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# CARBON COST PASS-THROUGH IN INDUSTRIAL SECTORS

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# Carbon cost pass-through in industrial sectors

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To achieve the ambitions of the 2015 Paris Climate Agreement, the decarbonization of energy-intensive industrial sectors is becoming increasingly important. This paper focuses on the economics of carbon cost pass-through: the change in product prices induced by carbon pricing. We provide a theoretical framework to understand pass-through at the sectoral level and a constructive review of the empirical evidence from the EU ETS and other jurisdictions. Our analysis is structured around three key drivers: international trade, market structure, and free allowance allocation. We provide a synthesis of our key findings for policymakers and identify gaps in the literature for future research.

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## 1 Introduction

The European Union's Emissions Trading Scheme (EU ETS) has now been in operation for almost 15 years since its pioneering launch in January 2005. Since then, jurisdictions around the world have introduced carbon pricing to help combat climate change. As of mid-2019, 57 such policies account for 20% of global $CO_2$ emissions (World Bank, 2019). This number looks set to grow notably as developing countries follow up on their commitments to the 2015 Paris Agreement.

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Pigou (1920) already pointed to the social value of using prices to internalize environmental externalities and thus achieve socially efficient outcomes. A carbon price implies that each regulated firm's marginal cost of production rises according to the emissions intensity of its production technology. This puts upward pressure on product market prices and corresponding downward pressure on demand and consumption. It also creates an incentive for firms to switch to cleaner inputs and adopt low-carbon technologies. We refer to this efficient policy outcome as Pigouvian full carbon price internalization.

This theoretical benchmark is based on a set of (implicit) assumptions. First, the carbon price is set at the social cost of carbon—or at a "target-consistent" level—that reflects global climate damages from additional emissions. Second, the carbon price applies to all firms that compete in the same product market. Third, each firm faces the full carbon price on its emissions, with no watering down e.g. by way of freely allocated allowances or compensation for $CO_2$-price-induced increases in electricity prices. Fourth, each emitter efficiently incorporates the carbon price into its internal decision-making on production and investment. Fifth, product markets are perfectly competitive with the market clearing price set by the marginal producer's production cost plus carbon cost.

Real-world climate policy currently falls short of this Pigouvian benchmark. Carbon prices, where they exist, are mostly well below estimates of social cost. Moreover, where firms in one jurisdiction are subject to a carbon price, their rivals in other jurisdictions may not be. Our analysis focuses on industries producing basic materials such as steel, cement, and aluminium—which account for around 25% of global carbon emissions (IEA, 2017). In Europe, these industries are covered by the EU ETS but compete with imports into the EU from less regulated regions. As a result, such emissions-intensive trade-exposed (EITE) sectors face the risk of carbon leakage and are often granted a free allowance allocation in an attempt to compensate for an uneven competitive playing field.

From an empirical perspective, however, it is challenging to quantify the extent of this policy gap. While the level of carbon prices is readily observed, other metrics like the degree to which competing firms are covered by carbon pricing, how well they incorporate carbon into their internal decision-making, and the extent to which product markets are competitive are much more difficult to precisely ascertain.

The degree of carbon cost pass-through by regulated firms offers a proxy to understand how policy departs from full carbon price internalization. The pass-through rate captures by how much the product market price rises if carbon pricing raises the marginal cost of production in a sector by $1. An important observation is that pass-through, as a market-driven measure, will reflect the impacts of many less-observable policy features. For example, if a subset of firms is not covered by carbon pricing, then this will be reflected in market prices—and hence in the degree of pass-through. Similarly, pass-through will reflect if carbon prices are not efficiently internalized by firms or if the product market is not perfect competitive. Under full carbon price internalization, pass-through rates should typically be close to 100%.

In this paper, our objective is to help policymakers find a shared understanding of the economics of carbon cost pass-through. With 15 years of real-world experience with carbon pricing, now seems a good time to take stock of what has been learned. Section 2 provides a synthesis of the policy implications of carbon cost pass-through. Section 3 presents a simple theoretical framework to understand the drivers of carbon pass-through for an individual industry. Section 4 provides a constructuve overview of the empirical evidence from the EU ETS and other jurisdictions. Section 5 concludes and identifies gaps in the literature for future research.

## 2 Policy synthesis

We here provide a synthesis aimed at policymakers based around answers to a set of questions. These combine insights from our theoretical framework with our review of empirical evidence on carbon cost pass-through. We also make suggestions for future policy and research.

*What is Pigouvian "full carbon price internalization"?* Following Pigou (1920), "full carbon price internalization" defines a policy design in which a carbon price fully internalizes the climate externality and thereby achieves a socially efficient outcome. This involves all decision-makers—polluting industry and consumers buying intermediate and final products—facing the efficient carbon price. It also hinges on a number of other factors, notably: the carbon price is set at the social cost of carbon (or at the level of the corresponding emissions target); all competing firms face the same carbon price with no exemptions or watering down by way of free allowance allocation; and product markets are perfectly competitive. Full carbon price internalization raises the marginal cost of production, puts upward pressure on product prices, and thereby creates efficient $CO_2$ mitigation incentives along the value chain.

*What is carbon cost pass-through and why does it matter?* Following in the footsteps of Pigou, policymakers are increasingly using carbon prices to help combat climate change. However, carbon prices around the world currently differ widely in their levels and scope. Carbon cost pass-through offers a useful way to think about the state of policy at the level of an individual industrial sector. The pass-through rate captures by how much the market price of a product rises if carbon pricing raises the marginal cost of production in a sector by \$1. A shared understanding of pass-through is relevant for at least two important aspects of policy design. First, pass-through measures the degree to which a carbon price signal is being transmitted along the value chain. This is becoming increasingly critical to decarbonization strategies centred around efficient use of energy and materials to achieve Paris climate objectives. Second, pass-through links to the policy discussion around the risk of carbon leakage and the free allowance allocations used to compensate for an uneven international competitive playing field.

*How does international trade affect carbon cost pass-through?* A robust result from economic theory is that carbon cost pass-through is reduced by the presence of less regulated competitors that are not covered by the carbon price. Empirical evidence confirms this economic intuition. In such cases, international trade means that the scope of the product market is wider than the scope of carbon policy. Empirical estimates of carbon cost pass-through vary widely across countries, time and industrial sectors (including cement, chemicals, glass, oil refining, steel). This heterogeneity may partly reflect differences in market structure, free allocation, and other market characteristics (such as demand and cost conditions, product differentiation, switching costs, and so on). In addition, however, existing pass-through estimates often come with substantial uncertainty, in form of wide statistical confidence intervals. On balance, the available evidence suggests that, in most cases, carbon cost pass-through for industry is likely to be "low"—probably less than 50%. This suggests that current policy likely falls well short of the Pigouvian benchmark of full carbon price internalization.

