# Measuring Leakage Risk

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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 debate 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 in a world of 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. Currently, a preferred strategy uses output-based allocation of allowances to mitigate the impacts of a regional policy on regulated producers. A growing literature demonstrates how this 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)). Output-based allocation is designed 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 via a production-based subsidy. Under a regional emissions trading program, permits are allocated for free on the basis of fuel use or production.

It is important to emphasize that this leakage mitigation strategy comes with strings attached. Economists have emphasized two 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] An additional consideration is the opportunity cost 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.

In light of these costs and limitations, 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 California's landmark GHG emissions trading program. The California Global Warming Solutions Act of 2006 (Assembly Bill 32, or AB32) requires California to reduce its GHG emissions to 1990 levels by 2020. As the lead implementing agency, the California Air Resources Board (CARB) is charged with the task of minimizing leakage to the extent

[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.

feasible.[2] In the program design phase, CARB considered carefully the leakage mitigation protocols developed in other regional policy contexts (namely the European Union, Australia, and the proposed American Clean Energy and Security Act of 2009). In all three cases, industry-specific measures of emissions intensity and trade share are used to gauge industry-level leakage risk. CARB has adopted this general approach for targeting leakage compensation under the auspices of the California Cap-and-Trade Program.

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.[3]

In the interest of informing policy implementation going forward, CARB has commissioned new research to investigate how output-based updating can serve to mitigate emissions leakage in the California context, including this and two companion studies. Some of this work has been targeted at particular sectors. Hamilton et al. (2016) estimate the impact of AB 32 on production costs, market transfer, and associated emissions leakage in tomato, sugar, wet corn, and cheese processing, respectively. In a broader companion study, Gray et al. (2016) analyze the effects of compliance costs in California on inter-state market transfers across 49 manufacturing sectors.

The aforementioned studies focus almost exclusively on intra-national, inter-state market transfers and associated emissions leakage. In some sectors, intra-national market transfers will be the primary driver of any emissions leakage that results from a California climate change policy. This would be the case, for example, in an industry where California producers compete exclusively with U.S. producers outside of California for market share. In contrast, international market transfers could be significant in industries where international imports and exports play an important role. In these industrial contexts, we would be remiss to ignore the potential for shifts of production and associated emissions leakage to international jurisdictions. Thus, our work assesses the potential for international market transfers and emissions leakage to jurisdictions outside the United States.

The contributions of our analysis is threefold. First, we introduce a conceptual framework that highlights intuitive relationships between estimable economic relationships and emissions leakage. Having identified critical determinants of international market transfers and associated emissions leakage in theory, we estimate these key components empirically. We bring rich data on individual import and export transactions and establishment-level operations from the U.S. Census, together with several public data

[2]AB32 defines emissions leakage as "a reduction in greenhouse gas (GHG) emissions within the state that is offset by an increase in GHG emissions outside the state." http://www.arb.ca.gov/cc/docs/ab32text.pdf

[3]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

sources, to this estimation exercise. Finally, we compare and contrast our measures of trade responsiveness measures across industries defined at the 6-digit NAICS level. We explore the robustness of our measures to alternative assumptions and estimation approaches.

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.

With these elasticity estimates in hand, we can assess the likely impacts of a $10 per metric ton of carbon dioxide price on trade flows. The effect of this carbon price is heterogeneous due to variation in the carbon intensity of production across industries. Our median estimates imply reductions in export values on the order of 6 percent or smaller for a majority of industries currently eligible for compensation in California. For all specifications considered, the effects of the carbon price in non-energy-intensive industries are small, on the order of less than one percent. 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 industries. Estimated impacts exceed 11 percent in cement, lime, and industrial gas industries.

Finally, we use our elasticity estimates to calibrate upper bounds on market transfer rates and associated leakage potential. The imprecision of our estimates makes it difficult to estimate leakage potential for any particular industry with any degree of precision. That said, looking across industries, clear patterns emerge. Consistent with CARB's policy, this study's leakage estimates are highest for those industries classified as "high" risk of leakage (see Table 8-1 of the Cap-and-Trade Regulation).

