Measuring Leakage Risk

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Abstract

When a policy regulating greenhouse gas emissions applies to only a subset of emitting sources, a policy-induced shift in economic activity to exempt (or less stringently regulated) sources can substantially undermine policy effectiveness via emissions "leakage". Under existing climate change policy regimes, output-based rebating of compliance costs is the preferred approach to mitigating this leakage risk. These implicit production subsidies have potentially significant implications for both economic efficiency and the distribution of policy impacts, so it is important to carefully target leakage mitigation to those industries truly at leakage risk. We provide a theoretically sound basis for deriving industry-specific, output-based subsidies under different policy objective functions and market structures. Key components include industry-level measures of emissions intensity, industry-level measures of import and export intensity, and industry-level measures of how domestic output, import flows, and export flows respond to changes in relative energy prices. Using rich transaction and firm-level data from the U.S. Census, we estimate these components and calibrate industry-specific, output-based subsidies for manufacturing sectors in the United States. We assess the efficiency and distributional implications of implementing a domestic carbon policy with and without these leakage mitigation provisions.

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1 Introduction

The global nature of the climate change problem creates challenges for regional climate change policy. When a policy regulating greenhouse gas emissions applies to only a subset of emitting firms (i.e., the policy is "incomplete"), operating costs of regulated sources can increase vis a vis their unregulated rivals. An increase in relative operating costs can, in turn, adversely impact the ability of regulated firms to compete in a global market. If this shifts production outside the regulated jurisdiction, any associated increase in emissions can undermine the effectiveness of regional policies.

Concerns about "emissions leakage" loom large in the debates about how to design and implement regional policy responses to the global climate change problem. Economists have shown that full auctioning of emissions allowances, together with a combination of border carbon price adjustment and export rebates, can be effective in mitigating emissions leakage under incomplete carbon regulation (see, for example, Fischer and Fox (2012)). For a number of reasons, however, this approach has been difficult to implement in practice. Thus, economists have been exploring alternative leakage mitigation strategies. Under existing and proposed policies, production-based subsidies are being used to offset the potentially adverse competitiveness impacts of a greenhouse gas emissions price. In the case of a regional carbon tax, energy- or product-based revenues are recycled to regulated producers via a production-based subsidy. Under a regional emissions trading program, permits are allocated for free per unit of industrial output.

A growing literature demonstrates how this output-based rebating approach can effectively mitigate leakage (e.g., Fischer and Fox (2007), Fowlie et al. (2016), Quirion (2009), Fischer and Fox (2012), Meunier et al. (2014)). But this leakage mitigation strategy comes with strings attached. Economists have emphasized two efficiency considerations in particular. First, an implicit production subsidy dilutes the carbon price signal and thus reduces the incentives to implement cost-effective emissions abatement.[1] Second, an opportunity cost is incurred when allowances are allocated for free or tax revenues are recycled to industrial producers. These allowance auction proceeds could instead be put to productive use elsewhere. Finally, output-based rebating will affect how the benefits and costs of an emissions regulation are allocated across stakeholders. These distributional implications can have substantive political ramifications.

In light of these efficiency and distributional considerations, it is important to judiciously allocate leakage mitigation measures to only those industries at leakage risk. Efficient targeting of leakage mitigating subsidies presumes that policy makers can identify ex ante those industries most at risk. Our analysis aims to inform the process by which policy makers assess the potential for leakage risk and implement measures to mitigate this risk.

Leakage mitigation comprises an important part of both existing and proposed GHG emissions

[1] A carbon price serves to internalize some (or all) of the social cost associated with the emissions byproduct of industrial production. If these costs are passed through, consumer prices will more accurately reflect the social costs of supplying these products. Demand for more emissions-intensive products will decrease; demand for relatively less emissions intensive substitutes will increase. Output-based updating dampens this consumer price signal.

trading programs around the world. The European Union, Australia, and California have all used industry-specific measures of emissions intensity and trade share are used to gauge industry-level leakage risk. In the interest of identifying ex ante the industries where emissions leakage is most likely to be an issue, industry-specific measures of emissions intensity and trade share provide a useful point of departure. These metrics are relatively transparent and straightforward to calibrate using publicly available data. However, concerns have been raised about the extent to which these measures accurately capture leakage risk.

Policy makers and other stakeholders have emphasized the need for supplemental analyses to inform the design and implementation of leakage mitigation protocols.[2] Our work assesses the potential for international market transfers and emissions leakage to jurisdictions outside the United States under a national cap-and-trade carbon policy.

The contributions of our analysis is threefold. First, we introduce a conceptual framework that highlights intuitive economic relationships which determine emissions leakage. We use this framework to derive an empirically tractable formulation of optimal leakage mitigating subsidies under a range of plausible objective functions.

Second, we estimate the component parts of these subsidies using rich data on individual import and export transactions and establishment-level operations, which are mainly import, export and production elasticities to carbon costs. To identify the import, export, and production elasticity parameters, we exploit recent production cost shocks in the domestic oil and gas industry which have generated significant variation in domestic energy prices vis a vis foreign energy prices.

Third, with these estimates in hand, we assess the potential for leakage under a domestic carbon pricing regime and calibrate measures of leakage risk. In future work, we will use the calibrated optimal subsidies to evaluate the efficiency and distributional implications of implementing the policy with and without leakage mitigation provisions.

Our preliminary results can be summarized as follow. We find that, for the median industry, a 10 percent increase in domestic energy prices is associated with reductions in domestic production in the approximate range of 4 to 10 percent, a 3 to 9 percent decrease in exports, and a 2 to 4 percent increase in imports. Industries with higher energy intensities have systematically larger responses across all three outcome variables. We assess the likely impacts of a $10 per metric ton of carbon dioxide price on trade flows. Our median estimates imply reductions in export values on the order of 6 percent or smaller for a majority of industries. Estimated effects in non-energy-intensive industries are small, on the order of less than one percent. However, for cement, lime, industrial gas, wet corn milling, nitrogen fertilizer, iron and steel industries, we estimate negative impacts on export volumes of 20 percent or greater. We find increases in imports of 4 percent or less for most

[2]The CARB report that discusses leakage risk metrics in detail can be accessed at: http://www.arb.ca.gov/regact/2010/capandtrade10/capv4appk.pdf. The CRS Report for Congress "'Carbon leakage and Trade: Issues and Approaches" may be accessed at: http://www.fas.org/sgp/crs/misc/R40100.pdf. The Australian Government released the White Paper in December 2008 that outlines the final design of the Carbon Pollution Reduction Scheme. Chapter 12 discusses the assistance for emissions intensive trade-exposed industries. Chapter 12 of the White Paper may be accessed at: http://pandora.nla.gov.au/pan/102841/20090728-0000/www.climatechange.gov.au/whitepaper/report/pubs/pdf/V2012Chapter.pdf

industries. Estimated impacts exceed 11 percent in cement, lime, and industrial gas industries.

Finally, we use our elasticity estimates to calibrate upper bound estimates on market transfer rates and associated leakage mitigating subsidies. The imprecision of our estimates makes it difficult to calibrate the subsidy for any particular industry with any degree of precision. Averaging across industries, clear patterns emerge. Our transfer rates are highest for those industries typically classified as having a "high" risk of leakage (i.e., energy intensive trade exposed industries). On the contrary, low emitting industries and industries that have low trade exposure do not appear to have substantial transfer rates.

2 Context

Economists have long been concerned about the effects of environmental regulation on industrial production and associated trade flows.[3] More recently, work in this area has expanded to evaluate policy mechanisms that mitigate adverse impacts on competitiveness and associated emissions leakage. In what follows, we briefly summarize the existing literature and characterize our relative contributions.

Industrial impacts of emissions regulations Early theoretical work predicts that the costs of complying with an environmental regulation that applies to only a subset of producers will weaken the competitive position of the regulated producers and possibly increase the market share of unregulated producers (see, for example, Pethig (1976) and Siebert (1977)). This intuitive theoretical prediction has motivated a rich empirical literature which examines, across a variety of contexts, how environmental regulations affect trade flows.

Early empirical tests were largely based on cross-sectional comparisons across industries or countries with varying degrees of environmental regulation (e.g., Grossman and Krueger (1995) and Mani (1996)). These early studies generally find no relationship, or a counter-intuitive positive relationship, between energy costs (a proxy for compliance costs) and net imports. Positive coefficients are presumably picking up the effects of confounding factors that are both correlated with levels of environmental stringency and determine trade flows.

The confounding effects of omitted variables complicates the investigation of how environmental regulations affect industrial production and associated trade flows. To mitigate potential biases, more recent work brings more sophisticated empirical methods and strategies to the analyses of how environmental policies impact industrial activity (see, for example Ederington et al. (2005)). Some of this work investigates how recently implemented regional policies, such as the EU ETS, have impacted industrial production and trade flows (Kenber et al., 2009; Petrick and Wagner, 2014). Other researchers have used variation in energy prices to proxy for policy-induced variation in operating costs (see, for example, **?**). In a paper closely related to ours, Aldy and Pizer (2015), use within-industry energy price variation to estimate the effect of a carbon price on domestic

[3] For an excellent review of the earlier literature on the effects of environmental regulation on manufacturing, see Brunnermeier and Levinson (2004).

production and net imports for U.S. manufacturing. They estimate that a \$15 CO_2 price would induce an economically significant decline in domestic production among energy intensive sectors. On average, approximately one-sixth of this decline in domestic production is transferrred to foreign producers as an increase in net imports.

We build on and extend this line of inquiry. Our use of disaggregated, establishment and transaction-level data from the U.S. Census supports a more detailed analysis of heterogeneity in the response to operating cost shocks. Moreover, the time period we analyze saw unprecedented variation in relative energy prices generated by production shocks in the domestic natural gas and oil industries. We leverage this variation to understand how domestic production, imports, and exports might respond to a policy-induced change in relative energy prices.

How has the shale gas boom impacted domestic manufacturing? Recent developments in the domestic energy sector have generated variation in relative energy prices that can support more detailed analysis of how trade flows respond to changes in relative energy prices. Over the past decade, production cost shocks in the domestic oil and gas industry have led to a significant increase in U.S. natural gas and oil production. Domestic natural gas prices have fallen dramatically. These positive energy supply shocks have been largely confined to the domestic market because natural gas is costly and complicated to export overseas. Figure 1 illustrates how the shale gas boom has generated a significant drop in domestic energy prices relative to our international trading partners.

One line of inquiry has examined how this domestic production cost shock has affected domestic manufacturing activity. Melick (2014) find that industrial production increased 2 to 3 percent as a result of the drop in natural gas prices. Estimated impacts are significantly larger in the most energy-intensive manufacturing sectors. Hausman and Kellogg (2015) also provide evidence to suggest that manufacturing sectors with the highest natural gas intensities (plastics and nitrogen fertilizer manufacturing in particular) have grown substantially faster than manufacturing in general as domestic energy costs fall relative to foreign energy prices.

Researchers have also been examining the incidence of recent energy price changes. Bushnell and Humber (2015) look at how the nitrogen fertilizer industry has been impacted by falling natural gas prices. They document low rates of pass-through which they attribute to capacity constraints or the exercise of market power. In related work, **?** investigate how domestic energy price changes are passed through to consumers in six industries: boxes, bread, cement, concrete, gasoline, and plywood. Their estimates imply incomplete rates of marginal cost pass-through in these industries.

Building on this related work that focuses on how domestic prices and quantities have responded to the change in domestic energy prices, we broaden the scope somewhat to include import and export flows in close to a hundred industries. We bring detailed data on the universe of domestic import and export transactions to our analysis. We are particularly interested in characterizing systematic heterogeneity in the relationship between energy prices, domestic production, and trade flows, both across and within industries.

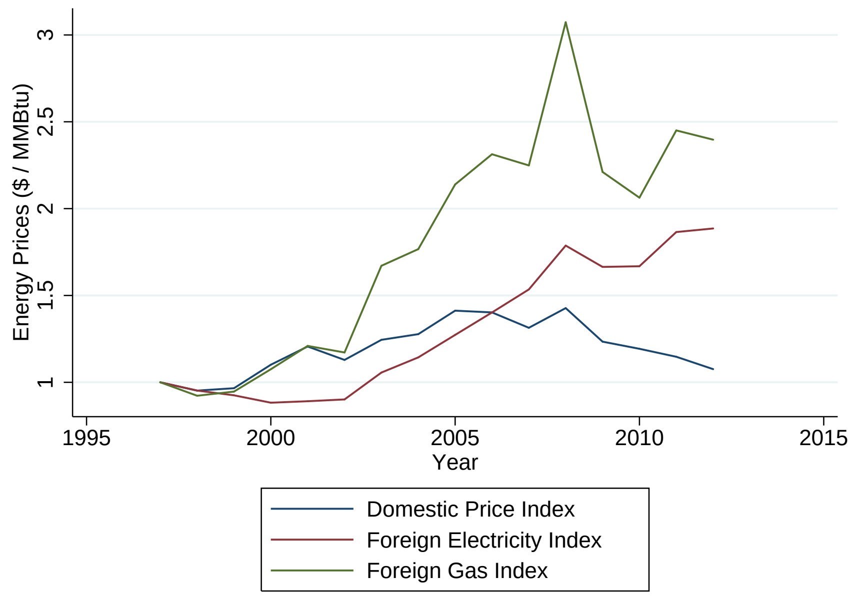


Figure 1: Evolution of Energy Prices over time

This figure summarizes intertemporal variation in domestic energy prices, foreign natural gas prices, and foreign electricity prices over time. These price indices are constructed as weighted averages of the energy prices paid by industrial producers relative to their prices in some base-year. All prices are weighted by value of shipments. Foreign energy prices are averaged across import and export shipments. For more details, see the discussion of data set construction.

Leakage measurement and mitigation The potential for emissions leakage threatens to undermine the efficiency and effectiveness of regional climate change policies. Concerns about emissions leakage are dominating the policy discussion. And a growing literature evaluates approaches to mitigating this emissions leakage risk.

An essential first step in the design of leakage mitigation measures involves identifying those industrial sources and sectors that are most vulnerable to leakage. Across existing and proposed regional GHG emissions trading programs, the approaches used assess leakage risk are very similar. In general, leakage risk is assessed on the basis of two quantitive metrics: emissions intensity and trade intensity.[4] These metrics are estimated separately for each regulated industry.

Figure 1 summarizes how this approach has been applied in two large regional emissions trading programs: the European ETS and California's GHG Emissions Trading Program. In both programs, leakage risk is assessed on the basis of emissions intensity and trade exposure. These metrics are calibrated using industry-level data on energy consumption, GHG emissions, production costs, imports, exports, and domestic production levels. The two dimensional space defined by these two metrics is divided into leakage risk classification categories. In general, industries as-

[4]These are the quantitative criteria laid out in Article 10a of the ETS directive (2009/29/EC). Leakage protocols developed in the EU ETS, Australia, the proposed American Clean Energy and Security Act of 2009, and California's GHG Trading Program, use industry-specific measures of emissions intensity and trade share to gauge industry-level leakage risk and allocate leakage mitigating compensation. Emerging programs in China are following this example (Wang et al. 2015).

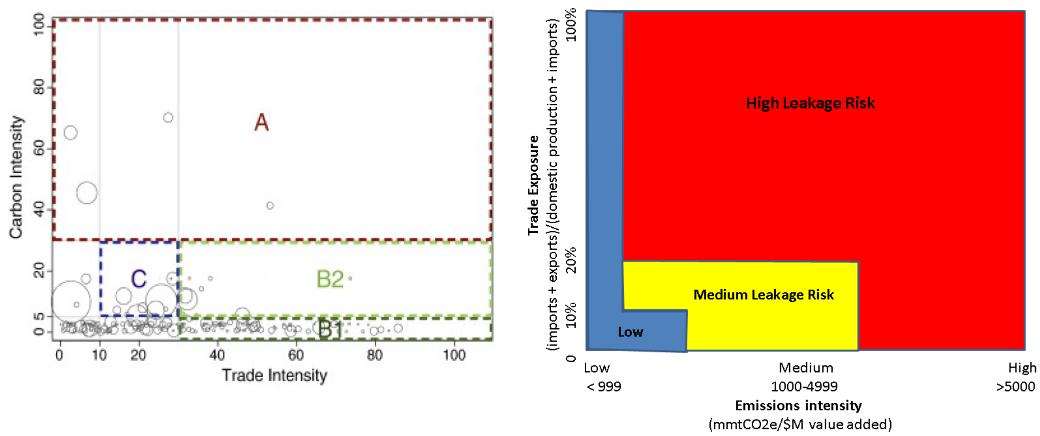


Figure 2: Criteria used to assess industrial leakage risk

This figure summarizes the approach to measuring leakage risk at the industry level in two regional GHG emissions trading programs. Directive 2009/29/EC of the EU ETS stipulates that leakage risk be assessed on the basis of carbon intensity and trade intensity. Circles represent individual sectors scaled to reflect annual GHG emissions. Eligible sectors are classified into mutually exclusive leakage risk categories (A,B, C) (Martin et al., 2015). The figure on the right summarizes leakage risk classification in California's GHG emissions trading program. The approach is similar, although emissions intensity and leakage risk thresholds are defined differently.[a]

[a]Source: https://www.arb.ca.gov/cc/capandtrade/meetings/20160518/staff-leakage-workshop-intro.pdf.

sociated with high emissions intensity and high trade exposure are classified as high risk, although the specifics of this categorization vary across phases and programs.[5]

Once industries associated with high levels of emissions intensity and/or high trade intensity have been identified, leakage mitigating subsidies are allocated accordingly. Under the EU Emissions Trading Scheme (EU ETS), the Californian GHG ETS and the Australian Carbon Price Mechanism, these subsidies come in the form of free permits. The precise mapping of leakage risk categories to free permit allocation varies across industries and trading programs. But in general, compensation is increasing with emissions intensity, trade share, and output. For example, under California's GHG emissions trading program, free permit allocations are determined using the product of an industry specific GHG emissions rate benchmark (measured in tons GHG/units of output), the level of output at the facility, and an industry-specific assistance factor that is increasing with emissions intensity and trade exposure.