*How does market structure affect carbon cost pass-through?* Economic theory suggests that, all else equal, a more concentrated market with fewer competing firms will typically lead to a lower rate of carbon cost pass-through. Producers with market power then have an incentive to absorb part of a cost shock so as to maintain higher output and the associated profits. However, this result can be sensitive to the finer details of demand and cost conditions in a market. For example, if pass-through exceeds 100% then greater competition may reduce pass-through (by pushing it down towards 100%). International empirical evidence confirms that, in general, the impact of market structure is ambiguous. Some studies, notably on gasoline markets, find that competition raises cost pass-through while others, notably on cement, find the opposite.

*How does free allowance allocation affect carbon cost pass-through?* A one-off, unconditional lump-sum allowance allocation does not alter market outcomes including prices, relative to auctioning permits, and therefore also does not affect carbon cost pass-through. In practice, allocations are now often partly output-based, in proportion to a benchmark and current production volumes. Firms therefore expect higher current production to lead to a greater allocation in future and take this into account in their decision-making. The implicit output subsidy in effect dampens the carbon price and thus mitigates the increase in the product price—even if the underlying rate of pass-through is unchanged. Allocation conditional on activity thresholds, like in the EU ETS, has a similar but typically less strong effect than output-based allocation. Over the longer term, free allowances can prevent or delay the closure of existing facilities and create incentives for investment in new production facilities. In both cases, the induced additional production will reduce the product price and dampen longer-term carbon cost pass-through.

*What are the policy lessons from carbon cost pass-through for full carbon price internalization?* The trade-off at the heart of allowance allocation is that too much free allocation may lead to windfall profits while too little may raise the risk of carbon leakage. The current empirical uncertainty around the degree of carbon cost pass-through in industry makes it difficult for policymakers to navigate this trade-off. To achieve full carbon price internalization, two other policy options may therefore warrant further consideration. First, a move to full auctioning would avoid the complexities and potential distortions underlying free allocations. This could be combined with a border carbon adjustment that mirrors the domestic carbon price in international trade. Second, a climate charge on consumption can have a similar economic effect. It could be levied per ton of material sold to final consumers, using the same benchmarks underlying free allocation of allowances to production. In theory, both options can reinstate full carbon price internalization.

*What research needs result from analysis on carbon cost pass-through?* Important research needs remain on carbon cost pass-through. First, the empirical analysis of pass-through in industrial sector would benefit from the availability of higher-frequency firm-level data on prices, costs and other metrics. This would help the literature go beyond simple time-series approaches and sharpen the confidence intervals around pass-through estimates. Second, a practice of *ex ante* announcements of study design could help resolve concerns about reporting bias (that might result if findings that do not align with stakeholder interests or are not significantly different from zero are not published). Third, theory and empirics could be used together more closely to understand how pass-through estimates based on historical data inform projections about the future—in which market structure and other factors may differ. Fourth, only little is currently known empirically about the pass-through effects of different forms of free allocation and about the internalization of carbon prices into decision-making inside firms (outside the electricity sector). Finally, as carbon pricing continues to spread around the world, more work is needed beyond the EU ETS which has to date dominated the literature.

# 3 Theoretical framework

We begin with a simple model that helps understand the drivers of carbon cost pass-through. We adopt a partial-equilibrium approach as our interest is in an individual sector that is part of a wider carbon-pricing system. A key feature of the setup is that the carbon price covers only a subset of firms in the industry, that is, the scope of regulation falls short of the scope of competition. For example, a carbon price may be local while competition in an industry is global or regulation applies to domestic producers while consumers are also served by imports from less regulated foreign suppliers. Our objective is to use a simple model to clearly bring out the roles of market structure, international trade and free allocation as drivers of carbon cost pass-through. As we further discuss in the extensions, the main insights from the model are robust to relaxing many of the simplifying assumptions.

Our model relates to two main strands of literature. First, industrial-organization papers including Bulow & Pfleiderer (1983), Kimmel (1992) and Weyl & Fabinger (2013) derive theoretical pass-through results with an emphasis on the role of market structures in the case where a cost shock applies symmetrically to all firms. Our model further develops results for Cournot competition in which only a subset of firms is exposed to a cost shock. Second, in the environmental-economics literature, papers including Demailly & Quirion (2006) derive pass-through expressions with a focus on different allocation approaches and carbon leakage. A Cournot-based approach along similar lines to ours has been widely used in the literature to study emissions-intensive industries such as electricity, cement, steel and aviation.

## 3.1 Setup of the model

Consider an emissions-intensive industry with a total of $N$ firms, of which $N_I \geq 1$ "inside" (regulated) firms face the introduction of a carbon price $\tau$ while $N_O \geq 1$ "outside" (unregulated) firms do not (where $N \equiv N_I + N_O$).

An inside firm $j$ produces $x_I^j$ units of output which lead to emissions $e_I^j$, where $z_I = e_I^j / x_I^j$ is its emissions intensity of output (assumed to be fixed and identical across inside firms). Similarly, an outside firm $i$ produces $x_O^i$ units of output with emissions $e_O^i$ at a common emissions intensity $z_O = e_O^i / x_O^i$. The potential asymmetry of emissions intensities between inside and outside firms ($z_I \neq z_O$) will play an important role. Let $X_I \equiv \sum_{j=1}^{N_I} x_I^j$ and $E_I \equiv \sum_{j=1}^{N_I} e_I^j$ denote the aggregate output and emissions of inside firms, and define $X_O$ and $E_O$ analogously for the outside firms. Hence global emissions are $E \equiv E_I + E_O$

Firms produce a homogenous product and face a linear inverse demand curve $p(X) = \alpha - \beta X$, where $X \equiv X_I + X_O$ is total industry-wide production, $\alpha$ is a parameter that reflects the level of demand, and $\beta$ is an inverse measure of the size of market.

We assume that all $N$ firms have the same linear marginal cost of production (excluding any carbon costs), as given by $C'(x_I^j) = c + m x_I^j$ for inside firm $j$ and analogously for the outside firms. The parameter $c$ reflects the level of marginal cost and $m$ its slope. Higher values of $m$ mean that production gets increasingly costly for higher output. The term $h \equiv m/\beta$ will be a useful measure of the extent of production constraints in the industry; it sets the slope of marginal cost $m$ against the slope of demand $\beta$.

