron and Steel Industries) for providing this data, and to Cameron Hepburn for his help in the process.

[38] There has been a trend towards increased consolidation in the steel industry over the last years, notably with the merger between Arcelor and Mittal Steel in 2007, see, e.g., the discussion in Mittal/Arcelor (COMP/M.4137, 02.06.2006).

for example, at 0.62 by Lord and Farr (2003) and as low as 0.27 by others (see, e.g., the references in Ghemawat, 1993). Based on these figures, I use an elasticity of 0.50 as a 'best guess' in the following calculations. With the mild assumption that demand is (weakly) more elastic at a higher price, this puts an lower bound on demand curvature of -3.[39] I report results for two of the most commonly-employed demand curves, linear and constant-elasticity demand (for which the bound on curvature is met). Note that this information on demand, combined with the data on market structure, is already sufficient to estimate the rate of output leakage from Proposition 1. Smale, Hartley, Hepburn, Ward and Grubb (2006) report that the market price for cold-rolled sheet steel was around $p^*(0) =$ €400 per ton of product in 2004 (converted using an exchange rate of €1.40/£). Finally, I take a value of 20% for the average operating profit margin of the inside firms, which is broadly consistent with IEA (2005) and Smale et al. (2006), so the (average) absolute operating profit margin $\bar{\mu}_I^*(0) =$ €80 per ton of product.

There are two principal production routes for steel products: the primary, basic oxygen furnace (BOF) route used in integrated steel mills and the secondary, electric arc furnace (EAF) route used in minimills.[40] Unfortunately, I do not know the identities of all firms in the market, and, in particular, I do not have data on the specific technologies used by different suppliers of cold-rolled sheet steel. However, it is known that almost 90% of such flat products were produced via the primary BOF route in the EU market in 2003.[41] Based on this figure, I assume in the modelling that all cold-rolled sheet steel is produced via the BOF route.[42] The emissions intensity of production via this route in the EU is around $\omega_I = 2\text{tCO}_2$ per ton of steel, based on estimates in IEA (2005), McKinsey (2006) and Smale et al. (2006). There is some evidence that non-EU producers are relatively more emissions-intensive, although there are also some differences between countries (Kim and Worrell, 2002). To be conservative, I assume that the pre-ETS emissions intensities

[39] Demand curvature $f''(X^*)X^*/f'(X^*) = -[1 + 1/\eta(X^*)] - [d \log \eta(X)/d \log X]_{X=X^*}$, where $\eta(X) = |f(X)/f'(X)X|$ is the price elasticity of demand, so $f''(X^*)X^*/f'(X^*) \geq -[1 + 1/\eta(X^*)]$ as long as demand is (weakly) more elastic at a higher price.

[40] A third route called open hearth furnace (OHF) has virtually ceased to exist in the EU and most other regions, but is still used to a limited extent in Russia and some developing countries. See Oster (1982) for an analysis of how the OHF technology was largely superseded by the innovation of the basic oxygen furnace in industrialized countries over a period covering the 1960s and 1970s.

[41] There are two main classes of steel products, flat and long. McKinsey (2006) reports that for the EU market in 2003, BOFs produced 114 million tons of steel, of which around 75% were flat products and the remainder were long products. By contrast, EAFs produced 70 million tons, of which around 15% were flat products and 85% were long products. It follows that almost 90% of flat products were produced via the BOF route.

[42] Smale et al. (2006) make the same assumption, also reporting that industry representatives thought it to be reasonable. Overall, the production share of the EAF route has increased over the last years, although it is still largely focused on lower-quality, long products due to technological constraints and sometimes limited availability of suitable scrap steel as an input to production. See also Ghemawat (1993) for a discussion of Nucor's (a US-based minimill operator) adoption of thin-slab casting in the 1980s to enter the market for higher-quality flat products, which until then had been exclusive to integrated mills.

of EU and non-EU producers are the same, so $\omega_O = \omega_I$. Finally, I take $t =$ €20/tCO_2 as the expected price of carbon emissions.

There is thought to be only limited scope for efficiency improvements to the BOF route of production, especially in the short run and in the absence of new breakthrough technologies. However, firms can reduce emissions intensities to some extent by changing their fuel mix, improving energy efficiency and upgrading the technology of existing facilities. In the longer run, there may also be a switch to the EAF route, which generally has a lower carbon-intensity.[43] Since the precise scope for efficiency improvements is unclear—and to avoid assuming a particular functional form for abatement costs—I make use of the implied bounds on inside firms' (minimized) carbon costs that $t\omega_I\,(1 + \Delta\omega_I^*/\omega_I) \leq k^*(t) \leq t\omega_I$, and present results for a wide range of scenarios on efficiency improvements.