This approach to assessing leakage risk and allocating associated compensation has come under some scrutiny, particularly in a European context. Cl (2010) raises concerns about how leakage risk assessment is conducted under the EU ETS and questions the ad hoc nature of the compensation determination. De Bruyn et al. (2013) raise concerns about the data used to calibrate these risk metrics. Martin et al. (2014) use qualitative data collected in interviews with business managers

[5] Juergens et al. (2012) trace the origins of this approach to leakage risk assessment back to report by Carbon Trust (2004) and subsequently Smale et al (2006), Hourcade et al (2006) and Graichen et. al. (2008).

to assess leakage risk. These authors argue that the current levels of leakage mitigation amount to overcompensation, and suggest some amendments. Sato et al. (2015) assess the robustness of these metrics across European member states. They document economically significant intra-industry variation in standard leakage risk metrics.

Our study takes a somewhat different approach. Building on work by Meunier et al. (2014), we construct a theoretical framework to analyze emissions leakage under an incomplete carbon pricing regime. We use the framework to derive the welfare maximizing subsidy schedule in terms of estimable parameters and quantities. We demonstrate how this micro-founded approach to leakage mitigation can be implemented empirically. We argue that our approach provides a micro-founded, empirically tractable, and likely welfare improving alternative to the current approach to defining leakage mitigation provisions.

3 Theoretical Framework

This section lays out the economic modeling framework that guides our empirical analysis. We introduce a simple theoretical model which highlights the economic relationships that determine the extent to which leakage occurs under an incomplete emissions regulation. We use this model to derive empirically tractable formulations for the welfare maximizing, leakage mitigating subsidy under alternative policy objective functions.

3.1 Graphical overview

Figure 3 summarizes the key economic relationships that determine leakage in our theoretical framework. The graph illustrates a baseline case of a singly industry in which domestic producers face competition from foreign producers, but do not export to foreign markets. For ease of exposition, we assume a constant emissions rate per unit of output e across domestic and foreign production.[6]

The right panel illustrates demand and supply in the domestic market, while the left panel represents the supply of imports from foreign producers. The thick black, kinked line in the right panel represents the "residual demand." Mechanically, this represents total domestic demand for goods produced in this industry less import supply. If we assume that domestic producers behave competitively, domestic firms will produce up to the point where their marginal costs equal the prevailing market price. Absent any emissions regulation, marginal operating costs are given by $C(q)$. Intuitively, the equilibrium market price p is determined by the intersection of the residual demand and the $C(q)$. Domestic output is q_d. Foreign producers supply q_f at this price. Total quantity, q, is equal to $q_d + q_f$.

Now suppose policy makers introduce a policy that assigns a carbon price of τ per metric ton of carbon dioxide (and equivalent greenhouse gases) to domestic producers. This carbon price is the tax rate under an emissions tax. It is the equilibrium permit price in an emissions trading program. For expositional ease, we assume that firms take this carbon price τ as given. Absent

[6] Below we generalize to a case where domestic producers face import competition and export to foreign markets.

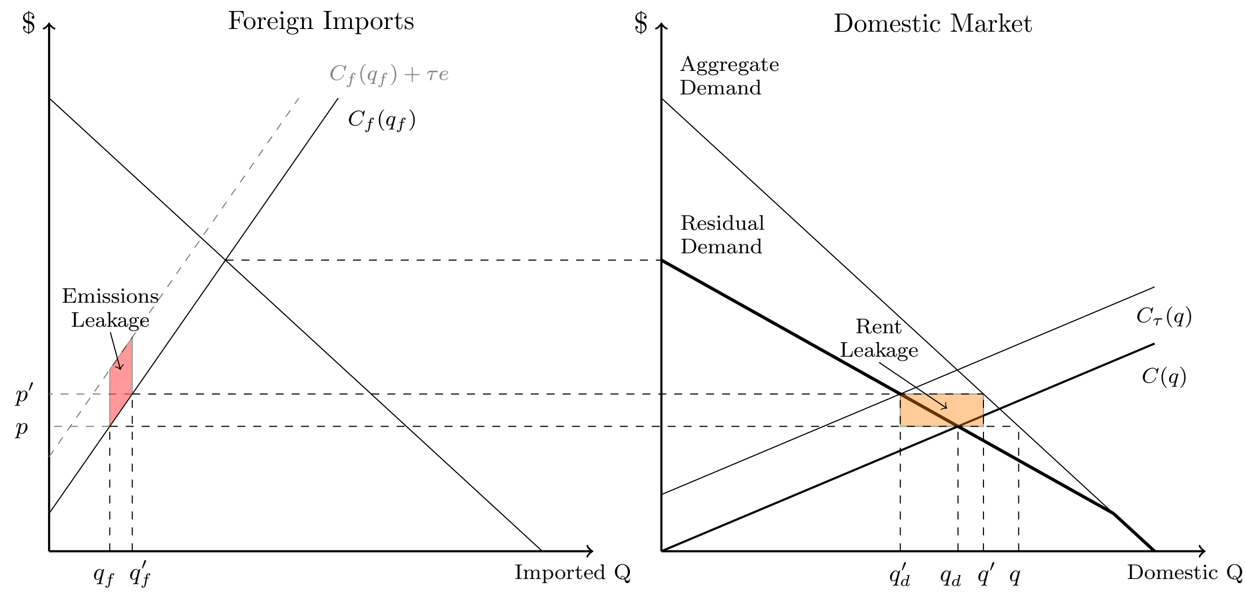


Figure 3: Leakage in Trade-Exposed Energy Intensive Industries

This figure shows equilibrium prices and quantities with and without a carbon tax. In the presence of a carbon tax, domestic consumption goes down (from q to q') as prices increase (from p to p'). Domestic production also goes down (from q_d to q'_d). Importantly, domestic production goes down by more than domestic consumption. Part of such reduction is covered by an increased in imports (from q_f to q'_f), as firms outside of the regulatory jurisdiction benefit from the absence of a carbon tax.

any output-based updating provisions, marginal operating costs under the policy will increase by $\tau \cdot e$. The curve labeled $C_\tau(q)$ represents the domestic industry supply curve under this emissions policy.

Suppose the domestic policy maker can regulate domestic emissions, but has no ability to regulate the emissions associated with foreign production. Under this kind of "incomplete" regulation, operating costs of foreign producers are unaffected by the policy. Domestic producers, who face an increase in their marginal cost, reduce their production to q'_d. The equilibrium market price rises to p', as determined by the intersection of the domestic supply curve and the higher domestic residual demand curve. Demand for imports increases to q'_f. Note that the increase in the overall average operating costs leads to a reduction in total domestic consumption from q to q'. The emissions reduction among domestic producers is denoted by the green area (a monetized measure that values emissions reductions at the allowance value τ). However, the increase in relative operating costs (i.e., costs of domestic producers relative to foreign producers) results in an increase in demand for imports and associated leakage.

This simple graphical framework clearly illustrates that *emissions leakage* that can result when a policy-induced increase in domestic operating costs causes domestic producers to lose market share to their foreign competitors. In the figure, the shaded parallelogram in the left panel captures the costs or damages associated with the policy-induced increase in foreign emissions (valuing these emissions-related damages at τ per unit of emissions). The dashed line in the left panel represents a measure of marginal cost of foreign producers that reflects emissions costs (valued at τ).

The figure also highlights the key determinants of this emissions leakage. One is the emissions intensity of the foreign producers, e_f. Another is the change in foreign production that is induced by the change in domestic production (i.e., the "market transfer"). Our empirical analysis seeks to estimate how the extent of market transfer that occurs in response to a given change in domestic energy costs varies across industries. In the figure, market transfer is represented by $q'_f - q_f$. If the policy-induced increase in operating costs among regulated producers is passed through to increase market prices, the market transfer of production (i.e., $q'_f - q_f$) will generally be smaller than the decrease in production in the regulated region ($q_d - q'_d$) except in the limiting case where demand is perfectly inelastic.

If the introduction of the emissions policy results in an increase in the market-clearing price, there will be a loss in consumer surplus (i.e., a reduction in consumer benefits in excess of the purchase price). Some of this loss is simply transferred to domestic producers or the government in the form of tax of allowance proceeds. But some fraction is transferred to foreign producers. In other words, along with emissions, there can be an associated transfer of surplus from domestic consumers to foreign producers (i.e., "rent leakage"). This rent leakage, denoted in the right panel of the figure, can also be of concern to policy makers looking to mitigate unintended impacts of the carbon pricing regime.

3.2 Baseline model: Emissions leakage, no exports

A stylized model serves to formalize the graph above and motivate the empirical quantities we estimate. In the most basic model, domestic consumers demand a homogenous good, which is produced in two competitive sectors: domestic and foreign, denoted by subscripts d and f, respectively. The inverse demand curve is given by $p(q)$, where $q = q_d + q_f$ represents total domestic demand. The cost of production is given by $C_d(q_d)$ and $C_f(q_f)$ in the domestic and foreign sector, respectively.

Production of the good generates an externality, σ. Domestic producers emit damaging pollution at a constant rate of e_d per unit of q_d, while the foreign firm emits at a constant rate of e_f per unit of q_f. The home firm is subject to regulation with a carbon price of τ per unit of emissions, e_d.[7] Foreign emissions and production fall outside the reach of this regional regulation.

The profit function for a domestic price-taking firm is:

$$\pi(q_d) = p(q)q_d + C(q_d) - \tau e_d q_d. \tag{1}$$

The competitive firms offer their production at marginal cost, as given by $C_d(q_d)$. Firms in the market produce to the point in which their marginal costs equal the equilibrium price. Similarly, foreign producers produce up to the point in which their marginal costs equal the market price. This generates the following first-order conditions:

$$C'_d(q_d) + e_d\tau = p(q_d + q_f), \tag{2}$$

$$C'_f(q_f) = p(q_d + q_f). \tag{3}$$

The solutions to these first-order conditions can be denoted as $q_d(\tau)$ and $q_f(\tau)$.

The carbon price increases production costs for domestic firms, but not foreign firms. This induces an inefficient shift, or "market transfer," from some of the low-cost domestic production to some of the high-cost foreign production. The associated increase in emissions e_f offsets emissions reductions achieved at home. Within this basic framework, emissions leakage is determined by two key parameters, the emissions intensity of foreign producers e_f and the policy-induced transfer to foreign production: $q_f(\tau) - q_f(0)$. In Figure 3, this transfer corresponds to $e_f(q'_f - q_f)$.

To mitigate emissions leakage, the regulator can introduce an output-based subsidy to partially rebate carbon prices. This production subsidy works to offset the policy-induced increase in operating costs $e_d\tau$ incurred by domestic producers. This induces a higher level domestic production (relative to a scenario in which the policy is implemented without the implicit subsidy) and thus reduces emissions leakage.

Following Meunier et al. (2014), maximizing total welfare in the market allows us to compute the optimal subsidy s^* in this context. In our baseline specification, the regulator's maximization

[7] In the theoretical literature, it is standard to assume that the carbon price is set to equal the external damages caused, but this is not necessarily the case in a practical setting, especially given the difficulties in determining the social cost of carbon precisely.

problem is:

$$\max_{s} \quad W(s) \equiv \underbrace{S(q_d(s) + q_f(s))}_{\text{Consumer Surplus}} - \underbrace{C_d(q_d(s))}_{\text{Domestic Costs}} - \underbrace{C_f(q_f(s))}_{\text{Foreign Costs}} - \underbrace{\sigma(e_d(q_d(s) + e_f q_f(s)).}_{\text{Emissions Externality}} \tag{4}$$

With welfare written as a function of s, $W(s)$, the regulator chooses the subsidy that maximizes welfare:

$$\frac{\partial W}{\partial q_d}\frac{\partial q_d}{\partial s} + \frac{\partial W}{\partial q_f}\frac{\partial q_f}{\partial s} = 0. \tag{5}$$

Substitutions involving first order conditions derived above imply:

$$\frac{\partial W}{\partial q_d}\frac{\partial q_d}{\partial s} = (p - C'_d(q_d) - \sigma e_d)\frac{\partial q_d}{\partial s} = -s\frac{\partial q_d}{\partial s}, \tag{6}$$

and,

$$\frac{\partial W}{\partial q_f}\frac{\partial q_f}{\partial s} = (p - C'_f(q_f) - \sigma e_f)\frac{\partial q_f}{\partial s} = -\sigma e_f\frac{\partial q_f}{\partial s}. \tag{7}$$

Putting these terms together and solving for s, we obtain:

$$s^* = -\sigma e_f \left(\frac{\frac{\partial q_f}{\partial s}}{\frac{\partial q_d}{\partial s}} \right). \tag{8}$$

The optimal subsidy is the product of τ, the emissions intensity of imports, and the rate at which equilibrium imports change as domestic production levels change. Intuitively, the subsidy internalizes a positive externality associated with domestic production: the displacement of emissions associated with foreign production. The extent to which an increase in the subsidy reduces emissions in foreign jurisdictions depends on the extent to which the subsidy increases domestic production and the market transfer rate. We can define the effective tax per unit of production as $\sigma e_d - s*$.

Equation (8) shows that the subsidy will be larger in those markets in which imports are most responsive to price changes. Intuitively, if the import supply curve is fully elastic, then there is complete leakage and the emissions mitigation policy is completely ineffective at reducing emissions. Therefore, the optimal subsidy will be a full refund in such case. At the other end of the spectrum, industries in which imports are completely insensitive to domestic productin should receive an optimal subsidy of zero, as there is no leakage. This is also formally equivalent to the case where imports are equal to zero.

The optimal subsidy increases with e_f. Holding all else constant and increasing e_f implies that there will be more emissions leakage, and thus the optimal subsidy is higher in such a case. Conversely, the stronger the domestic industry's response to the subsidy, the lower the subsidy will be. The explanation for why this term is in the denominator is that the regulator can reduce the level of the subsidy when the firms are more responsive to it.

This derivation of the optimal subsidy implicitly assumes that the policy-induced change in foreign imports, $\frac{\partial q_f}{\partial s}$, captures the policy induced change in foreign production. This need not be true if changes in foreign import supply come from a reallocation of foreign output that would otherwise have supplied other markets. For this reason, Equation (8) should be interpreted as an upper bound on the optimal subsidy. At the other extreme, a change foreign imports leaves total foreign production unchanged, and the optimal subsidy is zero.

We can also re-write the subsidy in terms of the standard leakage risk metrics:

$$s^* = \sigma \underbrace{e_f}_{\substack{\text{Foreign}\\\text{Emissions}\\\text{Factor}}} \times \underbrace{|\eta_f|}_{\substack{\text{Foreign}\\\text{Output}\\\text{Elasticity}}} \times \underbrace{\frac{q^f}{q^d}}_{\substack{\text{Trade}\\\text{Ratio}}}, \tag{9}$$

where η_f represents the equilibrium elasticity of the supply of imports to a change in domestic production induced by a change in domestic production costs.[8] Under existing and planned programs, leakage mitigating subsidies are typically determined based on measures of emissions intensity and trade share. What is missing from the standard formulation is the elasticity of foreign production to changes in domestic output. This is a crucial determinant and the focus of our empirical estimation.

Of course, the optimality of the subsidy derived here depends on a number of important assumptions that may not hold in practice as well as a series of simplifications. We analyze the role of the main assumptions and discuss several extensions: introducing exports and considering the cross-sectoral impact of subsidies.

3.3 Alternative assumptions behind optimal subsidies

The optimal subsidies as derived rely on three strong assumptions: the social planner values profits outside of its own jurisdiction, the market is perfectly competitive, and the carbon price equals the true marginal cost of the externality. We relax these aspects of the model by considering alternative assumptions.