We consider different types of free allocation of allowances $A^j$ that an inside firm may receive in a cap-and-trade system. First, under grandfathering, free allocation $A^j_{\mathrm{GF}}$ is based on its historical emissions and is therefore economically equivalent to a lump-sum transfer. Second, under output-based allocation (OBA), free allocation $A^j_{\mathrm{OBA}}$ is based on its current output so that $a_I = A^j_{\mathrm{OBA}}/x^j_I$ is its per-unit allocation (again equal across inside firms) and thus corresponds to an output subsidy. Inside firm $j$'s overall marginal cost of production is therefore $c+mx^j_I+\tau z_I$ under grandfathering and $c+mx^j_I+\tau(z_I-a_I)$ under OBA. Thus define $k_I(\tau) \equiv \tau(z_I - \phi_I a_I)$ as the marginal carbon cost where $\phi_I \in [0,1]$ is a parameter that captures the output effect of free allocation, where $\phi_I = 0$ under grandfathering and $\phi_I = 1$ under OBA. Intermediate allocations with dynamic effects are nested where $\phi_I \in (0,1)$; for example, higher output "today" may raise the prospect of more free allocation "tomorrow".

We assume that competition in the industry is à la Cournot, with each firm maximizing its own profit by choice of its level of output. The profit of inside firm $j$ is given by $\Pi^j_I = px^j_I - C(x^j_I) - \tau e^j_I + \tau A^j$, where the first term is its product-market revenues, the second is production costs, the third is carbon costs, and the final term is the value of its free allocation. Similarly, an outside firm $i$ makes profit $\Pi^i_O = px^i_O - C(x^i_O)$. A sufficient condition for an interior solution is that $\alpha > c + k_I$. We think of firms' output decisions as being roughly reflective of annual production choices.

The basic trade-off for inside firms is between protecting their profit margins or their market share. The model resolves this trade-off based on the standard logic of equalizing marginal revenue with marginal cost. In terms of the theory of environmental economics, this is equivalent to each inside firm equating the carbon price with its marginal abatement cost (i.e., the forgone profit from a marginal reduction in its emissions).

## 3.2 The economics of carbon cost pass-through

In the model, carbon pricing is always successful at reducing the emissions of inside firms $E_I$. Given the assumption of fixed emissions intensities, this occurs by way of output reductions, i.e., lower $X_I$. The flipside of the downward pressure on output is upward pressure on price.

We define the rate of carbon cost pass-through $\rho$ as the change in the equilibrium market price $p(\tau)$ resulting in response to the induced increase in the inside firms' carbon cost $k_I(\tau)$, that is:

$$\rho \equiv \frac{dp(\tau)/d\tau}{dk_I(\tau)/d\tau}.$$

This relative metric is unit-free and easy to interpret. The absolute magnitude of the change in the market price follows immediately as $dp = \rho \times [dk_I(\tau)/d\tau] \times d\tau$.

It will be useful to define $s \equiv N_O/N \in (0,1)$ as the share of unregulated firms in the total number of firms. This metric captures the degree to which carbon regulation is incomplete due to international trade. In the special case of a "small" carbon price, this is equivalent to the product market share of unregulated firms. By construction, at an initial carbon price of zero, $\tau = 0$, inside firms and outside firms are symmetric with identical cost structures. Therefore, they have identical equilibrium market shares. So the combined market share of outside firms is equal to $s = [X_O/X]_{\tau=0}$.

We thus obtain our first result:

**Proposition 1** *The equilibrium rate of carbon cost pass-through is given by:*

$$\rho = \frac{N_I}{(N_I + N_O + 1 + h)} = (1-s)\frac{N}{(N+1+h)} \equiv \rho(N, s, h) \in (0, 1).$$

Proposition 1 shows that carbon cost pass-through is always positive but less than 100%. It is driven by three forces: the industry's market structure as captured by the total number of firms $N$, the degree of international trade $s$ (and hence incompleteness of regulation), and production constraints as captured by $h \equiv m/\beta$.

The comparative statics are intuitive. First, a larger number of firms $N$ corresponds to greater competition for which the market price more closely tracks marginal cost—and so cost pass-through is closer to 100%. Put the other way, in a less concentrated market with fewer firms, there is greater market power and incentive to absorb part of the cost shock.

Second, a larger share of outside firms $s$ means that the cost shock affects a smaller subset of the industry; this limits the scope of carbon cost pass-through. In the limit, as the unregulated firms dominate the market, equilibrium pass-through becomes very small (i.e., $\rho \to 0$ as $s \to 1$). (A larger $s$ is also associated with a greater rate of carbon leakage to outside firms.)

Third, pass-through is also lower for an industry that faces greater production constraints, that is, a higher value of $h$. This means that production is less flexible to respond to changes in market conditions—which translates into a smaller price change. In the limit, as the industry's capacity constraint becomes binding, equilibrium pass-through becomes very small (i.e., $\rho \to 0$ as $h \to \infty$). Another way to think about this is that the carbon price reduces the output of an inside firm; whenever $h > 0$, this effect then reduces the (equilibrium) marginal cost—which in turns tends to dampen pass-through relative to the case with $h = 0$.

In the special case of complete regulation ($s = 0$) and no production constraints ($h = 0$), pass-through $\rho = N/(N + 1)$; this is a standard result for the Cournot-Nash model in which a cost shock is market-wide (see, e.g., Kimmel 1992). If, in addition, there are many firms in the industry so that it becomes perfectly competitive, then carbon cost pass-through tends to 100% as expected (i.e., $\rho \to 1$ as $N \to \infty$ with $s = h = 0$).

As a numerical example, suppose that the market structure is characterized by eight firms in total ($N = 8$), of which three are regulated ($N_I = 3$) and five are unregulated, serving the market by way of international trade ($N_O = 5$) so that $s = 62\frac{1}{2}\%$. Suppose that production constraints exist but are modest ($h = 1$). Using Proposition 1, carbon cost pass-through $\rho = 30\%$ showing that, in equilibrium, inside firms bear a greater fraction of the cost shock than consumers.

It is also worth being clear about what equilibrium pass-through does *not* depend on. Proposition 1 reveals that the level of demand $\alpha$, the level of marginal cost $c$, and the level of the carbon price $\tau$ itself have no impact on the pass-through rate (neither individually nor jointly). Varying these parameters shifts firms' marginal revenue and/or marginal cost—and thereby affects the firms' first-order conditions and hence the equilibrium market price. The point, however, is that they have no impact on the *slope* of the first-order conditions and this is what drives firms' optimal adjustment to *changes* in the carbon price—and hence equilibrium pass-through.

Finally, the rate of pass-through is identical for grandfathering and OBA. These lead to different cost shocks but the rate at which a same-sized shock translates into a higher price is the same. However, there is a wedge in terms of the absolute price increase, $dp = \rho \times [dk_I(\tau)/d\tau] \times d\tau$. The output subsidy baked into OBA mitigates the cost shock $dk_I(\tau)/d\tau$ and so OBA nonetheless mitigates the product price increase.