Table 1: Estimates of carbon leakage (in %) for the EU cold-rolled sheet steel market in the EU ETS (using 2004 data)

	Efficiency improvements $-\Delta\omega_I^*/\omega_I$ by regulated firms				
Demand curve	0%	5%	10%	20%	50%
Linear	75.0	54.7–55.6	41.9–44.1	26.8–31.3	8.8–16.7
Constant-elasticity	71.8	53.8–54.6	41.9–44.0	27.3–31.7	9.2–17.3

This information on the cold-rolled sheet steel sector is sufficient to derive estimates of carbon leakage as summarized in Table 1. The lower bounds are for the case when abatement is almost costless, while the upper bounds apply when the respective level of abatement is only just profitable. In the absence of any efficiency improvements, carbon leakage is solely driven by rates of output leakage that range from around 72% to 75%. Indeed, carbon leakage remains quite high as long as the efficiency gains by inside firms are moderate. For example, as long as the reduction in emissions intensities is less than 20%, equilibrium rates of carbon leakage are around 25–30% or (much) higher.

In practice, of course, the impact of emissions trading on a sector is much more complex than any simple model can capture. Nonetheless, these indicative calculations suggest that carbon leakage in the EU steel industry is likely to be significant unless rather substantial reductions in the emissions intensities of regulated firms can be achieved at the

[43] There may also be the possibility of reducing emissions by employing carbon capture and storage (CCS) technology. However, recent estimates suggest that CCS would only become commercially viable for steel producers at significantly higher carbon prices of around €50–60/tCO_2 (see, e.g., McKinsey, 2009). The effects of end-of-pipe abatement technologies are similar to those of the efficiency improvements modelled here, and I discuss them in detail in extension III of Section 8.

prevailing carbon price.[44] Leakage rates will tend to be lower than these estimates if there is a degree of product differentiation between firms or if there are significant switching costs that customers have in their choice of supplier. On the other hand, leakage rates will tend to be higher if industry conduct is more competitive (for example, because firms purse market share objectives) or if unregulated steel producers are indeed more emissions-intensive than those in the EU.[45]

8 Extensions

I. Carbon leakage with existing environmental regulation. For expositional purposes, the results presented thus far consider the situation in which, starting from zero carbon price for all, environmental regulation is introduced only for a subset of firms. However, with obvious modifications, all the results apply much more generally to situations in which environmental regulation is *tightened* only for a subset of firms. For example, a country or region may decide to increase a carbon tax, while existing policies elsewhere remain unchanged.

In particular, suppose that inside firms face a carbon price t_{low}, which tightening of regulation increases to t_{high}, while outside firms face a (constant) carbon price t_{other}.[46] What is the rate of carbon leakage associated with the policy? It is easiest to proceed using the ABC decomposition (from Lemma 1). Channel A again involves the ratio of emissions intensities *before* the policy is adjusted, but these are now measured as $\omega_I(t_{\text{high}})$ for the insiders and $\omega_O(t_{\text{other}})$ for the outsiders (instead of both at a zero carbon price). In response to the carbon price increase, each inside firm's (minimized) unit cost of production increases by $k^*(t_{\text{high}}) = (t_{\text{high}} - t_{\text{low}})\omega_I^*(t_{\text{high}}) + \varphi^*(t_{\text{high}})$. Each outside firm's unit cost remains unchanged, but may already be affected by prior environmental regulation. For channel B, the formula for output leakage from Proposition 1 is as before, except the strategic effect $\lambda_O(t_{\text{low}}, t_{\text{other}})$, for which outside firms' market share before the (insiders') policy is adjusted is $\sigma_O^*(t_{\text{low}}, t_{\text{other}})$. The sufficient conditions for output leakage to exceed 50% from Proposition 2 and 3 remain the same. Similarly, for channel C, for Proposition 4 the insiders' efficiency improvement needs to be measured relative to what it was at the lower (but non-zero) carbon price, so $\Delta\omega_I^*(t_{\text{high}}) = \omega_I^*(t_{\text{high}}) - \omega_I^*(t_{\text{low}}) \leq$

[44] The equilibrium rates of cost pass-through implied in these estimates are quite high (ranging from 75 to 92%), since the large majority of firms in the market are EU producers who all experience the cost increase due to carbon pricing. The percentage contraction in the inside firms output ranges from 6% to 14%, depending on the shape of the demand curve and the details of the carbon costs incurred.