Rent leakage In the welfare function above, the social planner considers foreign profits as part of its objective function. However, in practice, policy makers may only be concerned with domestic surplus and profits (or jobs). The transfer of surplus to a foreign jurisdiction is rent leakage; we capture such an effect by modifying the welfare function as follows:

$$\widetilde{W}(s) \equiv \underbrace{S(q_d(s) + q_f(s))}_{\text{Gross Consumer Surplus}} - \underbrace{C_d(q_d(s))}_{\text{Domestic Costs}} - \underbrace{p(q_d(s) + q_f(s))q_f(s)}_{\text{Foreign Payments}} - \underbrace{\sigma(e_d q_d(s) + e_f q_f(s))}_{\text{Emissions Externality}}, \tag{10}$$

where foreign production costs have been replaced by the consumer costs that arise from paying for imports, and the only consumer surplus that enters is domestic consumer surplus. Using this

[8] In an extension below, we show that a similar expression obtains if both imports and exports are accounted for.

objective function, the subsidy should be designed to mitigate both emissions and rent leakage.

Following the same strategy as above, deriving the optimal subsidy under this new environment leads to a modified subsidy:

$$s^*_{rent} = s^* - \frac{q_f \dfrac{\partial p(q)}{\partial q} \left(\dfrac{\partial q_d}{\partial s} + \dfrac{\partial q_f}{\partial s} \right)}{\dfrac{\partial q_d}{\partial s}}. \tag{11}$$

The additional term reflects the change in expenditures on foreign imports as the equilibrium price changes with the subsidy. An increased subsidy will tend to reduce the market price paid for imports, providing an additional benefit from the subsidy. Assuming that net domestic production increases with the subsidy, the optimal subsidy is higher than in the baseline case, i.e., $s^*_{rent} > s^*$.

Imperfect competition In our benchmark case, all markets are assumed to be perfectly competitive. In fact, many emissions intensive industries are highly concentrated. We therefore extend the model to account for the potential exercise of market power in the domestic market. We consider the extreme case in which the domestic firm is a monopolist. The profit-maximizing first-order condition becomes:

$$C'_d(q_d) + e_d\sigma - s = p(q) + p'(q)q_d. \tag{12}$$

Rather than setting marginal cost equal to price, the monopolist sets marginal cost equal to marginal revenue. This yields a modified subsidy:

$$s^*_{monopoly} = s^* - p'(q)q_d. \tag{13}$$

Compared to the base subsidy, there is an additional term incorporating the welfare-reduced effects of the exercise of market power. The second term is positive, as the demand curve slopes downward, and therefore the subsidy with market power is larger than the competitive case: $s^*_{monopoly} > s^*$.

Imperfect carbon prices A maintained assumption in the derivation of optimal subsidies is that the price of carbon is set optimally to reflect the carbon externality. Therefore, the optimal subsidy is a function of σ, the true externality. However, it is often the case that carbon prices are affected by political constraints or other considerations.[9]

The potential difference between the carbon price and the actual carbon externality might affect how important subsidies are deemed. For example, in a market with extremely low carbon prices (and considered sub-optimally low), discussion of subsidies might become less relevant. One way to see this discrepancy is by allowing $\tau < \sigma$. In such case,

$$s^*_{mispricing} = s^* - (\sigma - \tau)e_d. \tag{14}$$

[9]The carbon externality in itself is often hard to quantify and subject to its own caveats.

Intuitively, there is an incentive to correct the mispricing through the subsidy. Under the assumption that the carbon price is below the true externality, the correction calls for smaller subsidies, i.e., $s^*_{mispricing} < s^*$.

3.4 Introducing exports

The model can be readily extended to allow domestic firms to export q_e into foreign markets. The cost of production is now given by $C_d(q_d + q_e)$. This assumes that the firm produces identical goods for the domestic and export markets, and therefore the cost of production only depends on their sum.

The profit function for a domestic price-taking firm is augmented by revenues and cost arising from exports:

$$\pi(q_d, q_e) = p(q)(q_d + q_e) - C(q_d + q_e) - \tau e_d(q_d + q_e) + s(q_d + q_e), \tag{15}$$

where we assume the domestic market and international markets are fully integrated, i.e., they obtain the same price.

Adding exports, the optimal subsidy becomes:

$$s^*_{export} = -\sigma e_f \left(\frac{\frac{\partial q_f}{\partial s} - \frac{\partial q_e}{\partial s}}{\frac{\partial q_d}{\partial s} + \frac{\partial q_e}{\partial s}} \right). \tag{16}$$

Compared to Equation (8), the optimal subsidy has an extra term in the numerator to account for exports offsetting foreign production. Recalling that the partial derivative of imports with respect to the subsidy is negative, the numerator is now larger, which implies that s^*_{export} is larger than in Equation. The intuition is that emissions leakage is larger in this scenario than previously, as reductions in exports due to domestic cost increases now lead to increased foreign production, and consequently higher emissions. As in Equation (8), industries that are more responsive to subsidies have a lower optimal s^*_{export}, and here that responsiveness is augmented along the second dimension of exports.

The optimal subsidy in elasticity form becomes:

$$s^*_{export} = \sigma \ e_f \times \frac{|\eta_f| q^f + |\eta_e| q^e}{q^d + q^e}, \tag{17}$$

where the elasticities are now with respect to total domestic production, $q^d + q^e$.

This formulation of the optimal subsidy implicitly assumes that exports are additional to, versus substitutes for, foreign production. In fact, some of the policy-induced reduction in exports may be offset by increases in foreign production and associated foreign emissions. As a result, the optimal subsidy derived under these conditions provides a conservative upper bound on the level of the subsidy.

3.5 Introducing sectoral interactions

Thus far, our analysis has focused on a single industry in isolation. In fact, these leakage mitigating subidies are typically allocated across dozens of industries simultaneously. Subsidizing one sector can have general equilibrium effects for other sectors in the economy. Consider the general case where several sectors receive output-based subsidies. Now,

$$W(\mathbf{q}_h, \mathbf{q}_f, \sigma) = S(\mathbf{Q}) - C_h(\mathbf{q}_h) - C_f(\mathbf{q}_f) - \sigma(\mathbf{e}_h'\mathbf{q}_h + \mathbf{e}_f'\mathbf{q}_f), \tag{18}$$

where $\mathbf{q}_h, \mathbf{q}_f$ represent the output vector of a group of sectors, instead of just one sector. For simplicity, consider the case in which marginal damages are held constant (σ).

In a cap-and-trade market context, the permit price is determined by the marginal cost of meeting the emissions cap constraint:

$$\mathbf{e}_h'\mathbf{q}_h \leq \overline{E}. \tag{19}$$

Subsidizing one sector will affect abatement expenditures in other sectors through the emissions permit price (even abstracting from input complementarities or other product market interaction effects). An increase in the level of output-based subsidies paid to one or more sectors will weakly increase the equilibrium permit price, and weakly decrease the share of abatement delivered by the subsidized sectors.

The basic intuition can be illustrated using a stylized, two-sector economy where one sector is trade exposed and the other is not. The trade exposed sector is eligible for a partial subsidy (e.g. through output-based updating), due to the potential adverse effects of leakage, which is represented by s_1 per unit of output.

The competitive first-order conditions for the two sectors are as follows:

$$p_1 = C_1' + \lambda e_1 - s_1, \tag{20}$$

$$p_1 = C_f', \tag{21}$$

$$p_2 = C_2' + \lambda e_2. \tag{22}$$

where λ is the shadow value of the regulatory cap in (19) and therefore equals the price in the cap-and-trade system.

A subsidy introduces a wedge in the equalization of marginal costs across sectors, as seen in the FOC equalizing the price of emissions λ,

$$\frac{S_1' - C_1' + s_1}{e_1} = \frac{S_2' - C_2'}{e_2}. \tag{23}$$

The introduction of the subsidy shifts more of the abatement activity to the unsubsidized sector; marginal abatement costs are no longer equalized acruss sectors.

The regulatory problem of the social planner can be defined implicitly as follows:

$$\max_{s_1} \quad S_1(s_1) + S_2(s_1) - C_1(s_1) - C_2(s_1) - C_f(s_1) \\ -\sigma(e_1 q_1(s_1) + e_2 q_2(s_1) + e_f q_f(s_1)). \tag{24}$$

Solving for the welfare maximizing subsidy provide the same formulation as before. Intuitively, the formulation of the optimal subsidy is unchanged because the fundamental nature of the positive externality that the subsidy is designed to address is independent of the number of industries receiving a subsidy. However, the effective tax (i.e. $\lambda \cdot e_1 - s^*$) will be increasing with the number of industries receiving leakage mitigating subsidies.

3.6 Summary

In this section, we present a simple model of emissions leakage to motivate the empirical analysis. The two key determinants of leakage are the decrease in domestic production, the increase in foreign production, and the foreign emissions intensity. We also derive optimal measures of compensation in the presence of output-based subsidies.

As noted above, standard leakage risk measurement protocols use industry-specific measures of the emissions intensity of regulated producers and trade share to identify industries where emissions leakage is likely to be significant. These factors play a role in determining the theoretically optimal level of compensation, but we identify another critical determinant that is not explicitly captured by standard leakage risk metrics. Our empirical exercise is geared towards estimating this missing component.

4 Data

The conceptual framework developed in the previous section will guide our construction of industry-specific measures of leakage risk. This estimation and associated calibration uses detailed data on industrial operating costs, production, imports, and exports. In what follows, we summarize these data.

4.1 Data sources

We combine several public and restricted data sets to construct alternative measures of leakage risk. Table 1 summarizes the key data sets. The Longitudinal Firm Trade Transactions Database (LFTTD) details individual import and export transactions, including value, product, and the U.S. firm involved in the trade. The Census of Manufacturers (CMF) and Annual Survey of Manufacturers (ASM) report annual data on manufacturing establishments, including production value and input costs. The Longitudinal Business Database (LBD) provides a link between manufacturing establishments and firm ownership. The Manufacturing Energy Consumption Survey (MECS) aggregates primary energy consumption by fuel source at the industry-region level. The State Energy

Data System (SEDS) reports state-level prices for fuels consumed in the industrial sector. The Enerdata Global Energy Data and IEA Energy Prices and Taxes datasets report average annual prices of electricity and natural gas for most countries.

In the CMF and ASM datasets, we assign each establishment to an industry (i.e., a 6-digit NAICS classification) based on the product we observe the establishment producing the greatest value of when summed over all years. For example, if an establishment manufactures both flat glass and glass containers but produces a greater value of glass containers summed over all years, we assign that establishment to the glass containers industry. We then restrict our sample to establishments belonging to industries considered to be emissions-intensive and trade-exposed by the Waxman-Markey cap-and-trade bill that was passed by the U.S. House of Representatives in 2009. We similarly restrict the LFTTD to transactions of products in these same industries. Our analysis covers 96 NAICS6 industries in total. These are listed in Table 2.

4.2 Outcome variables

Our analysis focuses on three outcome variables: domestic production for the domestic market, domestic production destined for export, and foreign imports. For the purpose of this study, all three are measured in terms of the value of shipments. For each of these outcomes, the unit of observation is an industry-year; industries are defined at the 6-digit NAICS level. To calculate the value of shipments from a particular industry, we sum the annual value of shipments from all establishments assigned to that industry. To calculate the annual value of imports in an industry, we sum over the value of all import transactions of products falling into that industrial classification for each year, and similarly for the value of exports. We deflate all values to 2010 U.S. dollars.

Aggregate summary statistics are reported in Table 3. The values of imports and exports are similar on average for the industries we consider, although both of these values are less than the average value of shipments in these industries. However, there is large variation in all three outcomes across industries. Even when accounting for differences at the 3-digit NAICS and 2-digit NAICS-by-year levels, as shown in the third and fourth columns of Table 3, substantial variation remains in these outcomes. This provides evidence that including these levels of fixed effects in our analysis will not oversaturate our model and bias results.

4.3 Energy prices

Our analysis uses variation in domestic and foreign energy prices to estimate the effect of relative energy prices on the outcomes described above. Our measures of domestic energy price combine establishment-level electricity price from the CMF and ASM with state-level prices for primary fuels in the industrial sector from SEDS. We combine these prices by taking weighted averages over energy sources within an establishment and over establishments within an industry.[10] We calculate two measures of domestic energy prices, using different weights in the weighted averages, to allow

[10]Figure 4 shows the share of input costs attributed to electricity consumption and the share attributed to fuel costs across a wide range of industries.

or control for changes in energy consumption in response to changing energy prices. The measure that allows for a consumption response is described as using "contemporaneous shares" to denote that fuel shares correspond to the same year as the price data. The measure that controls for this response, and hence allows only for changes in underlying fuel and electricity prices, is described as using "baseline shares" to denote the fuel shares are held fixed. The calculation of these measures is described in detail in this section.

The first measure uses weights constructed from contemporaneous fuel shares, which allows for domestic energy price to respond not only to changes in the underlying fuel and electricity prices but also the composition of energy consumption across fuel types and the composition of the industry across establishments. We calculate this domestic energy price using contemporaneous shares as

$$p_{jt}^{energy} = \sum_{i \in j} \left[\left(\sum_{f} (p_{fsrt} \times \alpha_{fjrt}) \times (1 - \beta_{ijrst}) + p_{ijrst}^{elec} \times \beta_{ijrst} \right) \times \gamma_{ijrst} \right],$$

where j indexes industries and t indexes years. We aggregate each industry over a set of establishments, which are indexed by i, and each establishment is located in a state, s, and a region, r. Annual state-level fuel prices, p_{fsrt}, are reported in SEDS. We combine these prices with fuel shares at the industry-region-year level, which come from MECS[11] and are calculated as

$$\alpha_{fjrt} = \frac{q_{fjrt}}{\sum_f q_{fjrt}},$$

where f indexes the primary fuels used in manufacturing processes. This average of fuel prices weighted by fuel shares yields the average price of primary fuels consumed by manufacturing establishments in an industry-state-year. The other energy source for manufacturing establishments is electricity; establishment-level electricity price, which is denoted as p_{ijrst}^{elec}, is from CMF and ASM data.[12] We then calculate the establishment-level energy price as the weighted average of primary fuel prices and electricity at the establishment, with the weights equal to the share of energy consumed that is from that energy source. In the equation above, these shares are summarized by β_{ijrst}, which is the share of energy that is electricity,

$$\beta_{ijrst} = \frac{q_{ijrst}^{elec}}{q_{ijrst}^{energy}}.$$

We finally average the establishment-level energy prices over all establishments within an industry, weighting by the share of total industry energy consumption that occurs at each establishment.

[11] The MECS survey is taken every four years. We interpolate fuel shares for the intervening years.

[12] The CMF and ASM report the value and quantity of electricity purchased by each establishment. We calculate the average electricity price for the establishment as the ratio of value and quantity.

These shares are

$$\gamma_{ijrst} = \frac{q_{ijrst}^{energy}}{\sum_{i \in j} q_{ijrst}^{energy}}.$$

This yields the average domestic energy price for an industry-year using contemporaneous shares.

An alternative measure of domestic energy price holds all of the shares fixed over years, so changes in the price over time represent only changes to the underlying fuel and electricity prices and not changes in the fuel shares or industry composition. We calculate this domestic energy price using baseline shares as

$$\tilde{p}_{jt}^{energy} = \sum_{i \in j} \left[\left(\sum_{f} (p_{fsrt} \times \tilde{\alpha}_{fjr}) \times (1 - \tilde{\beta}_{ijrs}) + p_{ijrst}^{elec} \times \tilde{\beta}_{ijrs} \right) \times \tilde{\gamma}_{ijrs} \right].$$

In this measure we calculate each of the weights as the average share over all years in our data. That is,

$$\tilde{\alpha}_{fjr} = \frac{\sum_t q_{fjrt}}{\sum_t \sum_f q_{fjrt}},$$

$$\tilde{\beta}_{ijrs} = \frac{\sum_t q_{ijrst}^{elec}}{\sum_t q_{ijrst}^{energy}}, \text{ and}$$

$$\tilde{\gamma}_{ijrs} = \frac{\sum_t q_{ijrst}^{energy}}{\sum_t \sum_{i \in j} q_{ijrst}^{energy}}.$$

Domestic energy prices are summarized in Table 4 for both the full sample of EITE industries. The price using contemporaneous shares is less than that using baseline shares, which reflects manufacturing establishments adjusting the composition of energy sources in response to changing relative prices. There is also substantial variation across industries using either measure, even within the 3-digit NAICS and 2-digit NAICS-by-year levels, which again suggests there is sufficient variation in the data for this analysis.

We also include foreign energy prices in our analysis to capture differences in the energy prices faced by domestic and foreign producers. The relevant foreign energy prices to consider are the prices in countries where imports originate and where exports are destined, and we calculate a set of foreign energy price for each industry based on industry-specific trade partners. Enerdata Global Energy Data and IEA Energy Prices and Taxes datasets include electricity and natural gas prices for most countries in the world, including the largest trade partners of the United States. We calculate a weighted average of these prices with country weights equal to the average import or export trade volume for each industry in our analysis. The result is a set of four foreign energy prices for each industry: average electricity price for export destinations, average natural gas price for export destinations, average electricity price for import origins, and average natural gas price for import origins.