**A Pigouvian perspective**. It is useful to consider the theory through the lens of Pigou (1920), by splitting carbon cost pass-through into three components. First, policy failure: does the carbon price cover all firms? If it does not, then the environmental externality is not fully priced at its social cost. In our model, this is represented by a positive share of unregulated firms and international trade $s > 0$. Second, behavioural failure: do regulated firms full internalize the carbon price? This is a maintained assumption in our model—and almost all of the economics literature. Underlying it is the idea that firms (i) base their product-market decisions on marginal analysis, and (ii) understand the concept of opportunity cost: even if they have received free allocation, surrendering these is still costly. Third, market failure: are the markets in which polluting firms operate otherwise efficient? Our model allows for imperfect competition in the product market, as captured by the number of firms $N < \infty$. As we have seen, the intensity of competition influences pass-through—in addition to demand and cost conditions. The Pigouvian benchmark assumes that the environmental externality is fully priced (no policy failure), fully internalized by firms (no behavioural failure), and then priced into a competitive product market (no market failure). Our pass-through model generalizes this to allow for the additional channels of market structure and international trade.

## 3.3 Extensions to the model

The baseline model is deliberately simple so as to clearly bring out key features of carbon cost pass-through. We next discuss a number of extensions that bring additional richness to the analysis. These suggest that the main qualitative insights are reasonably robust to changes in model specification.

### 3.3.1 Pre-existing carbon prices

For expositional reasons, the baseline model considers a carbon price $\tau_I$ for regulated firms being tightened while others firms face a zero carbon price. However, Proposition 1 holds in exactly the same way in with pre-existing carbon prices $\tau_I, \tau_O > 0$ for inside and/or outside firms. Such pre-existing regulation changes inside and/or outside firms cost structures, and thus leads to a change in the equilibrium. However, as is clear from Proposition 1, pass-through is driven by firms' responses at the margin to a higher inside carbon price $\tau_I$. These are determined by the *slopes* of marginal revenue and marginal costs. Pre-existing carbon prices leaves the slopes unchanged—and thus does not alter pass-through.

### 3.3.2 Asymmetric cost structures

The baseline model assumes that, apart from carbon-related costs, the cost structures of inside and outside firms are identical with marginal cost $C'(x_I^j) = c + mx_I^j$ (and analogously for outside firms). Again, the expression for carbon cost pass-through from Proposition 1 is significantly more general. For example, allowing for asymmetric marginal cost components $c_I^j$ and $c_O^i$ would lead to exactly the same result. The reason is again that this does not affect firms' optimal responses at the margin.

Two other assumptions are more involved. First, incorporating asymmetries in the production constraint (different $m$) would make the model more difficult to solve—but the basic intuition that these tend to dampen pass-through is likely to be very robust. Second, incorporating asymmetric carbon cost shocks (different $dk_I(\tau)/d\tau$) would lead to the additional effect that relatively clean inside firms experience above-average pass-through.

### 3.3.3 Emissions abatement

The baseline model assumes that regulated firms' emissions intensity $z_I$ is fixed. This feels like a reasonable approximation for many emissions-intensive markets in which the scope to switch inputs and adopt new production technologies is limited in the short run (e.g., from year to year). Over time, the link between emissions and output will become weaker. By revealed preference, a regulated firm that switches to cleaner inputs mitigates the cost shock it experiences due to carbon pricing. A key point, however, is that for any given abatement-adjusted cost shock (maintaining the assumption of symmetry among inside firms), the *rate* of carbon pass-through will remain exactly as in Proposition 1.

### 3.3.4 Firm entry and exit

The baseline model is a short-run description in that firm numbers $N_I, N_O$ are fixed. More generally, asymmetric carbon prices can induce exit of regulated firms and perhaps also new entry both of new low-carbon entrants and new unregulated players. Free allowance allocations, in turn, can prevent or delay exit of regulated players. The pass-through effects of any such endogenous changes to market structure are ambiguous in general. There are two types of effects: (1) entry or exit causes a discrete drop or jump in the market price; (2) pass-through is affected by then different firm numbers, $N_I$ and/or $N_O$.

### 3.3.5 Non-linear demand

The baseline model makes the standard assumption that firms face a linear demand curve. Existing literature such as Bulow & Pfleiderer (1983) show that pass-through will tend to be lower (higher) than this benchmark if demand is concave (convex). With sufficiently convex demand, it is possible for pass-through of a common cost shock to all firms to exceed 100%; in this case, a less concentrated market (lower $N$) may therefore deliver *weaker* pass-through. Nonetheless, our findings that carbon pass-through is lower for a greater share of unregulated players (higher $s$) and greater production constraints (higher $m$) are likely to be robust to non-linear demand.

### 3.3.6 Product differentiation and switching costs

Like much of the existing literature on the industrial economics of carbon pricing, the baseline model assumes that firms' products are homogeneous. This is an appropriate simplifying assumption for many emissions-intensive industries in which any product differentiation between firms is likely modest. In other cases, the presence of product differentiation will often tend to mitigate the competitiveness impacts of regulation and raise the degree of carbon pass-through. Loosely put, a higher degree of product differentiation has a similar effect to a reduction in the degree of international trade $s$—the unregulated firms become less relevant. Similarly, the presence of switching costs, which lock consumers into their current suppliers and thereby tend to partially isolate them from unregulated rivals (Klemperer 1995), acts as a form of *ex post* product differentiation and will also tend to enhance pass-through.

### 3.3.7 Forward sales and hedging

The baseline model employs the concept of a static equilibrium in a single period setting. In this interpretation, the cost shock and the resulting price response occur at the same time. In practice, additional temporal considerations arise. Products are often sold forward and input costs are frequently hedged. This may lead to lags in the cost shock "filtering through" as hedges gradually expire and to delays in pass-through as price are "sticky" in the short term. Nonetheless, despite possible short-term frictions, these additional effects do not necessarily alter the equilibrium pass-through.