Overall, these results provide valuable insights into how a policy-induced increase in domestic operating costs can result in emissions leakage via international trade flows. Given available data, we are ineluctably limited in our ability to isolate the effect of a *California-specific* policy on *California-specific* imports and exports. Thus, our results are most accurately interpreted as capturing the effect of a regulation that increases domestic energy costs on import and export flows, respectively. These estimates are directly relevant to the assessment of a California Cap-and-Trade Program for those industries in which California producers comprise a majority of exports (or California manufacturers demand the majority of imports of a manufacturing input). However, in sectors where California does not dominate U.S. trade flows, our estimates should be viewed as an upper bound on projected impacts of a California-specific policy. In these cases, our estimates will overstate the impact of California's Cap-and-Trade program on international trade flows.

## 2 LITERATURE REVIEW

There is a growing body of economic research that explores the theoretical and empirical effects of environmental regulation on industrial production and associated trade flows.[4] In this section, we briefly

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

summarize three areas of this literature which are most germane to our analysis.

## 2.1 ESTIMATING THE INDUSTRIAL IMPACTS OF EMISSIONS REGULATIONS

The idea that incomplete environmental regulation can alter terms of trade with less stringently regulated jurisdictions is intuitive and finds plenty of theoretical support. Early theoretical work predicts that the costs of environmental regulation will weaken the competitive position of the jurisdiction imposing the regulation and increase the market share of less regulated producers (see, for example, Pethig (1976) and Siebert (1977)). These theoretical predictions serve to motivate a rich empirical literature that examines, across a variety of contexts, how environmental regulations affect trade flows.

This theoretical work inspired empirical researchers to test whether theoretical predictions find support in real-world data. 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 find no relationship, or a counter-intuitive positive relationship, between energy costs and net imports. Positive relationships are presumably picking up the effects of factors that determine trade flows, correlated with levels of environmental stringency, but not adequately controlled for by the researchers. The biases introduced by these omitted variables complicates the interpretation of these early empirical results.

To mitigate the confounding effects of omitted variables, more recent work brings richer data and more sophisticated empirical strategies to analyses of how environmental policies impact industrial activity. For example, Ederington et al. (2005) use a panel of 4-digit SIC industry data over the period 1978-1992 to estimate the relationship between pollution abatement operating costs and net imports. These authors find that, for most industries, environmental compliance costs have been too small to affect trade flows in an economically significant way. Rich data allows the authors to test for systematic heterogeneity in impacts across industries, and they do identify a subset of industries in which the effects of pollution abatement costs on trade flows are significant. The authors construct measures of 'immobility' (defined in terms of transportation and capital relocation costs). They find significant impacts among pollution-intensive industries that are relatively mobile. Notably, the authors find that pollution intensity is positively correlated with their measures of immobility. Failing to take account of this correlation yields the counter-intuitive finding that polluting industries are less sensitive to increases in environmental costs.

A more recent paper by Aldy and Pizer (2015) uses idiosyncratic, within-industry energy price variation to identify the effect of a change in relative energy prices on domestic production and net imports for U.S. manufacturing. They use their estimates to simulate the response to a $15 carbon price in 2009 dollars. They estimate a production decline of as much as 5 percent among key energy-intensive sectors (e.g., iron and steel, aluminum, and cement). Because market transfer effects arise through changes in market prices, total output will tend to decline in response to a positive cost shock in the regulated region. For this reason, the market transfer of production from the regulated region to other global production regions is generally smaller than the decrease in production in the regulated region. These authors estimate that, on average, only about one-sixth of the decline in domestic production is transferred to foreign