Foreign energy prices are summarized also in Table 4. Energy prices in countries where exports are shipped are greater on average than are those in countries where imports originate. This supports the intuition that the U.S. exports relatively more to countries with higher energy prices, and hence a greater cost of producing goods in these EITE industries, while importing relatively more from countries with a lower cost of producing these goods. As with other variables, there is substantial variation in foreign energy prices across industries and years, even within the 3-digit NAICS level. However, variation within the 2-digit NAICS-by-year level is much less because of common fluctuation in fuel prices with a year.

4.4 Energy and emissions intensity

We include energy intensity in this analysis as a source of leakage heterogeneity by industry. We calculate energy intensity as the portion of input costs that are energy consumption. The value of energy consumed and the total value of inputs for each establishment are reported in the CMF and ASM. As with domestic energy prices, we calculate two measures of energy intensity, to allow or control for changes in industry composition in response to changing energy prices. The measure that allows for a composition response is described as using "contemporaneous shares," and the measure that controls for this response by fixing the composition is described as using "baseline shares." The calculation of these measures is described in detail in this section.

The first measure of energy intensity is calculated as the portion of an industry-year's total input costs that are energy when summed over all establishments in the industry,

$$EI_{jt} = \frac{\sum_{i \in j} c_{it}^{energy}}{\sum_{i \in j} c_{it}^{total}},$$

where again j indexes industries, t indexes years, and i indexes establishments. c_{it} is input cost for establishment i in year t, and the superscript denotes either the energy component of this cost or the full input cost. This method is equivalent to calculating the energy intensity of each establishment and taking a weighted average with weights equal to the share of the industry's total input cost that is incurred at each establishment. This alternative formulation is

$$EI_{jt} = \sum_{i \in j} (EI_{it} \times \xi_{it}),$$

where

$$EI_{it} = \frac{c_{it}^{energy}}{c_{it}^{total}},$$

$$\xi_{it} = \frac{c_{it}^{total}}{\sum_{i \in j} c_{it}^{total}}.$$

Because this formulation uses input cost shares that vary annually, we refer to it as energy intensity using contemporaneous shares.

An alternative measure of energy intensity holds establishment shares fixed over years, so changes in energy intensity over time represent only changes in establishment-level energy intensity and not changes in the industry composition. We calculate this energy intensity using baseline shares as

$$\tilde{EI}_{jt} = \sum_{i \in j} \Big(EI_{it} \times \tilde{\xi}_i \Big).$$

In this measure we calculate the weights as the average share over all years in our data. That is,

$$\tilde{\xi}_i = \frac{\sum_t c_{it}^{total}}{\sum_t \sum_{i \in j} c_{it}^{total}}.$$

Table 4 displays summary statistics for these energy intensity measures. Energy intensity using contemporaneous shares is greater than energy intensity using baseline shares. This is likely mechanical because an increase in energy costs at an establishment will increase the total input cost at that establishment, and hence the weight that establishment receives under contemporaneous shares, particularly in the more energy-intensive industries. As with the other variables in this analysis, there is substantial variation in energy intensity, even among these industries that are all classified as being energy-intensive. This is also true when examining variation within the more aggregated 3-digit NAICS and 2-digit NAICS-by-year levels.

Figure 5 summarizes the evolution of energy intensity (measured as energy expenditures/input costs) over our time period. Averaged across all industries in our sample, energy intensity increases during the period, and then decreases after 2008, remaining between 4 and 6 percent during the sample period. The reason for the fall in energy intensity is due to the drop in energy prices during the period. When energy prices fall, the energy share of input costs falls if input shares are held constant. Trade exposure, defined as the value of imports and exports divided by imports plus domestic value, in contrast, exhibits a steady increase during the sample period, growing from around 18 percent to over 35 percent.

Separately, we construct several different industry-specific measures of CO_2 intensity. For each establishment-year, we convert megawatt-hours of electricity consumption to tons of CO_2 emitted using EIA's marginal emissions rates for purchased electricity, which vary at the state-year level. Likewise, we convert millions of British thermal units (MMBTUs) of primary fuel consumption into metric tons of CO_2. This is less straightforward, since the CMF/ASM reports total MMBTUs consumed, without differentiating across primary fuels with varying carbon intensities. We apply industry-region-specific primary fuel shares from MECS ($\tilde{\alpha}_{fjr}$, as described above) in order to assign MMBTUs of primary fuel consumption to specific fuels.[13] We then multiply consumption of each type of fuel by fuel-specific CO_2 intensities, which we also obtain from the EIA. This allows us to calculate a (rough) estimate of total CO_2 emissions from primary fuels, at the establishment-year level.

We aggregate these emissions estimates to construct three measures of emissions intensity, at

[13] For example, primary fuel consumption for cement manufactures in the Midwest census region may comprise 60 percent natural gas, 20 percent residual fuel oil, 10 percent petroleum coke, and 10 percent other fuels.

the industry level. First, we calculate the average CO_2 emissions rate, in metric tons of CO_2 per MMBTU consumed. For each industry j, we simply divide total CO_2 emissions across all establishments and years by the total MMBTUs consumed from electricity and primary fuels:[14]

$$\left(\frac{\text{metric tons CO}_2}{\text{MMBTU}}\right)_j = \frac{\sum_t \sum_{i\in j}\left(q_{irst}^{elec} e_{st}^{elec} + q_{irst}^{fuels}\sum_f \tilde{\alpha}_{fjr} e^f\right)}{\sum_t \sum_{i\in j}\left(q_{irst}^{elec} + q_{irst}^{fuels}\right)}.$$

Here, q_{irst}^{elec} and q_{irst}^{fuels} represent MMBTUs of electricity and aggregate non-electricity fuel consumption, rather than physical quantities, for establishment i in region r and state s, in year t. The fuel shares $\tilde{\alpha}_{fjr}$ are differentiated by industry j and region r. Marginal electricity emissions rates e_{st}^{elec} vary by state-year, while fuel-specific emissions factors e^f are constant. Next, to account for differences in size and economic value across industries, we calculate an analogous measure of average CO_2 intensity denominated by total value of domestic shipments:

$$\left(\frac{\text{tons CO}_2}{\$1000 \text{ value}}\right)_j = \frac{\sum_t \sum_{i\in j}\left(q_{irst}^{elec} e_{st}^{elec} + q_{irst}^{fuels}\sum_f \tilde{\alpha}_{fjr} e^f\right)}{\frac{1}{1000}\sum_t \sum_{i\in j} q_{irst}^{d}},$$

where q_{irst}^{d} represents the total value of shipments for establishment i in year t. Finally, we construct average "direct" CO_2 intensity, by including only emissions from primary fuels:

$$\left(\frac{\text{tons CO}_2 \text{ direct}}{\$1000 \text{ value}}\right)_j = \frac{\sum_t \sum_{i\in j}\left(q_{irst}^{fuels}\sum_f \tilde{\alpha}_{fjr} e^f\right)}{\frac{1}{1000}\sum_t \sum_{i\in j} q_{irst}^{d}}.$$

We summarize these three CO_2 intensities measures in Table 4 and, for selected industries, in Figure 4. We see that the average direct CO_2 intensity is close to half the total average CO_2 intensity, implying that close to half of emissions in these industries come from primary fuel consumption on site.

4.5 Capital and labor inputs

When analyzing the responsiveness of trade flows to changes in relative energy costs, it is important to control for other factors that determine production decisions and trade transactions. In particular, we use detailed data on labor and capital inputs to track variation in labor and capital costs across industries and across time.

Wages are calculated as the ratio of an industry's payroll to the industry's total number of employees, giving the average annual salary in the industry. The CMF and ASM report payroll and employees for each establishment-year, and we sum over all establishments in an industry to get industry totals. Wages are summarized in Table 3.

Capital intensity is measured as the portion of value added not accounted for by wages to

[14] We also weight this emissions rate by the average value of shipments for each industry.

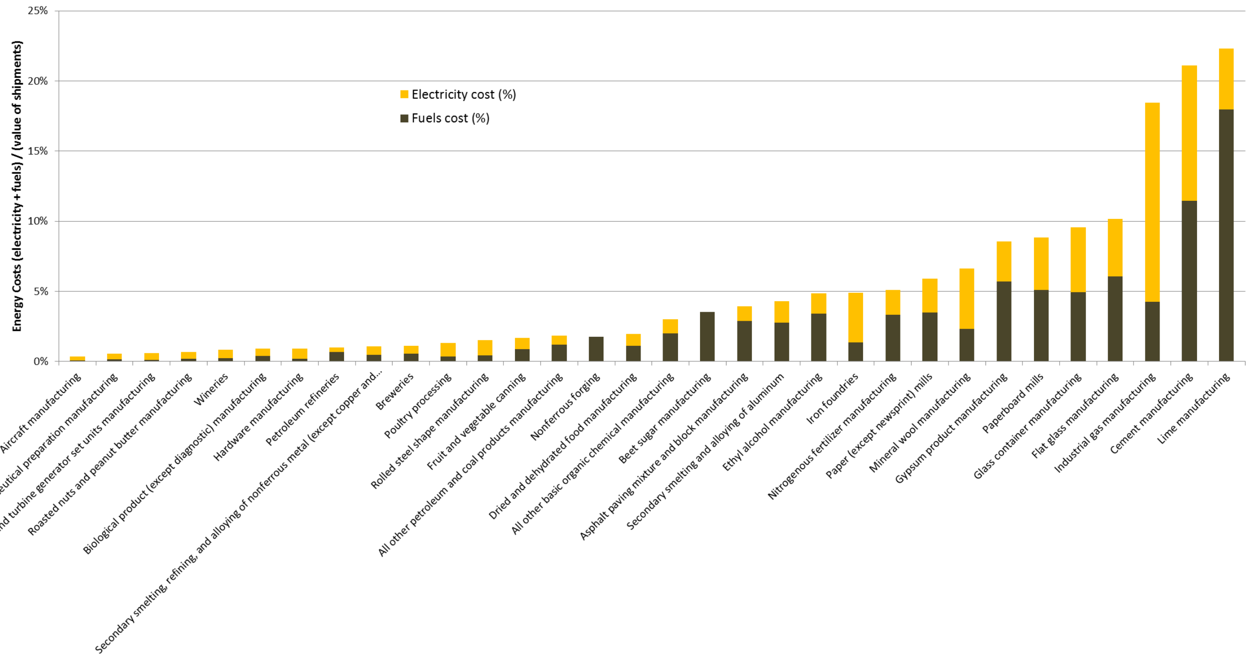


Figure 4: Energy Share and Composition Across Select Sectors

This figure shows the average cost of electricity and fuels as a share of the value of shipments in 2012 for select sectors in 2012. Source: U.S. Census (Economic Census) Public Data.

production workers. The CMF and ASM report value added and payroll for production workers for each establishment-year, which we sum over all establishments in each industry. We then take the difference between value added and production payroll and divide by value added to calculate capital intensity. This measure is summarized in Table 3.

5 Estimation

The theoretical analysis summarized in Section 3 provides an explicit basis for targeting leakage mitigation measures. Conditional on the maintained assumptions, the emissions leakage per unit of production in a given industry can be approximated by the product of foreign emissions intensity, e_f, foreign output elasticity, η, and a measure of trade share, $\frac{q^f}{q^d}$. The first and third arguments can (in principle) be calibrated directly using data on foreign emissions, foreign production, trade flows, and domestic production. Indeed, these are measures commonly used to determine leakage risk. The calibration of the elasticity of trade flows to changes in relative operating costs, η, is more complicated. One requires estimates of how responsive domestic production, imports, and exports are to policy-induced changes in operating costs.

Our empirical objective is to characterize the extent to which domestic production, imports and exports respond to changes in relative energy costs. The empirical estimation of these elasticities is the focus of this section. We begin by summarizing some important challenges that complicate

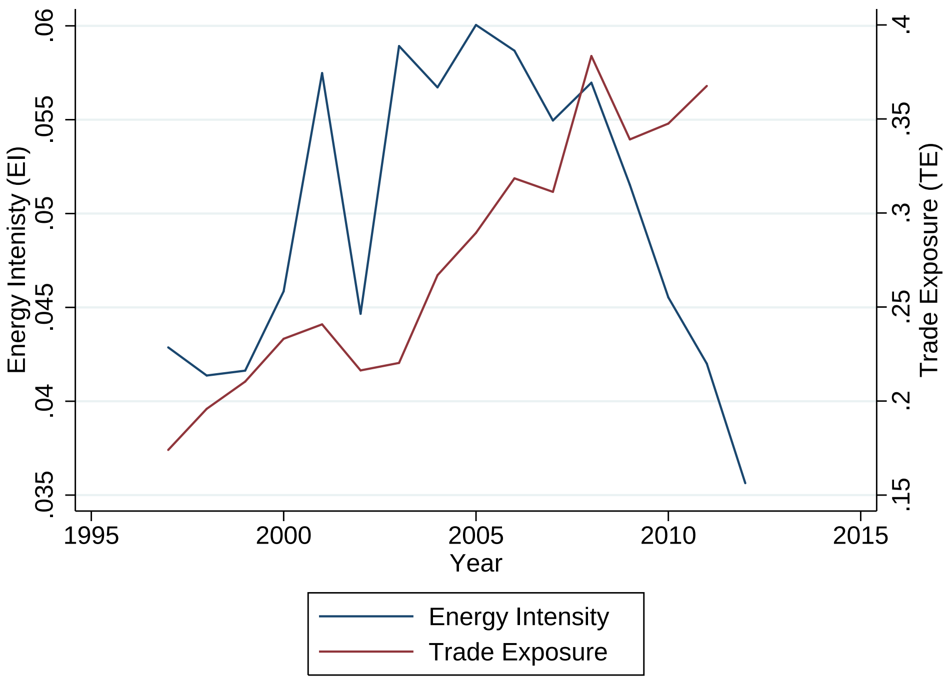


Figure 5: Evolution of Emissions Intensity and Trade Exposure Over Time

This figure displays the average energy intensity and trade share over our time period. Values are averaged across all establishments and transactions represented in our data. Energy Intensity (EI) is measured as the share of energy costs over total input costs. Trade exposure (TE) is measure as the share of imports and exports over imports and domestic production.

this kind of estimation exercise in general. We then present our estimation strategy and discuss how our approach responds to these challenges. Finally, we present our main results.

5.1 Empirical challenges

Five key challenges complicate any analysis of the causal impacts of environmental regulation on trade flows. We summarize these briefly below and discuss our strategies for dealing with each issue.

1. Although theory yields the clear prediction that policy-induced increases in domestic operating costs will reduce net exports in emissions-intensive industries, the theory does not yield estimable structural relationships between policy parameters and economic outcomes. To get any empirical traction, researchers need to make assumptions about the structure or functional form of these economic relationships. These choices can be fairly arbitrary, so it is important to evaluate how sensitive empirical results are to alternative plausible assumptions.

2. Policy-induced changes in operating costs are one of many factors affecting firms' import, export, and production choices. As noted above, if this policy-induced cost variation is correlated with other omitted factors, this can lead to spurious and misleading results. In what follows, we take several steps to purge our estimates of the effects of potential confounds.

3. Prices and quantities are simultaneously determined. This simple fact greatly complicates empirical tests for a causal effect of a regional emissions policy on trade flows. In our case, we are interested in estimating how changes in relative energy prices (a proxy for market-based climate change policy) affects trade patterns. Note that causal relationships can run in both directions. For example, suppose economic growth abroad increases demand for our exports. This could increase domestic manufacturing output, increase industrial energy demand, and increase domestic energy prices.

4. Industry-level response to production cost shocks can take time to play out completely; many industries have large capital shares that adjust slowly. Documenting industry response over short-time scales may capture only a fraction of the response to changes in relative operating costs (e.g., short-run re-optimization over inputs to production). Taking measurements over longer time horizons can capture long-run effects (e.g., effects on capital investment, entry, and exit), but the longer the time horizon, the greater the risk that changes over time are driven by other pertinent time-varying factors unrelated to regulation, leading to spurious responses between the policy and industry responses. Empirical researchers must take care to interpret results in the context of how they are constructed (i.e., short, medium, or long run changes).

5. There is significant inter-industry and intra-industry variation in production processes, market conditions, management strategies, etc. This variation could beget economically significant

differences in how firms and industries are impacted by policy-induced changes in energy costs. Thus, estimates of average effects can mask economically significant heterogeneity in industry and firm-level responses and impacts.

With our particular application, we confront two additional challenges.

1. We may overestimate the leakage risk in some industries. The preceding theoretical framework models the responsiveness of foreign production (q^f) to a policy-induced change in domestic operating costs (τ). However, we do not observe all foreign production in our data. Instead, we observe only imports into the U.S. and domestic exports to foreign markets. The focus of our estimation is, therefore, on the impacts on import and export flows. Estimated changes in import and export volumes can be used to construct an upper bound on market transfers.