# 4 Empirical evidence

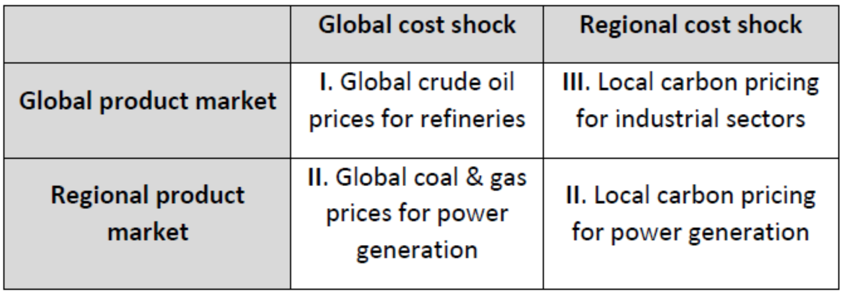
This section provides an overview of the empirical evidence on carbon cost pass-through in the EU ETS and other jurisdictions. We structure the discussion around three drivers of pass-through suggested by our theoretical framework: international trade, market structure, and free allowance allocation. Pass-through evidence splits into the power sector, for which competition is local, and industrial sectors such as steel and cement, for which there is significant international trade.

The literature employs a range of approaches to pass-through estimation. Some papers use time-series analysis on observed EU ETS carbon prices to estimate pass-through. Other papers rely on non-carbon cost shocks, such as variation in fuel prices, as proxies to estimate carbon cost pass-through. Existing literature focuses primarily on the measurement of pass-through by comparing cost increases based on emission intensity of the technology at the margin with product price increases. A smaller number of papers explores the underlying drivers of pass-through. In this sense, the theory and empirics of pass-through complement one another.

## 4.1 The role of international trade

Pass-through, as suggested by Proposition 1, will tend to be reduced if only a subset of players is covered by a carbon price. This economic intuition is confirmed by Muehlegger & Sweeney (2017) in an analysis of different types of cost shocks arising from the fracking boom in the US oil refining industry. Using firm-level data, they find pass-through close to zero of a cost shock specific to a single firm, around 20% for a cost shock in a regional US market, then rising to around 35% for a US-wide shock and, finally, just below 100% for a global cost increase. Importantly, the richness of their data translates into narrow confidence intervals for these four sets of pass-estimates. These findings are broadly in line with Proposition 1 in which, all else equal, pass-through is reduced by a factor of $(1 - s)$ where $s$ is the fraction of players not exposed to the cost shock.

Figure 1, as suggested by these findings, distinguishes four cases in terms of the scope of the product market and the scope of a cost shock. In Case I, an input factor such as crude oil is available to refineries globally at a similar price so the scope of the product market and of any cost shocks are both approximately global. In Case II, trading of a product such as electricity is local (e.g., within the EU) and so competing firms face similar cost shocks irrespective of whether cost shocks are also local (e.g., as in the case



| | Global cost shock | Regional cost shock |
|---|---|---|
| **Global product market** | **I.** Global crude oil prices for refineries | **III.** Local carbon pricing for industrial sectors |
| **Regional product market** | **II.** Global coal & gas prices for power generation | **II.** Local carbon pricing for power generation |

Figure 1: Scope of product market vs scope of cost shock

of the EU ETS) or global (e.g., as for coal and natural gas used as fuel inputs). Finally, in Case III, for many industrial sectors, the scope of the product market is (roughly) global while cost shocks from carbon pricing are currently local. We next summarize the empirical evidence for pass-through in the power sector under the EU ETS (Case II) and then turn to industrial sectors (Case III); thereafter, in our discussion of the role of market structure, we return to settings in which the cost shock corresponds to the product market (Case I).

*Empirical evidence from the power sector under the EU ETS*

The literature on the EU ETS provides significant empirical support for a high degree of carbon cost pass-through in liberalized electricity markets (Sijm et al. (2006), Zachmann & Hirschhausen (2008), Bushnell et al. (2013)). Jouvet and Solier (2013) confirm the overall results, but emphasize the high level of uncertainty of individual pass-through estimates. Hintermann (2016) confirms full pass-through by assessing pass-through rates for individual hours and the relevant marginal generation technology. Fabra & Reguant (2014) present an empirical study that no longer relies on market clearing prices, but uses firm-level data on marginal costs and auction bid prices in the Spanish wholesale electricity market. Consistent with prior literature, they find that emissions costs were almost fully passed on to wholesale prices, with carbon cost pass-through ranging from 80% to 100%.

This near-complete pass-through is explained by special features of competition in electricity markets. First, the high-frequency nature of electricity pricing means that it is routine for firms to adjust their bidding behavior on a daily basis and so any costs of price adjustment are small. Second, a high correlation of cost shocks across firms and the highly inelastic nature of aggregate demand mean that the strategic incentive for a firm to adjust its price-cost markup is limited. Third, although EU ETS electricity generators from 2005 to 2012 received free allowances, it was clear that power production volumes would not impact the level of future free allocation that was based on installed capacity in 2008-2012 and zero subsequently. Theory outlined in Section 3 would therefore suggest that firms price full opportunity carbon cost allowances into their product price. And indeed, the empirical evidence suggests that the EU power sector comes close to the ideal of full carbon price internalization, given the absence of international trade and few other behavioural and market distortions.

While our focus rests on the pass-through of (carbon) cost shocks on input factors to product prices, the results are in line with assessments of pass-through rates of carbon and other taxes levied on fuels to retail prices. Erutku (2019) finds pass-through rates of carbon taxes on gasoline in Canadian provinces on retail prices at and above 100% in line with his literature review.

*Empirical evidence from industrial sectors under the EU ETS*

Due to a shortage of suitable data, quantifying carbon cost pass-through in the EU industry sector has proved to be more challenging than for power. Pass-through estimation, in general, requires disaggregated data on prices and costs for all firms operating in a product market. To establish causality, it also requires plausibly exogenous variation in input costs together with information on how individual firms are exposed to the cost shock. Several studies have bypassed the lack of micro-level data by using time-series data to estimate pass-through at the market-level. Different studies have estimated pass-through in different industries and for different time periods so it is challenging to make any systematic cross-country or cross-industry comparisons is challenging. The paucity of replication studies makes it difficult to gauge the reasons underlying the wide heterogeneity in pass-through estimates. Moreover, prior to de Bruyn et al. (2015), pass-through analysis had been feasible due to data limitations only by using input costs other than the price of EUAs (EU emissions allowances)—except for the refineries industry for which better price data had already been available.