[45] Moving beyond the partial-equilibrium approach of this paper, carbon leakage rates may be lower because of the trade effects emphasized by Copeland and Taylor (2005), or higher because unregulated firms switch to dirtier production technologies given a fall in energy prices.

[46] Outside firms could also face different (but unchanging) carbon prices (with t_{other} a vector).

0. Likewise, the inside firms' (pre-policy adjustment) average operating profit margin $\bar{\mu}_I^*(t_{\text{low}}, t_{\text{other}})$, and the strategic effects $\lambda_I(t_{\text{low}}, t_{\text{other}})$ and $\lambda_O(t_{\text{low}}, t_{\text{other}})$.

With these modifications, therefore, the above formulae and results can easily be applied to situations in which environmental regulation is tightened only for a subset of firms. Carbon leakage then refers to how much of the *additional* emissions reductions by firms that experience the carbon price increase leak to other countries or regions. Note also that, in general, leakage rates will differ depending on the extent of regulation already in place: this affects the scope for (additional) environmental-efficiency gains, and also will have changed firms' market shares, profit margins, and so on, compared to the case of unilateral introduction of regulation.

II. Welfare implications: Consumer surplus, profit leakage, and global emissions. Environmental regulation that is applied only to a subset of firms in an industry usually leads to a degree of carbon leakage. This also has a number of related welfare implications for consumers and producers.

Consider again the benchmark Cournot-Nash model with linear demand curve, so that carbon leakage is unambiguously positive (since output leakage is positive) and the rate of cost pass-through $\rho^* = N_I/(N_I + N_O + 1)$ is constant. How does welfare with incomplete environmental regulation compare to the no-regulation case?

Equilibrium consumer surplus $S^* = \int_{z=0}^{X^*} [f(z) - f(X^*)]\, dz$ falls since the market price rises by $\Delta p^* = \rho^* k^*(t)$, and, to first order, $\Delta S^* \approx -\rho^*(X_I^* + X_O^*)k^*(t) < 0$.[47] The inside firms' profit decreases according to $\Delta\Pi_I^* \approx -2(1-\rho^*)X_I^* k^*(t) < 0$, while that of the outside firms increases with $\Delta\Pi_O^* \approx \rho^* X_O^* k^*(t)$. In other words, there is also a degree of *profit leakage* as outside firms free-ride on the price increase and gain market share. However, total industry profit may increase or decrease, depending on the distribution of market shares (before the regulation). To see why, observe that the change in industry profit $\Delta\Pi^* = \Delta\Pi_I^* + \Delta\Pi_O^* \leq 0$ only if cost pass-through is sufficiently low $\rho^* \leq \sigma_I^*$. In the other case, each outside firm benefits a lot (because of high pass-through) and outsiders have much weight in the overall calculation (because of high market share), so industry profit rises. The change in total (unweighted) surplus $\Delta S^* + \Delta\Pi^*$ is negative only if $\rho^*/2 \leq \sigma_I^*$; otherwise, the positive impact on outside firms outweighs both the negative effects on consumers and inside firms.[48]

In terms of environmental benefits, regulation decreases equilibrium global emissions, so $\Delta E_I^* + \Delta E_O^* \leq 0$, if (and only if) the rate of carbon leakage $L^* \leq 1$. The overall effect on social welfare depends on the weights assigned to consumer and producer surplus as well as

[47] To keep things simple, similar to the main analysis in Section 4 and 5, I use first-order approximations in the welfare analysis to obtain easily interpretable formulae.

[48] These calculations do not take into account the value of any freely allocated emissions permits that regulated firms may receive in a cap-and-trade scheme. See also extension IV in this section.

environmental benefits in the welfare function, in particular on how strongly the interests of regulated entities count relative to unregulated ones. However, two cases are clear-cut whenever welfare depends on the total (unweighted) surplus of consumers and all firms, as well as global emissions. First, if total industry profits are indeed lower and leakage exceeds 100%, then incomplete regulation reduces welfare. Second, and conversely, if total surplus rises and leakage is less than 100%, then welfare increases. So it is clear that, in general, the overall welfare impact of incomplete environmental regulation is ambiguous.