2. We are interested in assessing how a possible national cap-and-trade program for mitigating greenhouse gas could affect industrial activity and associated trade flows. Compliance costs include the cost of purchasing compliance instruments to offset CO_2 emissions in a regional emissions trading program and indirect costs that manifest as higher energy prices (which reflect the compliance costs of energy suppliers). We use variation in relative operating costs that mimics the effect of compliance costs to estimate the effects we are interested in.

5.2 Estimating framework

We estimate how a change in domestic energy costs, conditional on other factors (including foreign energy costs, labor costs, etc.), affects levels of domestic industrial production, import, and export flows. We are particularly interested in estimating how trade volumes respond to changes in relative operating cost because these estimates provide insights into the potential for market transfer in response to a change in relative energy costs.

As noted above, theory does not provide explicit guidance on the choice of functional form for these relationships. We thus evaluate a range of plausible forms. The most general form of the specifications we estimate can be summarized as follows:

$$\ln(y_{it}) = \alpha_0 + f(p_{it}^d, p_{it}^f, X_{it}; \beta) + \gamma \ln(w_{it}) + \phi_i + \eta_{st} + \varepsilon_{it},$$

where

$$\begin{aligned}
i &= \text{6-digit NAICS index,} \\
t &= \text{year index,} \\
y_{it} &= \text{aggregate outcome for industry } i \text{ in year } t, \\
p_{it}^d &= \text{domestic energy price,} \\
p_{it}^f &= \text{foreign energy price (a vector of foreign electricity and gas prices),} \\
X_{it} &= \text{Industry characteristics other than energy intensity (e.g., capital intensity),}
\end{aligned}$$

w_{it} = domestic wage,

ϕ_i = 3-digit NAICS fixed effects,

η_{st} = year by sector (2-digit NAICS) fixed effects.

The dependent variable, y_{it}, is the total value of domestic production, total value of imports, or total value of exports, deflated to 2010 dollars. The relationship between these outcomes, domestic energy prices (p_{it}^d), foreign energy prices (p_{it}^f), and observable industry characteristics (X_{it}) such as energy intensity and capital intensity is summarized above as $f(p_{it}^d, p_{it}^f, X_{it}; \beta)$. We estimate several alternative forms of this relationship. The vector of parameters to be estimated is β. One restriction we impose across all specifications is that foreign and domestic energy prices enter symmetrically.

Observations are weighted using the corresponding industry-specific average value. This is fairly standard in the literature because, in an unweighted regression, industries with very small shipments/import/export values will have disproportionate effects on estimates.[15] On another technical note, we find that some of our estimates are sensitive to a small number of outlying observations. Several of these appear to be the result of data entry errors. We follow the literature (e.g., Ederington et al. (2005)) and use an approach suggested by Hadi (1992, 1994) to identify outliers in our data set; these outliers (which comprise less than 0.2% of observations) are excluded from the analysis.

In addition to explicitly conditioning on time varying factors such as foreign energy prices and labor costs, we include a set of fixed effects to control for other factors that determine domestic production, import flows, and export flows, respectively. All preferred specifications include 4-digit NAICS industry fixed effects to control for the effects of time-invariant factors (such as persistent differences in foreign versus domestic production costs) that determine trade volumes and vary across industries. We also include 2-digit NAICS-by-year fixed effects to control for time-varying sectoral trends.

Our empirical strategy was designed with the aforementioned challenges in mind. In what follows, we briefly describe how out estimation strategy responds to each.

1. *Functional form assumptions:* Theory does not specify a particular functional form of the relationship between the outcome variables, relative energy prices, and energy intensity. We consider a range of plausible formulations (192 alternative specifications altogether). These specifications differ in terms of functional form and in terms of how key variables are defined and interacted. For example, we estimate specifications that include relative energy prices (rather than allowing domestic and foreign energy prices to enter separately and symmetrically). We experiment with the inclusion of lagged dependent variables and with specifications that are more or less saturated with fixed effects. In what follows, we will summarize estima-

[15]Some authors weight using average values that are computed using data from the period for which effects are estimated (e.g., Aldy and Pizer (2015)). Because our pre-period weights are highly correlated with weights that are constructed using data from our study period, our estimation results are not sensitive to how we construct the weights.

tion results from this range of plausible forms. This will allow readers to assess the sensitivity of key results to alternative structural assumptions.

2. *Endogeneity concerns:* There are many factors that drive trends in industrial production, imports, and exports. We cannot explicitly control for all of these factors. As noted above, if omitted variables are correlated with the factors we are most interested in (i.e., domestic energy prices), then our estimates of the relationship between outcomes and domestic energy prices can be biased and misleading. We include industry and sector-year fixed effects to sweep out the effects of possible confounding factors. The energy price parameters are thus identified from deviations in domestic energy prices from industry specific averages after adjusting for variation in foreign energy prices, wages, and annual shocks common to all industries within a sector. The error term in our estimating equations contain measurement and approximation error, plus any industry-specific time varying elements of the outcome variable that are not captured by the other controls. Given that results might be sensitive to alternative specifications, we present a battery of robustness checks below.

3. *Multiple margins of response:* We are somewhat limited in our abilities to capture long run responses given the available data. We do, however, make some distinction between responses to changes in relative energy prices that hold some margins of adjustment fixed (i.e., establishments are constrained in terms of their ability to re-optimize production) and responses that reflect firms' ability to adjust fuel shares and/or the location of domestic production.

4. *Heterogeneous responses:* We are particularly interested in the extent to which the response to a change in relative energy prices varies systematically with observable industry characteristics. We summarize estimation results from specifications that capture heterogeneity in terms of energy intensity and capital intensity. Capital intensity serves as a proxy for immobility; highly capital-intensive firms tend to be harder to relocate.

5. *Trade flows as a proxy for market transfer:* As noted above, our data does not include all foreign production. Instead, we use U.S. imports and exports as a proxy measure of changes in foreign production. We can use our estimates of how import and export flows respond to a change in domestic energy prices to bound the associated market transfer. If domestic imports are purely additional (i.e., when domestic demand for imports falls, foreign production falls one-for-one) and if domestic exports displace foreign production one-for-one, our estimated impacts on domestic imports and exports can be used to construct a proxy measure of changes in foreign production. In contrast, if an increase in domestic imports crowds out other demand, and/or if a reduction in foreign exports is not replaced one-for-one by foreign production, our estimated impacts on trade flows will over-estimate the market transfer. We will return to this point in the interpretation of our results.

6. *Energy price variation as a proxy for a carbon price:* Our empirical strategy leverages the

fact that we observe significant variation in domestic energy prices during our study period. As a result of sustained growth in domestic extraction, domestic natural gas prices have fallen substantially. Whereas natural gas is easy to transport by pipeline, it is costly to ship. Consequently, the domestic production shock has driven a wedge between domestic and foreign energy prices (see Figure 1). Ultimately, our ability to extract policy implications from this analysis is predicated on the assumption that a careful analysis of how firms have historically responded to persistent changes in relative energy costs can inform our understanding of how a carbon price would impact industrial production and international trade flows.

We use detailed establishment-level data on energy expenditures and foreign energy prices, summarized in Section 4, to construct industry-specific measures of relative energy price variation over the study period. We sweep out average differences across industries and sector-specific time trends. We also condition on foreign energy prices and other time varying determinants (e.g., labor costs). The variation in domestic energy costs that remains is used to estimate the relationship between energy costs, industrial production and associated trade patterns.

In some respects, this variation provides a useful proxy for policy-induced energy price changes. Compliance with a GHG emissions trading program affects industrial operating decisions primarily via an increase in relative energy costs (i.e., the energy costs of regulated firms vis a vis their unregulated rivals). Over the past several years we have seen firms and industries responding to a sustained change in energy prices that is largely confined to the United States. The magnitude of the energy price impacts associated with a \$10 or \$15 per metric ton of CO_2 carbon price lie within the scale of the variation in relative energy prices that we will use to identify impacts on production and trade flows.

That said, the identifying variation in energy prices is not perfectly isomorphic to the policy-induced change we wish to evaluate. One obvious difference is that we observe a decline in domestic energy prices relative to foreign energy prices, while a carbon policy would work in the opposite direction. Firms responses to recent reductions in relative energy prices can help us anticipate the response to a carbon price if the carbon policy effectively unwinds the effects of recent reductions in relative energy costs.

5.3 Illustrative Regressions

The theory above helps guide the empirical investigation by suggesting what factors are going to be important determinants of how production, imports, and exports respond to changes in relative energy prices. However, the theory leaves the exact relationship between those variables unspecified, which is why we have taken the approach of estimating many different functional forms. Our basic aim is to characterize robust empirical relationships between variables that are common across specifications, helping reduce concerns that our results are driven by specification error. Overall, we estimate close to 600 specifications using the full sample of data covering 98 EITE industries. This estimation exercise generates thousands of parameter estimates; far too many to report individually. To characterize the range of estimates we obtain across the full suite of specifications, we will summarize the complete distribution of the most policy relevant parameter estimates. To provide a more in depth understanding of the empirical results, we select a small subset of specifications and analyze these estimates in depth.

We begin by presenting the results for three closely-related specifications, where the regressions differ in how the response of the outcome variables to variation in domestic and foreign energy costs is modeled. In the linear specification, log transformed measures of domestic and foreign energy prices are interacted with an industry-specific measure of energy intensity. The log specification includes these same interactions, but using log-transformed measures of energy intensity. We also estimate a more flexible specification in which (log) energy prices are interacted with a piece-wise linear function of energy intensity.[16] All specifications include 3-digit NAICS fixed-effects, 2-digit NAICS-by-year fixed effects, and industry-specific measures of time-variant wages. Domestic and foreign energy prices enter symmetrically in all specifications.

Table 5 summarizes the regression results generated using a comprehensive measure of energy cost variation that reflects not only intertemporal variation in domestic and foreign energy prices but also changes in fuel mix and regional allocation of industrial activity. These estimates thus capture multiple margins of firms' re-optimizing response to changes in relative energy costs. Coefficient estimates are reported in the top panel of results. Given the large number of parameters to be estimated, we report only a subset of the coefficient estimates, omitting industry fixed effects, sector-year fixed effects, and interactions involving foreign energy prices. These unreported coefficients capture the effects of confounding factors but do not have direct interpretation with respect to leakage quantification.

These coefficient estimates are difficult to interpret individually, particularly given the number of parameters in each specification. To provide a more intuitive sense of what these estimates imply, we use these regression coefficient estimates to calibrate industry-specific estimates of how domestic production, imports, and exports respond to a given change in domestic energy prices. We construct these industry-specific responsiveness parameters as elasticities. These parameters measure the percent change in an outcome associated with a one percent change in domestic energy prices. The middle panel summarizes how these elasticity estimates vary across industries, with the 25th (P25), median (P50), and 75th (P75) percentile estimates reported.

The first three columns of Table 5 summarizes the results the regression equations that analyze variation in domestic production across time and across industries. Across all specifications, an increase in domestic energy costs (conditioning of foreign energy costs and other factors) is associated with a decrease in domestic production on average. The middle panel summarizes the distributions of elasticity estimates. The larger (in absolute value) the elasticity estimate, the larger the estimated effect of a change in energy costs on domestic production (in percentage terms). All

[16] In particular, we consider a spline with three different pieces, at the 33rd and 66th percentile of the distribution of energy intensity. This means that we allow the impacts to be different for the one third least energy-intensive industries, the midrange energy intensive industries, and the one third most energy intensive industries.

estimates are negative (i.e., an increase in energy costs is associated with a decrease in domestic production across all 97 industries).

As noted above, the table reports on specifications that differ in terms of the structure we impose on the relationship between the production response to energy costs and energy intensity. We find that our elasticity estimates are sensitive to how we specify the estimating equation. For example, using the log specification, our estimates imply that a 10% increase in domestic energy prices is associated with a 10.6% decrease in domestic production for the median industry. Using the linear or spline specifications, this median impact estimate is approximately half as large in absolute value.

The final six columns in Table 5 present analogous results for exports and imports, respectively. Intuitively, an increase in domestic energy prices is associated with an increase in imports from foreign markets and a decrease in export values. These estimated impacts are smaller in absolute value. For exports, a 10% increase in domestic energy prices is associated with reductions ranging from 2.4% to 8.6% in the median industry. For imports, a 10% increase in domestic energy prices is associated with an increase in import volumes ranging from 3.2% to 4.2% in the median industry. Several of these import and export effects are noisy and cannot be distinguished statistically from zero.

We also report a second set of results use only the variation in fuel prices and energy intensities generated by changes in domestic and foreign energy prices (i.e., holding fuel shares and the regional allocation of domestic production fixed at baseline levels). These estimates isolate the effects of variation in relative energy costs that is generated by changes in relative energy prices. Table 6 presents the estimates. The qualitative results are similar to those in Table 5. Estimated elasticity parameters are generally smaller in absolute value. This makes intuitive sense. The results summarized by Table 5 account for firms ability to re-optimize production (i.e., fuel mix and allocation of production across regions) in response to relative changes in energy prices. In Table 6, underlying specifications hold these margins of adjustment fixed at pre-period levels.

As another way of summarizing the output from our regressions, Figure 6 provides a graphical summary of the industry-specific elasticity parameters. For each industry, for each specification, we estimate the elasticity of domestic production, imports, and exports to a percentage change in domestic energy prices. Ordering industries according to energy intensity, we report the mean elasticity estimate together with the 95% confidence interval. So, for example, for industries located close to the average of the energy intensity distribution (i.e., with energy costs accounting for approximately 6 percent of input costs, an Energy Intensity of 0.06 in Figure 6.), a percentage increase in energy prices (conditioning on other determinants) is associated with a decrease in shipment values on the order of 0.5 percent. Whereas the point estimates for any given industry may be quite noisy, the general pattern is clear. Estimated impacts on production and trade flows, in percentage terms, are generally small among industries with low energy intensities. Estimated elasticities are larger in absolute value among the most energy-intensive industries. One can also see that domestic production is the most responsive to changes in domestic energy prices (in elasticity

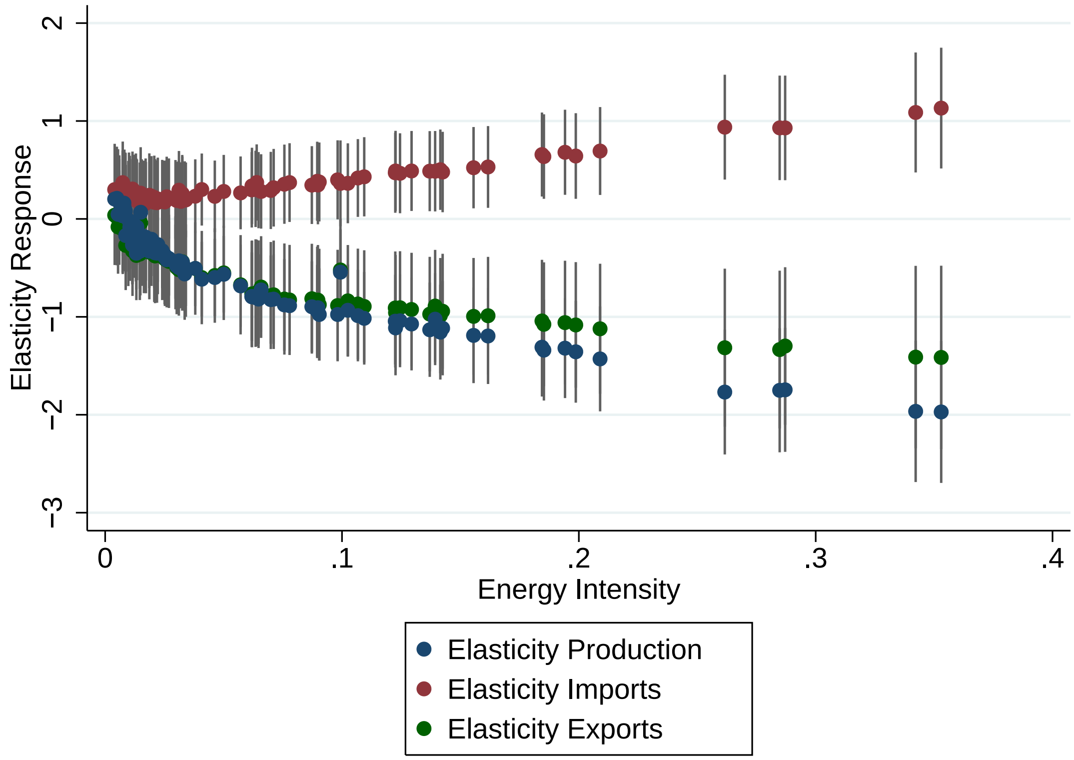


Figure 6: Coefficient Estimates along Energy Intensity

This figure displays the elasticities of domestic production, imports and exports with respect to domestic energy prices, as a function of energy intensity, together with their 95% confidence interval. Our estimates suggest that domestic production, imports and exports are most responsive for more energy-intensive industries.

terms), whereas imports are least responsive.

Interactions. Specifications summarized so far emphasize heterogeneity in response to changes in energy prices along the dimension of energy intensity. However, this production and trade responsiveness could vary along other observable dimensions. For example, "footlooseness," the mobility of the industry's production as a function of capital fixity, has been identified in the literature as a potentially important determinant. We thus consider the interaction between domestic energy prices and capital intensity.