Time-series estimates of carbon cost pass-through for basic materials, vary widely across sectors, countries, and phases of the EU ETS. Oberndorfer et al. (2010) assess the ability of UK producers to pass-through country-specific (non-carbon) input cost shocks to product prices in the glass, chemicals and ceramics sectors. In principle, the pass-through of country or region-specific cost shocks, e.g., from exchange rates, interest rates and electricity & gas prices, should be indicative of similar potential for carbon cost pass-through in situations where production volumes are not the basis of any current or future free allowance allocation (Zachmann, 2008). Similarly, Alexeeva-Talebi (2010) estimates pass-through of domestic cost shocks (labour, material, energy) and finds that German energy-intensive industrials in the paper, chemicals, glass, and cement are able to pass on certain cost shocks. De Bruyn et al. (2015) analyze the extent to which EU ETS carbon costs are passed through to product prices for a range of countries and industries. They estimate significant levels of carbon cost pass-through in cement, iron & steel, and refining. Sartor (2017) estimates carbon pass through for steel and cement using data from 2005-2015, and finds no significant evidence of pass-through for Germany and the

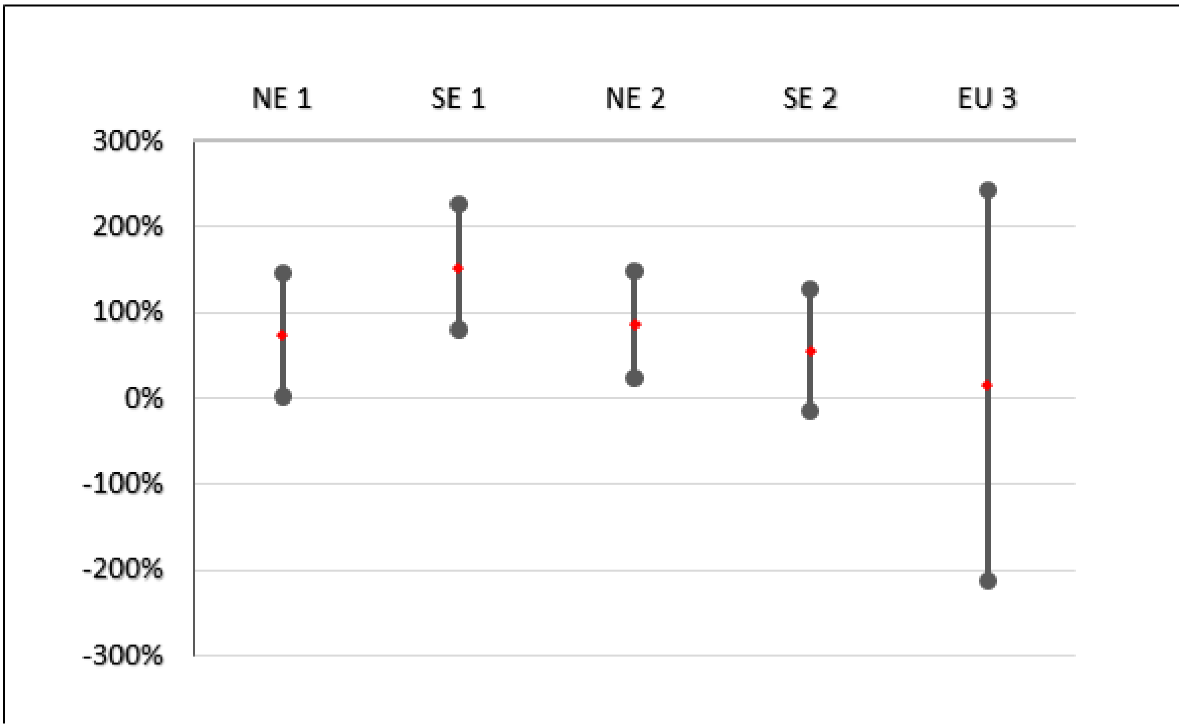


Figure 2: Carbon cost pass-through estimates for the EU ETS steel industry
Notes: NE1, SE1, NE2, and SE2 estimates are based on de Bruyn et al. (2015), while EU3 comes from Sartor (2017). The graph depicts 95% confidence intervals (DIW calculations). NE stands for Northern Europe, SE for Southern Europe, and EU for Western EU. 1 represents Flat Steel Hot Rolled Coil, 2 represents Flat Steel Cold Rolled Coil, 3 represents Western EU Steel Cold Rolled Coil.

UK as well as a barely significant 4% pass-through rate for France. For cold rolled coil-steel over the period 2005-2013, pass-through estimates are statistically indistinguishable from zero. Laing et al. (2014) find carbon cost pass-through rates ranging from 50 to 100% in the refining (diesel and gasoline) sector.

Figures 2 and 3 present key pass-through estimates, respectively, for steel and cement including both point estimates and their associated confidence intervals. This illustrates how pass-through rates appear to differ widely even within the same industry. It also reveals that pass-through estimates often come with substantial uncertainty. In some cases, the confidence levels include zero and 100% pass-through such that little can be ruled out based on the existing evidence.

Carbon cost pass-through estimates for the EU ETS cement industry
Notes: Estimates are taken from de Bruyn et al. (2015). The graph depicts 95% confidence intervals (DIW calculations). 1 represents total cement, 2 represents Portland Cement, 3 represents Clinker, Pooled 4 represents Portland Cement estimates for FR, UK, and DE using an OLS regression from Sartor (2017). UK 1 did not pass a misspecification test.

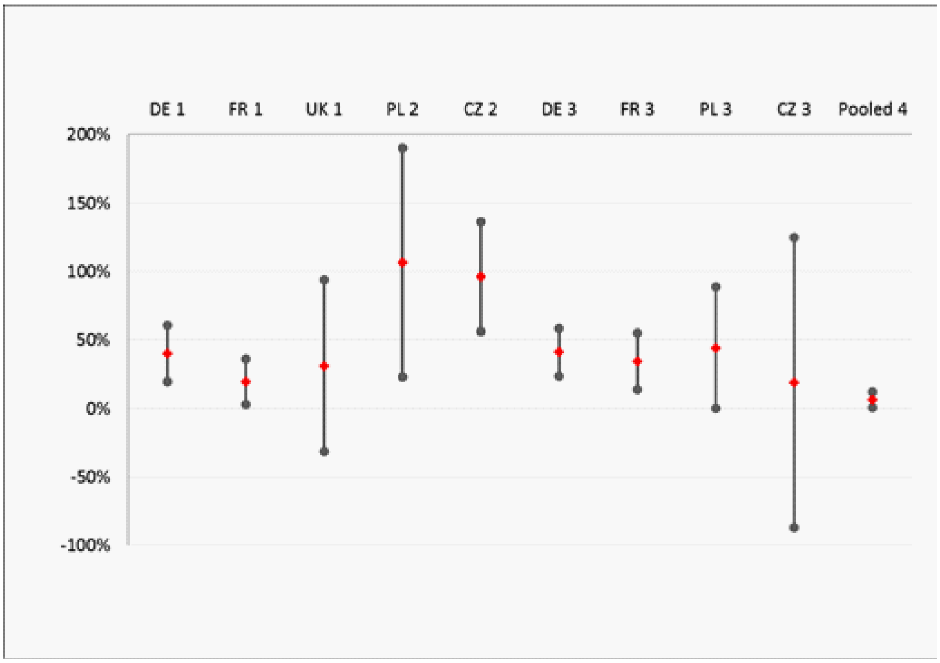


Figure 3: Carbon cost pass-through estimates for the EU ETS cement industry
Notes: Estimates are taken from de Bruyn et al. (2015). The graph depicts 95% confidence intervals (DIW calculations). 1 represents total cement, 2 represents Portland Cement, 3 represents Clinker, Pooled 4 represents Portland Cement estimates for FR, UK, and DE using an OLS regression from Sartor (2017). UK 1 did not pass a misspecification test.