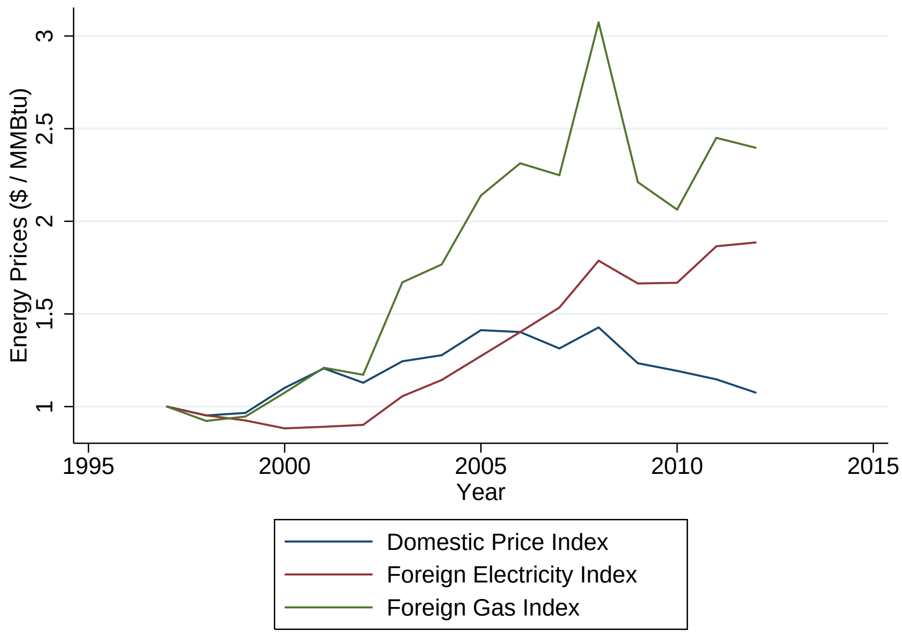



Figure 1: Evolution of Energy Prices over time

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.

producers.

Finally, very timely research commissioned by the California Air Resources Board estimates the effects of California climate change policies on production and associated emissions leakage in four food-processing industries: tomato processing, sugar refining, wet corn milling, and cheese production (Hamilton et al., 2016). Using detailed facility-level cost and sales data, these authors estimate that a $20 carbon compliance cost in California (absent any leakage mitigation measures) would lead to production decreases in California ranging from one-tenth of a percent (sugar) to approximately 2 percent (tomatoes). Estimated market transfer effects (i.e., the share of the decrease in in-state production transferred to out-of-state producers) range from 57 percent (processed cheese) to 76 percent (wet corn).

## 2.2 HOW HAS THE SHALE GAS BOOM IMPACTED DOMESTIC MANUFACTURING?

Our work is also germane to a growing literature examining the effects of the recent shale gas boom in the United States. 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 quite dramatically. These positive energy supply shocks have been localized because natural gas is costly and complicated to export overseas. Thus, the shale gas boom has generated a significant drop in domestic energy prices relative to our international trading partners (see Figure 1).

The isolated nature of this production cost shock mimics—to a certain extent—the effects of a domestic carbon regulation on energy prices paid by industrial producers. The key similarity lies in the fact that the shale gas boom, much like a U.S. compliance cost, delivers a persistent change in the relative energy prices paid by domestic producers vis a vis their foreign competitors. However, whereas the shale gas boom induced a relative decrease in domestic natural gas prices, a compliance cost would increase the prices of domestic fuels in proportion to carbon content.

Several recent papers examine the effects of this domestic production cost shock on manufacturing outcomes. Using highly-aggregated country-level data, Celasun et al. (2014) examine the role that falling natural gas prices played in U.S. manufacturing sector's strong rebound following the Great Recession relative to other G7 countries. They find limited evidence that natural gas prices played a role in increasing the competitiveness of manufacturing industries in the U.S. once one accounts for the real exchange rate and, most importantly, lower labor costs.

Whereas Celasun et al. (2014) use highly aggregated data, two related papers use more disaggregated data. Both Melick (2014) and Hausman and Kellogg (2015) examine the effects of the U.S. shale gas boom on manufacturing activity. Both of these papers highlight the interaction between energy intensity and manufacturing activity, as measured by value of output and employment. Melick (2014) finds that manufacturing activity increased 2 to 3 percent as a result of the drop in natural gas prices; estimated effects are significantly larger in the most energy-intensive manufacturing sectors. Hausman and Kellogg (2015) 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.