Table 7 summarizes the estimation results associated with these more flexible specifications that incorporate these additional interactions. The table pools estimates from across multiple specifications. Overall, the inclusion of additional interactions does not significantly affect the distribution of calibrated parameters summarized by the coefficients for P25, P50, and P75.

5.4 Main Results

As discussed above, theory provides an invaluable guide with respect to identifying key determinants of emissions leakage and specifying measures that can be use to assess or anticipate where emissions leakage is most likely to manifest. However, economic theory leaves much to be determined when it comes to specifying precisely the underlying economic relationships. This begs the question: how sensitive are our estimates of key parameters to these specification choices?

To address this question, we estimated close to 200 alternative specifications for each outcome variable. Specifications vary in terms of how energy prices enter the equation, the extent to which we saturate the model with fixed effects, how we construct our measures of energy costs, the set of interaction terms included, etc. Although it is impractical to report tables of estimates for all 576 specifications, we can summarize these results in a way that allows the reader to assess the robustness of the results.

Figure 7 provides a graphical summary of the range of estimates we obtain. These figures plot the distribution of elasticity estimates at each of three percentiles (25, 50, and 75) across 192 different model specifications. In the first row, we present density plots for domestic production elasticities at the 25, 50, and 75 percentiles of these elasticity distributions. Recall that the more extreme negative response is associated with the 25th percentile industry. So the top left graph plots the range of estimates we obtain at the 25th percentile of domestic production responses. At this 25th percentile, estimated elasticities are negative across the vast majority of specifications. Although the sign of the effect is robust, the magnitude of the estimated impacts are sensitive to our specification choices.

At the 75th percentile, we find a mass of estimates at zero which can be interpreted as a zero impact of changes in relative energy prices on domestic production. We do observe some positive elasticity estimates, particularly in the upper range of the distribution. Note that theory does not rule out a positive production response to an increase in domestic energy prices. A relative increase in domestic energy prices could lead to an *increase* in domestic production in relatively less carbon intensive sectors if the energy cost shock results in substitution of less emissions intensive products for relatively more emissions intensive products.[17]

The second row summarizes the range of estimates we obtain for exports. The results are comparable to those for domestic production, with estimates being mostly negative across a wide range of specifications. However, we find some extreme outliers in our estimates, for a small subset of specifications. These distributions also show that, in general, the response of exports tends to be smaller in absolute value as compared to the response in domestic production. In other words, we find that exports are less responsive to changes in relative energy prices.[18]

In the third row, we show the estimated effects for imports. Because these impacts are posi-

[17] Our simple analytical model does not account for substitution of industrial outputs. Extending the model to accommodate substitution between more and less emissions intensive products allows for positive production elasticities.

[18] This result is consistent with the empirical trade literature, which has shown that firms which export more are also usually the most productive, and therefore potentially more able to weather the impacts of a carbon price.

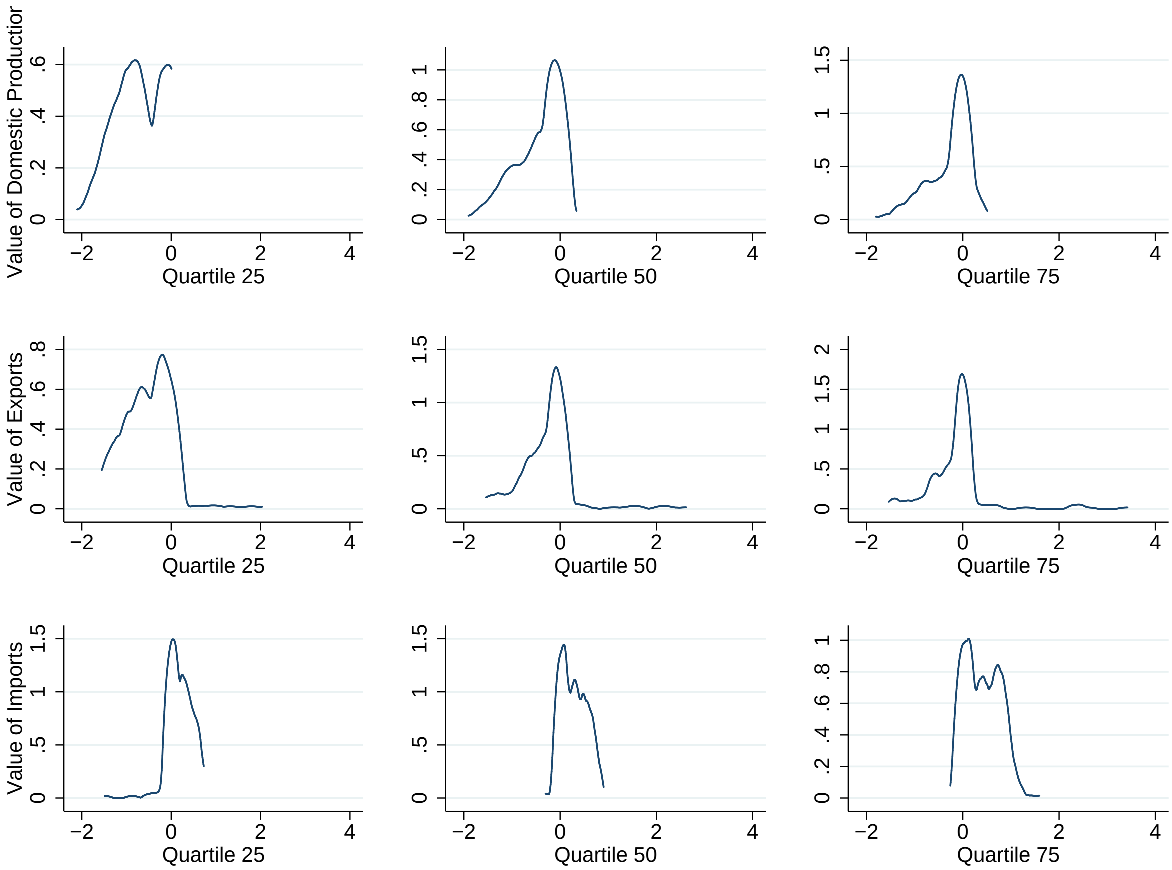


Figure 7: Elasticity Estimates Across Specifications

This figure displays the density plots of the estimated elasticities over 192 different specifications.

tive (i.e., an increase in domestic energy prices is generally associated with an increase in import flows), the relatively large responses are associated with the 75th percentile industries. At the 25th percentile, there is a mass of zero impact estimates. Similar to exports, the sensitivity of imports is lower than that of domestic production.

Finally, Table 8 reports industry-specific distributions of elasticity estimates for production, imports, and exports. This table summarizes estimated production and trade responsiveness parameters (in terms of elasticities) for each industry across the full suite of specifications estimated. Using the first industry (breakfast cereal 311230) as an example, we see that the median estimate of the domestic production elasticity is -0.42 and that 50 percent of estimates lie between -0.19 (P75) and -0.55 (P25). In other words, a 1 percent increase in domestic energy prices is associated with reductions in domestic production on the order of 0.2 to 0.6 percent.

6 Simulation results

6.1 Simulated policy impacts

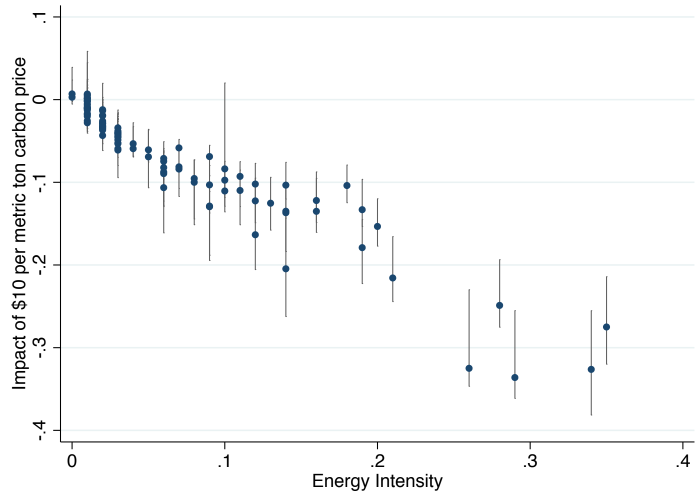
These estimates can be used to simulate the effects of a carbon price on domestic production, imports, and exports. Assuming complete pass-through by energy suppliers, we can calculate the effect of a given carbon price on industry-specific energy prices by multiplying the carbon price (measured in \$ per metric ton CO_2) by the industry-specific carbon intensity (measured in metric tons of CO_2/MMBTU) and the industry-specific energy price (measured in \$/MMBTU). Combining these price impacts with our industry-specific elasticity estimates, we estimate the impact of a given carbon price on domestic production, exports, and imports.

A specific example helps to fix ideas and connect the dots across two related studies. Consider the example of fruit and vegetable processing (NAICS 311421). Based on our estimates of the emissions intensity of energy inputs in this industry, and assuming complete pass through in energy prices, a \$10 per metric ton of CO_2 carbon price would increase energy costs by approximately 8 percent. Combining this energy price increase with our industry-specific elasticity estimates, we estimate reductions in domestic production ranging from 2 percent (25th percentile estimate) to 5 percent (75th percentile estimate). This is consistent with Hamilton et al. (2016), who estimate that a \$10 per metric ton of CO_2 carbon price would result in a 4 percent decrease in California tomato processing.

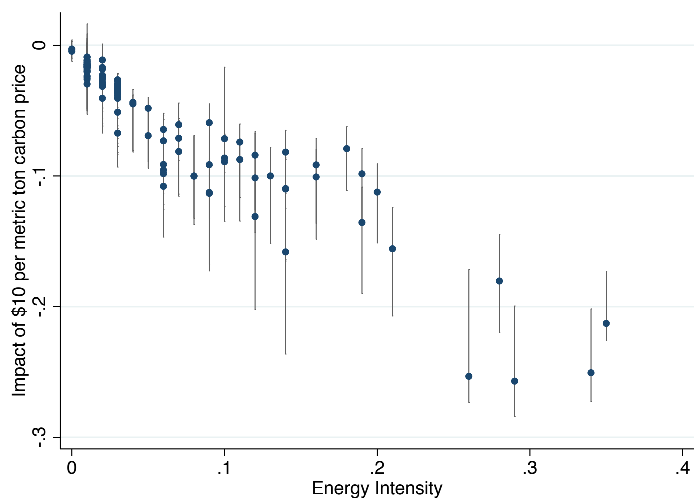
It is important to note that the vast majority of industries in our data are not highly energy or emissions intensive (e.g., with energy intensity above 0.2). Therefore, the estimated impacts in this range are much more sensitive to the specification that we consider, with the interquartile range being quite spread out. For energy-intensive industries for which we have more observations (i.e., in the 0.1 to 0.2 range), impacts on domestic production imply at most a 15 to 20 percent reduction, with exports being around 10 to 15 percent at most, and import response being between 5 to 7 percent at most. For all specifications, predicted impacts for non-energy-intensive industries are small.

Table 9 summarizes these results in greater detail. For each industry, we summarize the distribution of elasticity estimates obtained across the 192 specifications we evaluate. Starting with the estimated impacts on production, the most impacted are the emissions-intensive industries such as lime, cement, and nitrogen fertilizer. For these industries, median estimated impacts on production are on the order of 20-30 percent. For the majority of industries, estimated effects are much smaller. For industries classified by the Cap-and-Trade Regulation as low leakage risk, estimated median impacts average less than one percent.

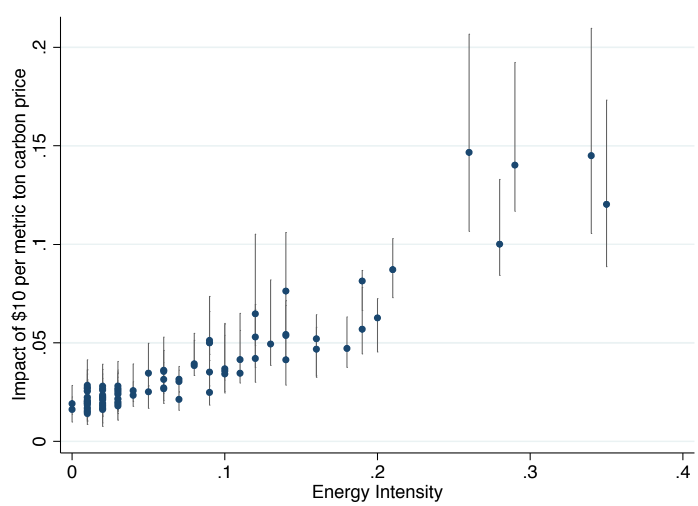
Turning to estimated impacts on exports, we see qualitatively similar patterns, although percentage estimates are somewhat smaller in absolute value. Import estimates are even smaller (in absolute value). Largest impacts among the top five emissions-intensive sectors range from 6 to 15 percent. Median impacts among industries classified by ARB as low leakage risk under the Cap-and-Trade Program are much smaller (on the order of 1 to 2 percent).



(a) Domestic production



(b) Exports



(c) Imports

Figure 8: Impact of a \$10 per Metric Ton of CO_2 Carbon Price

This figure displays the estimated impacts of a \$10 per metric ton of CO_2 carbon price, in percent.

In our analysis, we have focused on CO_2 emissions that are released in the process of consuming energy

and the associated costs incurred under a Cap-and-Trade program. As our empirical strategy leverages historic energy prices to estimate impacts on domestic production and trade flows, our regression estimates are relatively well suited to projecting the impacts of policy impacts that work via energy cost increases. However, some industries, such as gas manufacturing or lime, also face additional compliance costs due to the regulation of process emissions. In other words, these producers must purchase allowances to offset not only energy-related emissions, but also emissions generated during the industrial production process. In principle, we can extend our simulations of carbon price impacts to include these regulated process emissions. Table 10 presents a comparison between our estimated impacts with and without process emissions for those industries that generate carbon emissions in excess of those directly related to fossil fuel combustion. One can see that the impacts of a $10 carbon price can be substantially larger for industries in which process emissions represent a large share of total emissions.

One of the challenges for the interpretation of these estimates is that we use variation in relative energy prices to identify the effect of energy costs on production patterns. We do not explicitly control for variation in input prices other than energy and labor. Sector fixed effects will capture sectoral trends in input prices, intra-sector variation in input prices over time (especially energy intensive inputs) can confound our ability to isolate the effect of variation in energy costs from the effects of variation in energy-intensive input costs. For those industries in which non-energy input costs are strongly correlated with the energy price index (e.g., nitrogen fertilizer and industrial gas manufacturing), our estimates of the impact of energy price variation on production patterns is capturing both the direct and indirect effects of energy prices on production costs. This confounds the interpretation of the impacts from process and non-process emissions. In some sense, we have already accounted for the effects of energy price variation on energy (and carbon) intensive non-energy input costs. Thus, accounting for process emissions in addition to energy-related emissions can significantly overstate the impacts of a carbon price on production. For this reason, our preferred estimates are those that simulate impacts of a policy induced increase in energy costs. Given our empirical strategy, these will indirectly capture a substantial component of process-related compliance costs.

6.2 Implications for leakage

Thus far, we have used our empirical results to estimate the responsiveness of domestic production and trade flows to changes in relative energy prices. We have also simulated the impact of a carbon price on domestic industrial production, foreign imports, and domestic imports (in percentage terms).

The natural next step, from the perspective of a policy maker looking to assess leakage risk and target leakage mitigation measures, is to translate these responsiveness measures to corresponding measures of market transfer and associated emissions leakage. However, pushing on to this next step amounts to pushing up against the limits of available data. One complication is that calibrating the measures of leakage risk implied by the theory requires dividing one noisy estimate by another. Other caveats include the fact that we cannot directly observe foreign production and instead employ an imperfect proxy. In what follows, we describe a conceptually consistent, albeit noisy and caveated, derivation of leakage risk measures.

In principle, policy makers should target output-based subsidies at those industries where emissions leakage per unit of output is greatest. In section 2, emissions leakage is defined to be the policy induced increase in foreign emissions: $e_f \cdot dq_f$. Emissions leakage can also be expressed per unit of domestic production. In other words, when a carbon policy reduces domestic production incrementally, by how much do emissions increase in foreign jurisdictions. This international leakage rate can be defined as follows:

$$\text{output-based leakage rate} = e_f \cdot \frac{dq_f}{dq_d}$$

This is just the product of the market transfer rate and a measure of the marginal emissions intensity of foreign production. Intuitively, this expression helps to clarify the rationale behind output-based allowance allocation updating. A carbon price serves to internalize the damages caused by domestic emissions. But the implicit production subsidy conferred by output-based subsidy reflects the emissions avoided in foreign jurisdictions per unit of output in the regulated jurisdiction. The larger the impact on foreign emissions, the higher the leakage risk, the larger the justifiable subsidy.