In sum, the empirical evidence for carbon cost pass-through in industry reveals how estimates are highly contingent on time and space; pass-through estimates are typically both small and come with substantial uncertainty. In any case, the available evidence suggests that EU climate policy for industry still falls substantially short of the Pigouvian benchmark of full carbon price internalization.

*Empirical evidence from an EU ETS event study*

Using an event study methodology, Bushnell et al. (2013) estimate the impact of the sharp drop in the EUA price in April 2006 on the stock market valuations of publicly-traded EU ETS firms. This sidesteps the problem of data availability on firm-level marginal costs and product prices. However, to inform the debate on pass-through, it still requires disentangling the effect of the carbon price on the value of grandfathered allowances held by EU ETS firms at the time.

We now provide an *illustrative* pass-through calculation for steel based on Bushnell et al.'s (2013) results. For simplicity, we consider a representative (average) EU firm in the sector and assume that the product market is perfectly competitive. We also assume that the drop in the carbon price affects profits in the current year but then reverts back to its expected trajectory. (The firm's stock market value $V$ at time $t$ can be thought of its discounted profit stream, $V(t) = \Pi(t) + \delta V(t+1)$; our approach considers only $dV = d\Pi$.) Our calculation is (very) short-term in that we allow product prices to adjust but assume that firms' production and emissions are fixed.

The firm's current profits can be written in terms of the carbon price $\tau$ as $\Pi(\tau) = p(\tau)x(\tau) - C(x(\tau)) - \tau e(\tau) + \tau A$, where $A$ is its grandfathered free allocation. The profit impact of a change in the carbon price is therefore given by:

$$\frac{d\Pi}{d\tau} = \rho e(\tau) + [p(\tau) - C'(x(\tau))] \frac{dx(\tau)}{d\tau} - \tau \frac{de(\tau)}{d\tau} + [A - e(\tau)],$$

where $dp(\tau)/d\tau = \rho e(\tau)$ in which $\rho$, as before, is the rate of carbon cost pass-through (as the emissions intensity $z \equiv e/x$). Given the assumption that production $x(\tau)$ and emissions $e(\tau)$ are fixed, we obtain a simplified version: $dV = d\Pi = [(\rho - 1)e + A]\, d\tau$. Rearranging in terms of carbon cost pass-through yields:

$$\rho = \left[ \frac{dV/V}{[(A-e)d\tau]/V} - 1 \right] \frac{(A-e)}{e}.$$

This equation allows us to translate the findings from the event study into implied pass-through estimates. First, using data on firm-level allocation and emissions, Bushnell et al. (2013) calculate firm-level surplus allowance allocations with an average surplus $(A-e)/e = 18\%$. Second, they find that the change in the value of this allowance surplus due to changes in the carbon price corresponds, on average, to $[(A-e)d\tau]/V = 1.3\%$. Third, using variation in the share of firms' sales to the European market, they find that for the average steel firm the carbon price drop resulted in a valuation decline of $dV/V = 1.8\%$. Using these three findings yields an implied rate of carbon cost pass-through of $\rho \simeq 7\%$. While this estimate should be regarded only as a first approximation, it appears in line with other findings in the literature that pass-through in industrial sectors is low.

## 4.2 The role of market structure

Market structure can have a significant impact on cost pass-through. Proposition 1 suggests that a more concentrated market yields lower pass-through as firms with more market power have an incentive to absorb more of a cost shock. However, as discussed in our model extensions, this conclusion can be sensitive to the shape of the demand curve. Therefore, unlike for international trade, microeconomic theory offers no unambiguous guidance on the role of market structure. This is confirmed by Gulli and Chernyavska (2013) based on a review of estimated pass-through rates of carbon prices in European Power markets and potential theoretical drivers.

A small number of recent empirical papers have obtained evidence on the relationship between pass-through of fuel cost shocks and competition using micro-level data. These papers focus on settings in which our two other potential drivers of pass-through—international trade and free allocation—play no role. In the EU ETS context, the empirical evidence is very limited, with Alexeeva-Talebi (2010) finding that higher market power among industrial firms in relatively homogenous product markets is associated with lower domestic cost pass-through.

Some papers find that competition is associated with lower cost pass-through. Ganapati et al. (2019) estimate pass-through of energy cost shocks for six homogenous single-product US manufacturing industries: boxes, bread, cement, concrete, gasoline, and plywood. For industries also represented in the EU ETS, they find considerable inter-industry heterogeneity with cost pass-through of 80% for concrete, above 100% for cement, and 36% for gasoline. In terms of market structure, cement is the industry that appears to be the least competitive but also has the highest pass-through. Miller et al. (2017) obtain a related result in an analysis of fuel cost shocks in the US Portland cement industry; they also estimate that cost pass-through exceeds 100% and further find that a larger number of rivals is associated with weaker pass-through that declines towards 100% with more competition. Similarly, Kopczuk et al. (2016) does not find strong evidence of greater cost pass-through of gasoline taxes in US states with more concentrated wholesale markets.

Some recent work has estimated firm-level pass-through that accounts for differences in firms' production technologies. Grey & Ritz (2018) use fuel cost shocks to estimate pass-through in the context of the US airline industry. The central feature of their empirical analysis is that low-cost carriers such as Southwest tend to fly newer, more fuel-efficient aircraft than the incumbent legacy airlines—so fuel cost shocks are asymmetric. Firm-level pass-through therefore measures how a firm's price responds to a $1 increase in its marginal cost—where its rivals may experience cost shocks of varying magnitudes. They find that firm-level pass-through for Southwest exceeds 100% while average pass-through across legacy carriers is significantly below 100% but only limited evidence for the importance of market structure.

In sum, as already suggested by microeconomic theory, the empirical evidence on the role of market structure as a driver of cost pass-through is mixed. Some papers find evidence for the traditional result that competition intensifies pass-through and others find the opposite.