III. End-of-pipe abatement technologies. In the benchmark model, the efficiency improvements achieved by inside firms reducing their emissions intensities also affect their production decisions. An alternative, yet also important, way for firms to reduce their emissions is by way of "end-of-pipe" abatement technologies for which production and abatement costs are separable. I now show that the basic insights on output leakage and impact of efficiency improvement also apply here.

Write inside firm j's profits as $\Pi_I^j = (p - c_I^j)x_I^j - te_I^j - [\kappa/(\gamma+1)]\,(\omega_I x_I^j - e_I^j)^{\gamma+1}$, where the last term represents abatement costs, ω_I is the (gross) emissions intensity before abatement (as in the benchmark model), and e_I^j is net emissions. From the first-order conditions $\partial\Pi_I^j/\partial x_I^j = 0$ and $\partial\Pi_I^j/\partial e_I^j = 0$, it is easy to show that $t = k(\omega_I x_I^j - e_I^j)^\gamma$ in equilibrium, so the carbon price equals the marginal cost of abatement (for all j). Moreover, since a firm's unit cost of production is unaffected by end-of-pipe abatement, its carbon costs (per unit of output) $k^*(t) = t\omega_I$, just as in the benchmark model without any efficiency improvements. Total inside emissions $E_I^*(t) = \omega_I X_I^*(t) - N_I(t/\kappa)^{1/\gamma} \geq 0$, so the change in emissions $\Delta E_I^* = \omega_I \Delta X_I^* - N_I(t/\kappa)^{1/\gamma}$, while that of the unregulated firms $\Delta E_O^* = \omega_O \Delta X_O^*$.[49] Therefore, the equilibrium rate of carbon leakage

$$L^* = \frac{\omega_O}{\omega_I}\left[\frac{\Delta X_O^*}{-\Delta X_I^* + (N_I/\omega_I)(t/\kappa)^{1/\gamma}}\right]. \tag{8}$$

Note first that carbon leakage is again positive if and only if output leakage is positive. With zero abatement (that is, as $\kappa \to \infty$), carbon leakage is only driven by the first two effects of the ABC decomposition, namely the relative emissions intensities and output leakage, so $L^* = (\omega_O/\omega_I)\,[\Delta X_O^*/(-\Delta X_I^*)]$. More end-of-pipe abatement reduces leakage, similar to the benchmark model—although it does not allow inside firms to regain market share. In the limit, as $E_I^*(t) \to 0$ and inside firms become "zero carbon", leakage $L^* = (\omega_O/\omega_I)\,(\Delta X_O^*/\Delta X_I^*)\,(\Delta X_I^*/X_I^*)$ just as in the benchmark model.[50]

Throughout, the rate of output leakage and the percentage contraction in the regulated

[49] This assumes that the installation of end-of-pipe technology does not involve any setup costs. If it did, the technology is profitable only if the carbon price exceeds the *average* cost of abatement.

[50] The sign of $\partial L^*/\partial t$ depends on the shape of the demand curve and the marginal cost of abatement, so it is ambigious whether a higher carbon price increases or decreases leakage—just as in Proposition 5.

firms' output can be calculated using the formulae from Propositions 1 and 4 (with carbon costs $k^*(t) = t\omega_I$). Moreover, the 50% benchmark on output leakage from Propositions 2 and 3 continues to apply. Overall, therefore, the basic insights from the benchmark model extend to the case with end-of-pipe abatement technologies.

IV. Free permit allocations and relocation of production facilities. Much of the policy debate around cap-and-trade schemes revolves around the degree to which emissions permits are freely allocated to firms as a central design feature of such schemes. There are usually two arguments made in favour of free allocations (as opposed to auctioning permits): first, the political-economy argument that a more free permits ensure greater "buy in" to climate policy by industry, and, second, the environmental argument that free allocation reduces carbon leakage.[51]

I now argue that the latter point is correct, but only in a somewhat limited sense. Note first that all results on carbon leakage up to this point in the paper are entirely driven by the impact of environmental regulation on firms' decisions at the margin. Inside firms experience an increase in their costs, which induces them to cut output and emissions. In response, outside firms typically expand their market share and emissions, leading to a degree of carbon leakage.