Finally, it is also insightful to measure emissions leakage per metric ton of emissions reduced within the regulated jurisdiction:

$$\text{emissions-based leakage rate} = \frac{e_f}{e_d} \cdot \frac{dq_f}{dq_d}$$

In words, this emissions-based leakage rate is equal to the increase in foreign emissions per unit of emissions reductions achieved under the incomplete (domestic) policy. This can also be expressed as the market transfer rate (i.e., the rate at which a reduction in domestic production translates into an increase in foreign production), multiplied by the ratio of marginal emissions rates $\frac{e_f}{e_d}$.

A key component of both the emissions-based and output-based leakage rate is the market transfer rate. The first step towards calibrating the market transfer rate using our empirical estimates involves converting our estimated elasticities into level changes in imports, exports, and domestic production, respectively. Herein lies our first data limitation. We focus on estimating level changes in the trade flows that we can reliably measure. We multiply our estimated elasticities by the corresponding baseline level of imports and exports, respectively. For each industry, we use the national average value of shipments, average import value, and average export values over the period 2010-2014.

These estimates are used to construct an estimate of the national average rate of market transfer:

$$TransferRate = \frac{|ElasImp| \cdot Imp + |ElasExp| \cdot Exp}{|ElasProd| \cdot Prod}.$$

More precisely, we estimate the increase in foreign imports plus the reduction in domestic exports (measured in dollar terms) associated with a dollar reduction in domestic production. Recall that we cannot measure foreign production directly, so the sum of the change in imports plus exports can be interpreted as an upper bound on the change in foreign production.

Note that these industry-specific transfer rates are constructed as a ratio of our imprecise elasticity estimates. A ratio of noisy numbers can be very noisy; our industry-specific estimates of market transfer rates are sensitive to changes in how the underlying estimating equations are specified. Keeping in mind this lack of precision, point estimates of this upper bound estimate of market transfer rates are below 20 percent for most industries. These are interpreted as upper bounds because we expect that some fraction of the increase in import demand represents a re-allocation of foreign production (versus absolute increase).

In sum, this calibration exercise generates an approximate upper bound on national rates of market-transfer. To convert these market transfer rates to production-based leakage rates, one would need to multiply by industry-specific estimates of the marginal emissions intensity of foreign production. This would provide an upper bound on how an incremental reduction in domestic production affects carbon emissions in foreign jurisdictions, and an empirically calibrated measure of leakage risk.

Given the noisiness of these estimates, we cannot estimate the transfer rate for any given industry with any degree of confidence. But we can summarize general patterns in the estimates we obtain. Figure 9 shows a stylized heat map of maximum transfer rates as a function of energy intensity and trade shares. The diamond markers represent the combinations of energy intensity and trade exposure for the industries in our sample. One can see that there are some combinations of energy intensity and trade exposure that do not exist in our data. The graph is relying in extrapolation based on a regression model where we regress transfer rates for the industries that we observe on energy intensity and trade exposure. Our transfer rates are highest for those industries classified as having a "high" risk of leakage. On the contrary, low emitting industries and industries that have low trade exposure do not appear to have substantial transfer rates.

To convert these estimated market transfer rates into emissions leakage rates, we would need an estimate of the ratio of marginal emissions intensities ($\frac{e_f}{e_d}$). If the marginal emissions intensity of foreign production is equal to the marginal emissions intensity of domestic production, $\frac{e_f}{e_d} = 1$, and this transfer rate can be interpreted as the emissions leakage rate. If the marginal emissions intensity associated with foreign production is higher (lower) than the domestic emissions intensity, our measure will under (over) estimate the rate of emissions leakage.

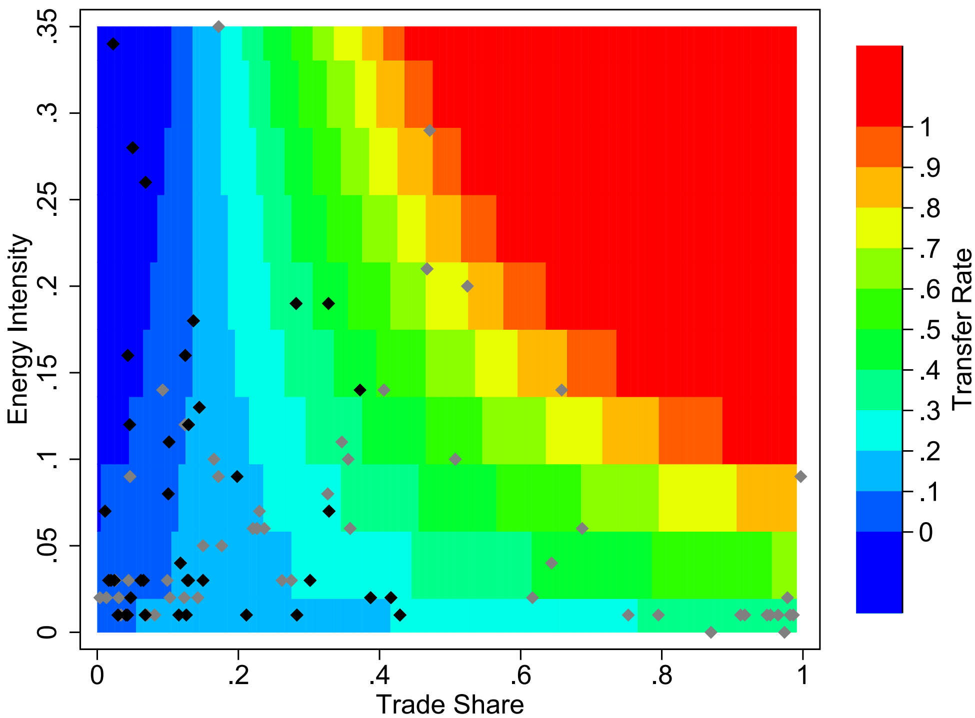


Figure 9: Heat Map of Transfer Rates

This figure displays estimated transfer rates as a function of energy intensity and trade share, as defined in the text. It represents a smooth relationship between transfer rates and EITE characteristics, obtained by regressing predicted transfer rates at the NAICS6 level on energy intensity, trade shares, and their interaction.

7 Conclusion

Regional climate change policies are ineluctably incomplete; only a subset of the emissions sources that contribute to the global climate change problem are subject to the regulation. Thus, policymakers working to reduce global climate change must try to strike a balance between reducing emissions within their jurisdiction and mitigating emissions leakage beyond their regulatory reach.

This report uses a simple analytical framework to understand the economic relationships that give rise to emissions leakage. Intuitively, two key determining factors are the responsiveness of unregulated/outside producers to policy-induced changes in domestic operating costs (i.e., the market transfer rate) and the emissions intensity of the unregulated producers who respond.

To date, policy makers have used industry-level measures of domestic emissions intensity and trade share to proxy for these determinants. This paper takes a different approach to measuring international leakage risk. We leverage the fact that, in recent years, we observe significant variation in domestic energy prices. In response to a production shock in the domestic oil and natural gas industries, domestic energy prices have fallen substantially relative to foreign prices. We argue that some portion of this variation can be used to isolate and estimate how changes in relative industrial operating costs (i.e., domestic versus foreign) have impacted domestic production and associated trade patterns across different industries. We use the estimated response of domestic production, foreign imports, and domestic exports to changes in relative operating costs to calibrate industry-specific measures of market transfer rates.

In order to use our estimates to project the likely impact of a carbon price on trade flows, we must assume that firms' past response to recent changes in relative energy prices (i.e., domestic energy prices relative to energy costs of our international trading partners) are informative about how these same firms are responding/will respond to a climate policy-induced change in relative energy prices. Invoking this assumption, we estimate the effects of a change in relative energy prices that mimics a \$10 per metric ton of CO_2 price (in 2010 dollars).

For most of the industries we consider, a \$10 per metric ton of CO_2 carbon price has a fairly small impact on trade flows in percentage terms. Our median estimates imply reductions in export values on the order of 6 percent or smaller for a majority of industries. For a handful of industries, we estimate larger impacts. For cement, lime, industrial gas, wet corn milling, nitrogen fertilizer, iron and steel industries, we estimate impacts on export volumes of 20 percent or greater. Our estimates yield somewhat smaller (in absolute value) percentage impacts on imports. We find increases in imports of 4 percent or less for most industries. Estimated impacts exceed 11 percent in cement, lime, and industrial gas industries.

Estimating the responsiveness of trade flows to energy price changes in percentage terms makes our estimates more comparable across industries. But of course, the extent of the emissions leakage that occurs will depend not only on the percentage change, but also the baseline level of trade flows, domestic production, and the emissions intensities of the foreign producers that respond. In principle, elasticity estimates can be combined with baseline measures of trade flows and domestic production to identify those industries where international market transfer rates (i.e., the rate at which reductions in domestic production translates into increases in foreign production) are potentially high. Combining these calibrated transfer rates with estimates marginal emissions intensities in foreign jurisdictions provides a measure of leakage risk.

We use our estimates to calibrate upper bounds on market transfer rates. The imprecision of our estimates makes it difficult to estimate leakage potential for any particular industry with any degree of precision. However, the general patterns that emerge are insightful. Our estimated market transfer rates, which should be viewed as an upper bound given that changes in net exports are unlikely to translate one-for-one into increases in foreign production, fall at or below 20 percent for most industries. Consistent with EITE mitigation policies, the leakage estimates are highest for those industries typically classified under cap-and-trade programs as "high" leakage risk. Those classified as "low risk" are generally associated with smaller market transfer rates. These estimated transfer rates, coupled with estimates of foreign emissions intensities, provide a basis for allocating output-based compensation to mitigate international emissions leakage.

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Table 1: Relevant Data Sets

Data Set	Main Variables	Level Aggregation	Years	Notes
Longitudinal Firm Trade Transactions Database (LFTTD)	Value of transaction, product HS code, U.S. firm in trade, port of entry/exit, country of origin/ destination	Transaction	1993–2011	Restricted
Census of Manufacturers (CMF)	Value of shipments, value and quantity of electricity purchased, value of primary fuels purchased, wages, input costs, capital intensity	Establishment-Year	1997, 2002, 2007, 2012	Restricted
Annual Survey of Manufacturers (ASM)	Same as CMF	Establishment-Year	1993–2012 (excluding CMF years)	Restricted
Longitudinal Business Database (LBD)	Establishment-to-firm linkage	Establishment-Year	1993–2012	Restricted
Manufacturing Energy Consumption Survey (MECS)	Primary energy consumption by fuel type	Industry-Region-Year	1998, 2002, 2006, 2010	Public
State Energy Data System (SEDS)	Primary energy price by fuel type	State-Year	1993–2012	Public
Enerdata Global Energy Data	Foreign electricity and natural gas prices	Country-Year	1989–2011	Proprietary
IEA Energy Prices and Taxes	Foreign electricity and natural gas prices	Country-Year	1989–2011	Proprietary

Source: Own elaboration.

Table 2: List of Included NAICS6 Industries

311111, 311119, 311211, 311212, 311213, 311221, 311222, 311223, 311225, 311230, 31131X, 311320, 311340, 311411, 311421, 311422, 311423, 311511, 311512, 311513, 311514, 311520, 311611, 311613, 311615, 311711, 31181X, 311822, 311823, 311911, 311919, 311920, 311930, 311941, 311942, 311999, 312120, 312130, 315221, 315222, 315223, 315224, 315228, 315231, 315232, 315233, 315234, 315239, 315291, 315292, 321219, 322110, 322121, 322122, 322130, 324110, 324121, 325110, 325120, 325131, 325181, 325188, 325192, 325193, 325199, 325211, 325212, 325221, 325222, 325311, 325412, 325414, 327112, 327113, 327125, 327211, 327212, 327213, 327310, 327410, 327420, 327992, 327993, 331111, 331112, 331221, 331311, 331312, 331314, 331411, 331419, 331492, 331511, 332510, 333611, 335991, 336411, 336414

Notes: These are the NAICS6 codes included in our regression analysis.

Table 3: Summary Statistics of Main Variables (U.S./CA)

	Mean	SD	SD within NAICS3	SD NAICS3 & yr $\times$ NAICS2
ln Value of shipments	22.68	1.46	1.16	1.11
Share shipments CA/US	0.11	0.16	0.13	0.13
ln Value of imports	20.60	2.33	2.10	2.07
ln Value of exports	20.37	1.88	1.72	1.69
Domestic energy price	11.31	3.71	2.63	2.37
Foreign electricity price (exp)	8.19	2.33	2.28	1.13
Foreign electricity price (imp)	7.69	2.89	2.76	1.64
Foreign gas price (exp)	2.20	0.84	0.83	0.45
Foreign gas price (imp)	1.87	0.92	0.86	0.57
Energy intensity	0.07	0.08	0.06	0.06
Capital intensity	0.68	2.61	2.60	2.58
ln Wage	55.44	16.56	9.43	8.96

Table 4: Summary Statistics of Energy Variables (U.S./CA)

	Mean (SD)	SD within NAICS3	SD NAICS3 & yr × NAICS2
Domestic energy price ($/MMBtu), using contemporaneous shares	11.310 (3.707)	2.632	2.365
Domestic energy price ($/MMBtu), using baseline shares	12.359 (5.172)	4.025	3.936
Energy intensity (share of inputs), using contemporaneous shares	0.067 (0.079)	0.058	0.057
Energy intensity (share of inputs), using baseline shares	0.056 (0.066)	0.049	0.049
Average CO_2 emissions (tons per MMBtu)	0.116 (0.024)	0.021	
Average CO_2 intensity (tons per $1,000 value)	0.420 (0.585)	0.467	
Average direct CO_2 intensity (tons per $1,000 value)	0.204 (0.317)	0.257	

Table 5: Subset Regression Results: Contemporaneous Energy Intensity Measure

	Value of Domestic Production			Value of Exports			Value of Imports		
	Linear	Logged	Spline	Linear	Logged	Spline	Linear	Logged	Spline
P	−0.27	−2.73***	0.11	−0.22	−1.98***	0.03	0.27	0.79*	0.38
	(0.18)	(0.29)	(0.33)	(0.23)	(0.50)	(0.35)	(0.19)	(0.43)	(0.34)
P x EI	−6.79***	−0.48***	−26.08***	−3.14*	−0.32***	−1.96*	4.72***	0.11	−5.49***
	(1.08)	(0.07)	(−26.08)	(1.64)	(0.11)	(−1.96)	(1.31)	(0.09)	(−5.49)
P x $EI2_{p33\text{-}p66}$			−12.38**			−19.65**			−1.29
			(5.42)			(9.10)			(12.09)
P x $EI3_{p66\text{-}p100}$			−2.45*			3.12			8.51***
			(1.44)			(2.25)			(1.65)
P Elec Exp	0.46	0.36	0.60*	2.23***	1.84**	2.68***			
	(0.35)	(0.38)	(0.34)	(0.72)	(0.79)	(0.74)			
P Gas Exp	−0.70*	−1.21***	−1.46***	0.95*	0.91	0.24			
	(0.39)	(0.35)	(0.32)	(0.57)	(0.57)	(0.52)			
P Elec Imp	−1.06***	0.23	−0.82**				1.47*	0.20	1.20
	(0.22)	(0.38)	(0.33)				(0.77)	(0.75)	(0.80)
P Gas Imp	2.07***	1.90***	2.19***				0.77***	0.93***	1.23***
	(0.25)	(0.26)	(0.25)				(0.29)	(0.31)	(0.30)
Wages	−0.87***	−0.88***	−0.76***	0.28	0.22	0.46*	0.68***	0.49***	0.37*
	(0.17)	(0.16)	(0.16)	(0.27)	(0.24)	(0.25)	(0.18)	(0.19)	(0.20)
P25	−0.94***	−1.61***	−1.05***	−0.53**	−1.24***	−0.75**	0.34*	0.31	0.27
	(0.17)	(0.18)	(0.22)	(0.23)	(0.29)	(0.32)	(0.19)	(0.20)	(0.34)
P50	−0.48***	−1.06***	−0.54***	−0.32	−0.86***	−0.24	0.42**	0.39*	0.32
	(0.17)	(0.17)	(0.18)	(0.22)	(0.23)	(0.27)	(0.18)	(0.21)	(0.33)
P75	−0.37**	−0.71***	−0.28	−0.26	−0.65***	−0.00	0.74***	0.52**	0.48
	(0.17)	(0.18)	(0.18)	(0.22)	(0.22)	(0.25)	(0.19)	(0.26)	(0.32)
R2	0.67	0.68	0.70	0.70	0.69	0.72	0.42	0.41	0.45
Obs.	1,524	1,524	1,524	1,426	1,426	1,426	1,426	1,426	1,426

Notes: Dependent variables are the log transformed value of domestic production, value of imports, and value of exports, respectively. The unit of observation is an industry-year, where industry is defined at the NAICS6 level. All specifications include industry fixed effects, sector-year fixed effects, industry specific measures of labor costs, domestic energy costs, and foreign energy costs. Domestic and foreign energy costs are interacted with contemporaneous industry-specific measures of energy intensity. Each set of regression results can be used to calibrate industry-specific estimates of the percentage change in the dependent variable associated with a percentage change in domestic energy prices. The distribution of these industry-specific elasticity parameters are summarized in the second panel. Robust standard errors are reported in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: Subset Regression Results: Invariant Energy Intensity Measure