## 4.3 The role of free allowance allocation

We now to turn to the free allocation of carbon allowances as our final driver of carbon cost pass-through. Free allocation has to date played an important role in ETS design, notably in terms of the debate on international competition and risks of carbon leakage. As an analytical benchmark, if free allowance allocation comprises an unconditional, one-off allocation then it does not alter market outcomes including prices (Coase, 1960; Montgomery, 1972) relative to auctioning permits—and therefore also does not affect rates of carbon cost pass-through. This would be consistent with a grandfathered allocation that is not expected to have any bearing on the future.

Empirical evidence on the role of free allowance allocation is very limited. Fabra & Reguant (2014) address the issue as part of their carbon cost pass-through analysis for the EU ETS power sector. During their sample period in the mid-2000s, electricity generators received a large allocation of grandfathered permits that was often close to sufficient to cover their demand for allowances. Their analysis suggests that market participants indeed did not expect their emissions to impact current or future allowance allocations, which was in line with the free allowance allocation provisions under EU ETS. Moreover, market participants were sufficiently sophisticated to recognize that the option to sell freely allocated allowances represents an opportunity cost—which they fully priced into their decision-making. This is consistent with the Coasian benchmark and suggest that, at least in this case, the role of any behavioural failures on the part of firms was limited.

Given the paucity of empirical evidence, we now discuss other literature that informs the economic principles underlying allocations and the impacts on carbon cost pass-through. In the short-term, the design of free allocation may be "non-neutral" for two sets of reasons:

(1) *Output based allocation (OBA) and other dynamic effects*: Free allocation does affect incentives if a firm's current behaviour has an influence on future allocation or a current allocation is conditional on current behaviour such as its output (Burtraw et al, 2005; Harrison & Radov, 2002). Under OBA, allocation in the current year or subsequent years is proportional to current production volume times a benchmark coefficient. Hence the current marginal cost of production is reduced by the value of implied additional free allocation. As also shown in our theoretical framework, the output subsidy mitigates the increase in the product price (Jensen and Rasmussen 2000).

(2) *Allocation conditional on activity level thresholds*: Since the beginning of EU ETS Phase 3 in 2012, allocation has been conditional on activity levels such as 50%. While this is often not a binding constraint, at times of weak demand and low capacity utilization a firm may have an incentive to keep its output above the trigger level to avoid loss of free allowances. This can motivate pricing below marginal cost and thus also reduce pass-through (Branger et al., 2015).

Over the longer term, free allowance allocation can have several other market impacts. In particular, the prospect of free allowances can prevent or delay the closure of existing facilities and also create incentives for investment in new production facilities (Neuhoff et al., 2006). First, free allocation to an existing facility may push its average cost below the market price and therefore prevent its closure. Second, free allocation to a new installation—irrespective of the precise mode of allocation—reduces its overall production cost. In both cases, the induced additional production will reduce the market price and dampen longer-term pass-through in this sense.

# 5 Conclusions

The economic theory and empirical evidence on carbon cost pass-through in industry can be structured into three drivers. First, on international trade, a robust result from economic theory, confirmed by empirical evidence, is that a larger share of less regulated competitors weakens pass-through. Empirical estimates of cost pass-through vary widely by sector, country, and time period; they are also frequently insignificant due to wide confidence intervals and data-related challenges. Second, on market structure, theoretical guidance is less clear-cut: the traditional view is that competition raises pass-through but this result can be overturned under particular demand conditions. Indeed, empirical work has also found evidence for both views. Third, dynamic or conditional free allocation, such as output-based allocation, tend to water down the carbon cost shock by subsidizing current production—and therefore mitigate the increase in product prices (even if the underlying pass-through rate remains unchanged). Empirical evidence is scarce except for power markets—in which firms understand the opportunity cost of "free" permits.

Important research needs remain on carbon cost pass-through. First, the empirical analysis of pass-through in industrial sector would benefit from the availability of higher-frequency firm-level data on prices, costs and other metrics. This would help the literature go beyond simple time-series approaches and sharpen the confidence intervals around pass-through estimates. Second, a practice of *ex ante* announcements of study design could help resolve concerns about reporting bias (that might result if findings that do not align with stakeholder interests or are not significantly different from zero are not published). Third, theory and empirics could be used together more closely to understand how pass-through estimates based on historical data inform projections about the future—in which market structure and other factors may differ. Fourth, only little is currently known empirically about the pass-through effects of different forms of free allocation and about the internalization of carbon prices into decision-making inside firms (outside the electricity sector). Finally, as carbon pricing continues to spread around the world, more work is needed beyond the EU ETS which has to date dominated the literature.

The current empirical uncertainty around the degree of carbon cost pass-through in industry makes it difficult for policymakers to navigate the trade-off between windfall profits and carbon leakage. To achieve full carbon price internalization, two other policy options may therefore warrant further consideration. First, a move to full auctioning would avoid the complexities and potential distortions underlying free allocations. This could be combined with a border carbon adjustment that mirrors the domestic carbon price in international trade. Second, a climate charge on consumption can have a similar economic effect. It could be levied per ton of material sold to final consumers, using the same benchmarks underlying free allocation of allowances to production. In theory, both options can reinstate full carbon price internalization.

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# Appendix

**Proof of Proposition 1**. The proof uses the first-order conditions for profit-maximization for all firms to derive the equilibrium market price and hence the rate of pass-through. The first-order condition for inside firm $j$ is given by $\partial\Pi_I^j/\partial x_I^j = p - \beta x_I^j - c - m x_I^j - k_I = 0$. Summing this condition over the $N_I$ inside firms gives an aggregate version for $X_I$:

$$N_I p - (\beta + m)X_I - N_I(c + k_I) = 0.$$

Likewise, the first-order condition for outside firm $i$ is given by $\partial\Pi_O^i/\partial x_O^i = p - \beta x_O^i - c - m x_O^i = 0$, and so the corresponding aggregate version for $X_O$ is:

$$N_O p - (\beta + m)X_O - N_O c = 0$$

Adding these two aggregate versions yields an industry-wide expression for total output $X$:

$$(N_I + N_O)(\alpha - \beta X) - (\beta + m)X - (N_I + N_O)c - N_I k_I = 0.$$

Instead writing this in terms of the market price $p = \alpha - \beta X$ gives:

$$(N_I + N_O)p - \left(1 + \frac{m}{\beta}\right)(\alpha - p) - (N_I + N_O)c - N_I k_I = 0,$$

and so:

$$p(\tau) = \frac{(1 + h)\,\alpha + (N_I + N_O)c + N_I k_I(\tau)}{(N_I + N_O + 1 + h)} \Rightarrow \rho = \frac{N_I}{(N_I + N_O + 1 + h)},$$

where $h \equiv m/\beta$ and from which the result follows straightforwardly as claimed.