These conclusions apply equally to regulation in form of a carbon tax or for a cap-and-trade scheme in which emissions permits are fully auctioned. They also apply to a cap-and-trade scheme in which some (or all) permits are freely allocated by way of "grandfathering" based on firms' historical emissions—as has been the case in the EU ETS since 2005, for example. The reason is that regulated firms here still face the opportunity cost of *not* selling the permits they have received for free. Therefore, all else equal, the results up to here are independent of the level of grandfathering.

Such free allocation can, however, make a difference if regulated firms can relocate their production facilities to somewhere not covered by emissions trading. Then a sufficiently large amount of free allocation can prevent (or defer) such relocation, and may thereby prevent higher carbon leakage.[52] Perhaps the key point from my analysis is that leakage rates can be high even without any production relocation, so grandfathering may only have limited bite in terms of reducing carbon leakage. A simple numerical example makes the point most clearly: suppose that leakage for an industry without any relocation of production facilities is 30% (from the benchmark model), and that this figure becomes 50%

[51] Of course, there are other arguments for auctioning permits, for instance that this allows permits to go to those who value them most highly and that governments can use the auction revenue to reduce debt and distortions in the economy. See also Hepburn, Quah and Ritz (2009) for an analysis of "profit-neutral" permit allocations in a similar setting to this paper (in which all firms are regulated).

[52] Relatedly, free permit allocations could play a similar role in a model in which the entry and exit decisions of firms are explicitly treated.

if one regulated firm decides to relocate. A sufficiently large free allocation can prevent relocation, and thus reduce carbon leakage from 50% to 30%—but not any further than that. Any free allocation beyond this level increases firm profits but has no further impact on carbon leakage.[53]

9 Conclusions

Carbon leakage is a major concern of policymakers involved with environmental initiatives such as the EU ETS and proposed cap-and-trade schemes in Australia, New Zealand, the United States, and elsewhere. With the exception of certain markets in which competition is geographically limited (for example, due to transport issues or other regulatory restrictions), leakage issues are potentially relevant for a wide range of emissions-intensive industries such as aluminium, cement, oil and gas, pulp and paper, steel, and others. The absence of a level playing field among firms in these sectors can significantly undermine climate policy effectiveness.

This paper has provided a framework to understand the drivers of carbon leakage for an industry, based on an "ABC" decomposition of leakage three underlying channels. The formulae obtained can be implemented empirically using information that is typically available to the analyst (or can at least be estimated), making the approach suitable for *ex ante* analysis. An important feature of my modelling approach is that it does not impose any significant *a priori* restrictions on the sign or magnitude of carbon leakage. The framework provides a natural starting point for more detailed analysis of any particular sector (to be) covered by market-based climate policy.

In general, industry characteristics matter a lot, so leakage rates may vary considerably across sectors—such as those included in a multi-sector cap-and-trade scheme. However, the analysis shows that output leakage exceeds 50% under fairly weak conditions, and can be substantial even if only a small proportion of an industry is not covered by regulation. Whenever unregulated firms are no less emissions-intensive than regulated firms in the industry, this translates into carbon leakage rates that are at least as high. Importantly, however, even relatively small environmental-efficiency improvements by regulated firms can reduce leakage rates significantly, suggesting that these also deserve considerable attention in policy analysis.

The overall welfare effect of incomplete environmental regulation is ambiguous; amongst other things, it depends on the weight given to different stakeholders in the calculation and on the degree of carbon leakage. However, although leakage rates can be negative in

[53]However, additional effects may also emerge whenever the method of free allocation is more complicated than grandfathering (which is equivalent to a lump-sum transfer to firms), notably in settings where permit allocations depend on current output and emissions.

some circumstances, and exceed 100% in others, in many relevant cases they are probably in between. So the emissions reductions achieved by regulated firms are (only) *partially* offset by emissions increases from unregulated firms—and global carbon emissions can indeed be expected to decrease as a consequence of unilateral regulation.

Current policy analysis of whether a sector is "at risk" of carbon leakage mainly revolves around two key metrics, "carbon costs" (sometimes called "emissions intensity") and "trade exposure".[54] However, while insightful, my analysis shows that these criteria alone are not sufficient. To see why, suppose that industry Y and industry Z are identical in terms of firms' market shares, emissions intensities, and so on, except that competitive conduct in industry Y is tougher. Then carbon leakage is likely to be significantly higher in industry Y than in industry Z—even though they may appear to be interchangeable on the carbon cost and trade criteria alone. My analysis suggests that incorporating such additional industry features may be important.