	Value of Domestic Production			Value of Exports			Value of Imports		
	Linear	Logged	Spline	Linear	Logged	Spline	Linear	Logged	Spline
P	0.10	−2.90***	1.51***	−0.11	−2.62***	1.22***	0.16	0.37	0.55
	(0.19)	(0.51)	(0.40)	(0.24)	(0.62)	(0.37)	(0.19)	(0.29)	(0.44)
EI x P	−8.22***	−0.65***	−91.47***	−5.21***	−0.53***	−80.99***	2.46**	0.03	−23.99***
	(1.61)	(0.11)	(−91.47)	(1.86)	(0.13)	(−80.99)	(1.06)	(0.08)	(−23.99)
EI2 x P			−12.76**			−13.62*			2.16
			(6.24)			(8.13)			(6.16)
EI3 x P			−1.09			−0.41			4.51***
			(1.62)			(2.11)			(1.49)
P Elec Exp	−1.25**	−2.20***	−1.82***	0.85	0.89	0.44			
	(0.59)	(0.49)	(0.49)	(0.66)	(0.86)	(0.67)			
P Gas Exp	−0.02	−0.21	−0.51	1.85***	1.52***	0.93*			
	(0.50)	(0.39)	(0.38)	(0.64)	(0.57)	(0.53)			
P Elec Imp	−2.01***	0.21	−2.01***				−0.98**	−1.54***	−1.16
	(0.33)	(0.56)	(0.46)				(0.47)	(0.57)	(0.71)
P Gas Imp	2.75***	2.06***	2.27***				2.41***	2.39***	2.62***
	(0.29)	(0.29)	(0.29)				(0.46)	(0.47)	(0.47)
Wages	−0.90***	−0.47***	−0.23	0.13	0.60***	0.90***	0.70***	0.64***	0.66***
	(0.16)	(0.14)	(0.15)	(0.25)	(0.21)	(0.23)	(0.18)	(0.19)	(0.20)
P25	−0.54***	−1.24***	−0.75**	−0.52**	−1.28***	−0.88**	0.20	0.25	0.14
	(0.19)	(0.28)	(0.34)	(0.22)	(0.34)	(0.39)	(0.19)	(0.20)	(0.21)
P50	−0.09	−0.46**	−0.21	−0.23	−0.66***	−0.31	0.22	0.26	0.23
	(0.18)	(0.22)	(0.21)	(0.22)	(0.25)	(0.27)	(0.18)	(0.18)	(0.22)
P75	−0.02	−0.17	0.11	−0.19	−0.42*	−0.02	0.35**	0.30*	0.34
	(0.18)	(0.21)	(0.20)	(0.23)	(0.24)	(0.26)	(0.16)	(0.17)	(0.22)
R2	0.66	0.70	0.71	0.70	0.71	0.73	0.40	0.40	0.42
Obs.	1,524	1,524	1,524	1,426	1,426	1,426	1,426	1,426	1,426

Notes: Dependent variables are the log transformed value of domestic production, value of imports, and value of exports, respectively. The unit of observation is an industry-year, where industry is defined at the NAICS6 level. All specifications include industry fixed effects, sector-year fixed effects, industry specific measures of labor costs, domestic energy costs, and foreign energy costs. Domestic and foreign energy costs are interacted with time-invariant industry-specific measures of energy intensity. Each set of regression results can be used to calibrate industry-specific estimates of the percentage change in the dependent variable associated with a percentage change in domestic energy prices. The distribution of these industry-specific elasticity parameters are summarized in the second panel. Robust standard errors are reported in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Regression Results with Capital Intensity Interactions

	Value of Production	Value of Exports	Value of Imports
P25	-0.994^{***}	-0.858^{***}	0.207
	(0.238)	(0.291)	(0.211)
P50	-0.479^{**}	-0.453^{*}	0.268
	(0.193)	(0.245)	(0.201)
P75	-0.252	-0.274	0.404^{*}
	(0.191)	(0.237)	(0.212)
Interaction Capital	-0.005^{*}	0.004	-0.003
	(0.008)	(0.018)	(0.005)
R2	0.69	0.70	0.42
Obs.	1,524	1,426	1,426

Notes: Dependent variables are the log transformed value of domestic production, value of imports, and value of exports, respectively. The unit of observation is an industry-year, where industry is defined at the NAICS6 level. All specifications include industry fixed effects, sector-year fixed effects, industry specific measures of labor costs, domestic energy costs, and foreign energy costs. Domestic and foreign energy costs are interacted with industry-specific measures of energy intensity and capital share (Capital). Robust standard errors are reported in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The distribution of the implied industry-specific elasticity parameters are summarized in the table.

Table 8: Coefficient Estimates of Elasticities with respect to Energy Price by NAICS6

	Production			Exports			Imports		
NAICS6	P25	P50	P75	P25	P50	P75	P25	P50	P75
311230	-0.55	-0.42	-0.19	-0.61	-0.32	-0.27	0.12	0.21	0.27
311310	-0.77	-0.50	-0.26	-0.68	-0.50	-0.37	0.20	0.25	0.36
311421	-0.55	-0.48	-0.20	-0.58	-0.32	-0.26	0.19	0.26	0.32
311423	-0.73	-0.57	-0.35	-0.86	-0.48	-0.36	0.19	0.25	0.42
311512	-0.27	-0.16	-0.03	-0.47	-0.21	-0.18	0.11	0.18	0.25
311513	-0.27	-0.12	0.07	-0.30	-0.19	-0.02	0.10	0.18	0.29
311514	-0.48	-0.40	-0.16	-0.62	-0.30	-0.26	0.17	0.21	0.27
311611	-0.11	0.05	0.50	-0.24	-0.13	0.14	0.17	0.23	0.31
311613	-1.24	-1.02	-0.77	-1.26	-0.84	-0.66	0.30	0.42	0.67
311615	-0.43	-0.33	0.00	-0.35	-0.29	-0.17	0.18	0.21	0.28
311911	-0.19	-0.11	0.04	-0.35	-0.20	0.00	0.18	0.24	0.32
311919	-0.56	-0.43	-0.19	-0.70	-0.32	-0.29	0.19	0.26	0.39
311999	-0.49	-0.40	-0.18	-0.68	-0.31	-0.27	0.18	0.22	0.27
312120	-0.52	-0.46	-0.21	-0.69	-0.32	-0.28	0.15	0.21	0.27
312130	-0.48	-0.30	-0.22	-0.60	-0.26	-0.21	0.18	0.25	0.31
322121	-1.35	-0.98	-0.76	-1.20	-0.78	-0.64	0.32	0.37	0.58
322130	-1.45	-1.22	-0.86	-1.34	-0.91	-0.72	0.30	0.47	0.58
324110	-0.42	-0.29	-0.20	-0.52	-0.27	-0.21	0.14	0.19	0.27
324121	-1.04	-0.74	-0.61	-1.12	-0.77	-0.56	0.20	0.27	0.32
325120	-2.09	-1.89	-1.47	-1.67	-1.37	-1.10	0.64	0.76	1.01
325188	-1.49	-1.11	-0.85	-1.34	-0.89	-0.71	0.35	0.44	0.58
325193	-1.35	-1.11	-0.86	-1.30	-0.92	-0.61	0.34	0.48	0.63
325199	-1.08	-0.75	-0.56	-1.05	-0.75	-0.53	0.23	0.28	0.35
325311	-1.64	-1.32	-1.07	-1.40	-1.00	-0.80	0.49	0.60	0.64
325412	-0.37	-0.27	-0.14	-0.51	-0.26	-0.20	0.09	0.18	0.25
325414	-0.45	-0.36	-0.11	-0.53	-0.28	-0.20	0.14	0.20	0.28
327211	-1.59	-1.38	-1.00	-1.41	-1.02	-0.82	0.46	0.59	0.81
327213	-1.56	-1.30	-0.99	-1.39	-0.99	-0.78	0.47	0.59	0.79
327310	-2.08	-1.95	-1.38	-1.64	-1.52	-1.03	0.64	0.88	1.24
327410	-2.42	-2.07	-1.62	-1.73	-1.59	-1.28	0.67	0.92	1.33
327420	-1.46	-1.20	-0.86	-1.34	-0.90	-0.70	0.32	0.46	0.57
327993	-1.31	-1.04	-0.78	-1.26	-0.83	-0.65	0.32	0.41	0.68
331111	-1.28	-0.88	-0.69	-1.14	-0.77	-0.59	0.30	0.34	0.50
331221	-0.65	-0.48	-0.28	-0.80	-0.39	-0.28	0.15	0.21	0.27
331314	-0.60	-0.50	-0.28	-0.81	-0.39	-0.33	0.13	0.23	0.27
331492	-0.81	-0.51	-0.38	-0.80	-0.44	-0.32	0.15	0.23	0.28
331511	-1.18	-0.78	-0.57	-1.07	-0.78	-0.54	0.29	0.30	0.40
332510	-0.32	-0.13	0.21	-0.27	-0.12	0.01	0.17	0.25	0.34
333611	-0.28	-0.14	-0.05	-0.36	-0.24	-0.17	0.16	0.19	0.25
336411	-0.08	0.07	0.46	-0.14	-0.12	0.09	0.15	0.20	0.30
336414	-0.10	-0.01	0.14	-0.25	-0.18	0.01	0.23	0.31	0.58

Notes: This table reports the estimates in Figures 6 and 7 at the NAICS6 level.

Table 9: Impact of a $10 per Metric Ton of CO_2 Carbon Price by 6-digit NAICS

NAICS6	CO_2 / MMBtu	P ($/MMBtu)	Production P25	Production P50	Production P75	Exports P25	Exports P50	Exports P75	Imports P25	Imports P50	Imports P75
311230	0.12	9.46	-0.07	-0.05	-0.02	-0.08	-0.04	-0.03	0.02	0.03	0.03
311310	0.08	5.78	-0.11	-0.07	-0.04	-0.09	-0.07	-0.05	0.03	0.03	0.05
311421	0.09	10.90	-0.05	-0.04	-0.02	-0.05	-0.03	-0.02	0.02	0.02	0.03
311423	0.09	9.62	-0.07	-0.05	-0.03	-0.08	-0.04	-0.03	0.02	0.02	0.04
311512	0.11	9.80	-0.03	-0.02	-0.00	-0.05	-0.02	-0.02	0.01	0.02	0.03
311513	0.11	10.27	-0.03	-0.01	0.01	-0.03	-0.02	-0.00	0.01	0.02	0.03
311514	0.10	9.75	-0.05	-0.04	-0.02	-0.06	-0.03	-0.03	0.02	0.02	0.03
311611	0.12	10.28	-0.01	0.01	0.06	-0.03	-0.02	0.02	0.02	0.03	0.04
311613	0.09	8.99	-0.12	-0.10	-0.08	-0.13	-0.08	-0.07	0.03	0.04	0.07
311615	0.13	12.18	-0.05	-0.04	0.00	-0.04	-0.03	-0.02	0.02	0.02	0.03
311911	0.12	13.75	-0.02	-0.01	0.00	-0.03	-0.02	0.00	0.02	0.02	0.03
311919	0.09	9.68	-0.05	-0.04	-0.02	-0.07	-0.03	-0.03	0.02	0.02	0.04
311999	0.13	11.45	-0.06	-0.05	-0.02	-0.08	-0.04	-0.03	0.02	0.02	0.03
312120	0.10	10.57	-0.05	-0.04	-0.02	-0.07	-0.03	-0.03	0.01	0.02	0.03
312130	0.10	17.74	-0.03	-0.02	-0.01	-0.03	-0.01	-0.01	0.01	0.01	0.02
322121	0.10	8.92	-0.15	-0.11	-0.09	-0.13	-0.09	-0.07	0.04	0.04	0.07
322130	0.10	9.03	-0.16	-0.14	-0.10	-0.15	-0.10	-0.08	0.03	0.05	0.06
324110	0.10	10.35	-0.04	-0.03	-0.02	-0.05	-0.03	-0.02	0.01	0.02	0.03
324121	0.08	10.14	-0.08	-0.06	-0.05	-0.09	-0.06	-0.04	0.02	0.02	0.03
325120	0.15	11.39	-0.28	-0.25	-0.19	-0.22	-0.18	-0.14	0.08	0.10	0.13
325188	0.13	10.55	-0.18	-0.14	-0.10	-0.17	-0.11	-0.09	0.04	0.05	0.07
325193	0.08	7.25	-0.15	-0.12	-0.09	-0.14	-0.10	-0.07	0.04	0.05	0.07
325199	0.09	8.30	-0.12	-0.08	-0.06	-0.11	-0.08	-0.06	0.02	0.03	0.04
325311	0.11	8.11	-0.22	-0.18	-0.15	-0.19	-0.14	-0.11	0.07	0.08	0.09
325412	0.12	12.65	-0.04	-0.03	-0.01	-0.05	-0.02	-0.02	0.01	0.02	0.02
325414	0.12	13.40	-0.04	-0.03	-0.01	-0.05	-0.03	-0.02	0.01	0.02	0.03
327211	0.09	9.33	-0.15	-0.13	-0.10	-0.14	-0.10	-0.08	0.04	0.06	0.08
327213	0.08	10.01	-0.12	-0.10	-0.08	-0.11	-0.08	-0.06	0.04	0.05	0.06
327310	0.12	7.20	-0.35	-0.33	-0.23	-0.27	-0.25	-0.17	0.11	0.15	0.21
327410	0.09	5.71	-0.38	-0.33	-0.26	-0.27	-0.25	-0.20	0.11	0.15	0.21
327420	0.09	8.85	-0.15	-0.12	-0.09	-0.14	-0.09	-0.07	0.03	0.05	0.06
327993	0.12	9.96	-0.16	-0.13	-0.09	-0.15	-0.10	-0.08	0.04	0.05	0.08
331111	0.13	8.84	-0.19	-0.13	-0.10	-0.17	-0.11	-0.09	0.04	0.05	0.07
331221	0.11	11.75	-0.06	-0.04	-0.03	-0.07	-0.04	-0.03	0.01	0.02	0.03
331314	0.08	9.59	-0.05	-0.04	-0.02	-0.07	-0.03	-0.03	0.01	0.02	0.02
331492	0.13	11.16	-0.09	-0.06	-0.04	-0.09	-0.05	-0.04	0.02	0.03	0.03
331511	0.14	10.92	-0.15	-0.10	-0.07	-0.14	-0.10	-0.07	0.04	0.04	0.05
332510	0.14	14.91	-0.03	-0.01	0.02	-0.03	-0.01	0.00	0.02	0.02	0.03
333611	0.13	16.73	-0.02	-0.01	-0.00	-0.03	-0.02	-0.01	0.01	0.01	0.02
336411	0.14	14.43	-0.01	0.01	0.04	-0.01	-0.01	0.01	0.01	0.02	0.03
336414	0.13	18.23	-0.01	-0.00	0.01	-0.02	-0.01	0.00	0.02	0.02	0.04

Notes: This table reports the estimates in Figure 8 at the 6-digit NAICS level for a $10 carbon price per metric ton of CO_2 in 2010 U.S. dollars.

Table 10: Impact of a $10 per Metric Ton of CO_2 Carbon Price with Process Emissions

NAICS6	Industry	Production P50 No process	Production P50 Process	Exports P50 No process	Exports P50 Process	Imports P50 No process	Imports P50 Process
324110	Petroleum Refineries	-0.03	-0.04	-0.03	-0.04	0.02	0.03
325120	Industrial Gas Manufacturing	-0.25	-4.98	-0.18	-3.61	0.10	2.00
325311	Nitrogenous Fertilizer Manufacturing	-0.18	-0.72	-0.14	-0.54	0.08	0.33
327211	Flat Glass Manufacturing	-0.13	-0.18	-0.10	-0.13	0.06	0.08
327213	Glass Container Manufacturing	-0.10	-0.14	-0.08	-0.11	0.05	0.06
327310	Cement Manufacturing	-0.33	-0.72	-0.25	-0.56	0.15	0.33
327410	Lime Manufacturing	-0.33	-1.09	-0.25	-0.84	0.15	0.48
327993	Mineral Wool Manufacturing	-0.13	-0.15	-0.10	-0.12	0.05	0.06
331111	Iron and Steel Mills and Ferroalloy Manufacturing	-0.13	-0.20	-0.11	-0.17	0.05	0.08
331492	Secondary Smelting/Refining/Alloying of Nonferrous Metal	-0.06	-0.24	-0.05	-0.21	0.03	0.11

Notes: This table reports the estimated median impacts of a $10 carbon price per metric ton of CO_2 in 2010 U.S. dollars for industries with substantial process emissions. The table provides a comparison of estimates without including process emissions ("No process"), which are our baseline estimates in Table 9, and including them ("Process").