Appendix

Proof of Proposition 1. In equilibrium, each inside firms' unit cost of production increases by $k^*(t) = t\omega_I^*(t) + \varphi^*(t)$, where $k^*(0) = 0$ at a zero carbon price, $t = 0$. To first order, the inside firms' equilibrium change in output $\Delta X_I^* = X_I'(0) \cdot k^*(t)$, where $X_I'(0) = [dX_I^*(k)/dk]_{k^*(0)=0}$, and, similarly, $\Delta X_O^* = X_I'(0) \cdot k^*(t)$, where $X_O'(0) = [dX_O^*(k)/dk]_{k^*(0)=0}$ for the outside firms. Note also that the outside firms' equilibrium output depends on the carbon price only indirectly as they are not covered by the regulation, $X_O^*(k) = X_O^*(X_I^*(k))$, so $X_O'(0) = [dX_O^*/dX_I^*]_{k^*(0)=0} \cdot X_I'(0)$. Now summing the N_O first-order conditions $\partial\Pi_O^i/\partial x_O^i = 0$ for the outside firms yields $N_O f(X^*) - \sum_{i=1}^{N_O} c_O^i + f'(X^*)X_O^* = 0$. Differentiating this expression gives the slope of the outside firms' (combined) best response curve as

$$\left.\frac{dX_O^*}{dX_I^*}\right|_{k^*(0)=0} = -\left[\frac{N_O f'(X^*) + \sigma_O^* f''(X^*)X^*}{(N_O+1)f'(X^*) + \sigma_O^*(t) f''(X^*)X^*}\right], \tag{9}$$

where their market share $\sigma_O^* = X_O^*/X^*$. Recalling the definition of the strategic effect $\lambda_O = N_O + \sigma_O^*\left[f''(X^*)X^*/f'(X^*)\right]$ and some simplifying yields that shows that $-\Delta X_O^*/\Delta X_I^* = \lambda_O/(\lambda_O+1)$ as claimed.

Proof of Proposition 2. The rate of output leakage exceeds 50% if and only if $\lambda_O \geq 1$.

[54] For example, under proposals for the post-2012 design of the EU ETS, a sector is deemed "at risk" of carbon leakage if it exceeds certain thresholds of carbon costs (including both direct and indirect costs) and trade intensity (non-EU imports and exports). Similar methods for determining carbon leakage are also being considered for Australia's CPRS and by cap-and-trade proposals in the United States.

Recalling the definition of the strategic effect $\lambda_O = N_O + \sigma_O^* [f''(X^*)X^*/f'(X^*)]$, this is equivalent to

$$-(N_O - 1) \leq \sigma_O^* \frac{f''(X^*)X^*}{f'(X^*)}. \tag{10}$$

Note that the left-hand side of this expression is non-positive.

Condition (i) holds since the right-hand side of the expression is clearly positive if the demand curve is concave or linear (since then $f''(X^*) \leq 0$). By contrast, if demand is convex (so $f''(X^*) > 0$), the right-hand side is negative, but *less* negative than only $f''(X^*)X^*/f'(X^*)$, since the outside firms' market share $\sigma_O^* \in (0,1)$. Condition (ii) holds since log-concavity of the direct demand curve $f^{-1}(p^*)$ is equivalent to $f''(X^*)X^*/f'(X^*) \leq -1$, so the expression clearly is satisfied if $N_O \geq 2$. Condition (iii) holds similarly since downward-sloping industry marginal revenue is equivalent to $f''(X^*)X^*/f'(X^*) \leq -2$, so the expression is clearly satisfied if $N_O \geq 3$. Condition (iv) holds since the left-hand side of the expression becomes arbitrarily negative as N_O increases, while the right-hand side is bounded below since $f''(X^*)X^*/f'(X^*)$ is bounded below by assumption and $\sigma_O^* \in (0,1)$.

Proof of Proposition 3. For part (i), recall that output leakage $-\Delta X_O^*/\Delta X_I^* = \lambda_O/(\lambda_O + 1)$ by Proposition 1. It is easy to check that for a given market structure (that is, fixed N_O and σ_O^*), this is increasing in demand curvature $f''(X^*)X^*/f'(X^*)$, so output leakage is higher for more concave demand. The claim now follows since the rate of cost pass-through $\rho^* = N_I/(\lambda_I + \lambda_O + 1)$ is lower for more concave demand. For part (ii), note from the proof of Proposition 2 that output leakage certainly exceeds 50% if $-(N_O - 1) \leq f''(X^*)X^*/f'(X^*)$. Using $f''(X^*)X^*/f'(X^*) = N_I/\rho^* - (N_I + N_O + 1)$ to express this condition in terms of pass-through gives $-(N_O - 1) \leq N_I/\rho^* - (N_I + N_O + 1)$, and some rearranging shows that this is equivalent to $\rho^* \leq N_I/(N_I + 2) \equiv \overline{\rho}$, as claimed.

Proof of Proposition 4. To first order, from the proof of Proposition 1, the inside firms' equilibrium change in output $\Delta X_I^* = X_I'(0) \cdot k^*(t)$, where $X_I'(0) = [dX_I^*(k)/dk]_{k^*(0)=0}$. Note also that $X_I'(k) = dX_I^*(k)/dk = \partial X_I^*(k)/\partial k + [dX_I^*/dX_O^*][dX_O^*(k)/dk]$ and, similarly, $X_O'(k) = dX_O^*(k)/dk = [dX_O^*/dX_I^*][dX_I^*(k)/dk]$ (since $\partial X_O^*(k)/\partial k = 0$). Combining these two expressions yields that

$$X_I'(0) = \left[\frac{\partial X_I^*(k)/\partial k}{1 - \frac{dX_I^*}{dX_O^*} \cdot \frac{dX_O^*}{dX_I^*}} \right]_{k^*(0)=0}, \tag{11}$$

where $\partial X_I^*(k)/\partial k$ gives the partial response of the insiders' output along their (aggregate) best response curve, and the denominator determines the full adjustment to equilibrium, taking into account the slopes of both the inside and outside firms' best responses. Now summing the N_I first-order conditions $\partial\Pi_I^j/\partial x_I^j = 0$ for the inside firms yields $N_I f(X^*) - \sum_{j=1}^{N_I} \left[c_I^j(0) + k^*(t)\right] + f'(X^*)X_I^* = 0$. Differentiating this expression yields that

$$\left.\frac{\partial X_I^*(k)}{\partial k}\right|_{k^*(0)=0} = \frac{N_I}{(N_I+1)f'(X^*) + \sigma_I^* f''(X^*)X^*}, \tag{12}$$

where $\sigma_I^* = X_I^*/X^*$, or, equivalently, $[\partial X_I^*(k)/\partial k]_{k^*(0)=0} = N_I/f'(X^*)(\lambda_I+1)$. From the proof of Proposition 1, the slope of the outside firms' best response curve $dX_O^*/dX_I^* = -\lambda_O/(\lambda_O+1)$, and analogously, for the inside firms, $dX_I^*/dX_O^* = -\lambda_I/(\lambda_I+1)$. Putting these results together shows that

$$\Delta X_I^* = \frac{N_I(\lambda_O+1)}{f'(X^*)(\lambda_I+\lambda_O+1)} k^*(t). \tag{13}$$

Finally, again from the inside firms' first-order conditions, their equilibrium output at a zero carbon price $X_I^* = N_I \bar{\mu}_I^*(0)/f'(X^*)$, where $\bar{\mu}_I^*(0) \equiv \frac{1}{N_I}\sum_{j=1}^{N_I}\left[p^*(0) - c_I^j\right]$ is the inside firms' average operating profit margin. Combining this with the expression for ΔX_I^* yields that $-\Delta X_I^*/X_I^* = [k^*(t)/\bar{\mu}_I^*(0)] \cdot [(\lambda_O+1)/(\lambda_I+\lambda_O+1)]$, as claimed.

Proof of Proposition 5. Recalling the decomposition of carbon leakage from Lemma 1, note that the first channel is independent of the carbon price, and, from Proposition 1, that the second channel, to first order, also does not depend on the carbon price. The third channel, however, depends on the carbon price via the term $\Omega \equiv \Delta\omega_I/\omega_I\,(X_I/\Delta X_I + 1) \geq 0$. In particular, $\partial L^*/\partial t \geq 0$ if and only if $\partial\Omega/\partial t \geq 0$. Straightforward differentiation shows that this holds in equilibrium whenever $\epsilon_X \geq \epsilon_\omega\,(1 + \Delta X_I^*/X_I)$, where $\epsilon_\omega \equiv d\log(-\Delta\omega_I)/d\log t$ and $\epsilon_X \equiv d\log(-\Delta X_I)/d\log t$, as claimed.

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