Finally, a recent paper by Bushnell and Humber (2015) takes a closer look at how the nitrogen fertilizer industry has been impacted by falling natural gas prices. These authors note that, while the decline in domestic gas prices has reduced production costs significantly, this has not translated into lower fertilizer prices. Low pass-through of production cost changes are attributed to capacity constraints or the exercise of market power. One implication of these findings is that output-based subsidies designed to mitigate emissions leakage in this carbon-intensive industry would result in windfall gains for producers.

## 2.3 LEAKAGE MEASUREMENT AND MITIGATION

Finally, our work contributes to an important literature that examines the issue of how to measure and mitigate leakage.

Some influential work in this area uses computational general equilibrium models calibrated to match specific policy contexts to analyze the impacts of alternative emissions leakage mitigation strategies. This is the approach taken by Fischer and Fox (2012) in a paper that assesses the relative effectiveness of carbon taxes, border tax adjustments, export rebates, and output-based updating. They show that the relative effectiveness of each policy depends critically on a combination of preferences and supply conditions.

In prior work, Fowlie et al. (2016), we examined the question of how effective and efficient various allowance allocation schemes would be in mitigating leakage in one industry in particular: the U.S. Portland cement industry. We evaluate economic outcomes under four alternative cap-and-trade program designs for allocating allowances: auctioning, grandfathering, output-based updating, and auctioning with border carbon adjustments. In addition to short-run impacts, we examine the dynamic effects of the various allocation schemes. We find that border carbon adjustments and output-based updating are both effective at mitigating emissions leakage. The relative efficiency of the two systems depends on the competitiveness of the industry and the trade exposure of the market.

Other literature has combined qualitative survey information with administrative records to understand the mechanisms through which firms have responded to carbon pricing in the European Union's (EU) Emissions Trading System (ETS). Kenber et al. (2009) surveyed the senior management of eight major emitters in Europe and one financial firm. The range of questions covered how the EU ETS has influenced the ways that firms conduct their operations and make investments, how firms perceive changes to their costs directly through allowance prices and the costs of their inputs and what effects those changes had, whether firms had relocated business in response to compliance costs, and how the introduction of the EU ETS had changed strategic planning. Petrick and Wagner (2014) use information from manager surveys collected by Martin et al. (2014) to help understand how firms in the EU ETS achieved the reductions documented in linked German Census data. The survey augmented Census data by providing a more granular look at how firms achieved reductions in emissions through a variety of avenues, such as optimization of existing systems, installation of more energy-efficient systems, use of renewable resources, improvements in energy efficiency in buildings and lighting, improved staff training, and the use of external energy audits. Such information is useful in helping understand how firms are responding to incentives presented by the cap-and-trade system.

Our research extends the body of work summarized above in several ways. On the empirical side, we use variation in energy prices generated by the shale gas boom in the United States to estimate the relationships between relative energy prices, domestic production, imports, and net exports. Highly disaggregated establishment and transaction-level data from the U.S. Census allow us to analyze heterogeneity in response to operating cost shocks with unprecedented precision. On the theoretical side, our empirical work is based on an intuitive analytical framework that translates economic fundamentals into empirically estimable relationships. This integration of theory and empirical work provides a foundation for our estimates, and guidance for how these estimates can be used to construct leakage metrics.

# 3 THEORETICAL FRAMEWORK

This section presents the economic modeling framework that guides our empirical analysis. We use the model to derive a precise definition of "leakage" and to highlight the factors that determine (in theory) the extent of the leakage that occurs as a result of a given policy change.

Figure 2 illustrates the core intuition captured by the model for the special case of an industry in which domestic producers face competition from foreign producers, but do not export to foreign markets. This simple model generalizes to a case where domestic producers face import competition and export to foreign markets. Recall that our work focuses exclusively on *international* leakage. More specifically, we assess how a policy-induced increase in industry operating costs can result in emissions leakage via

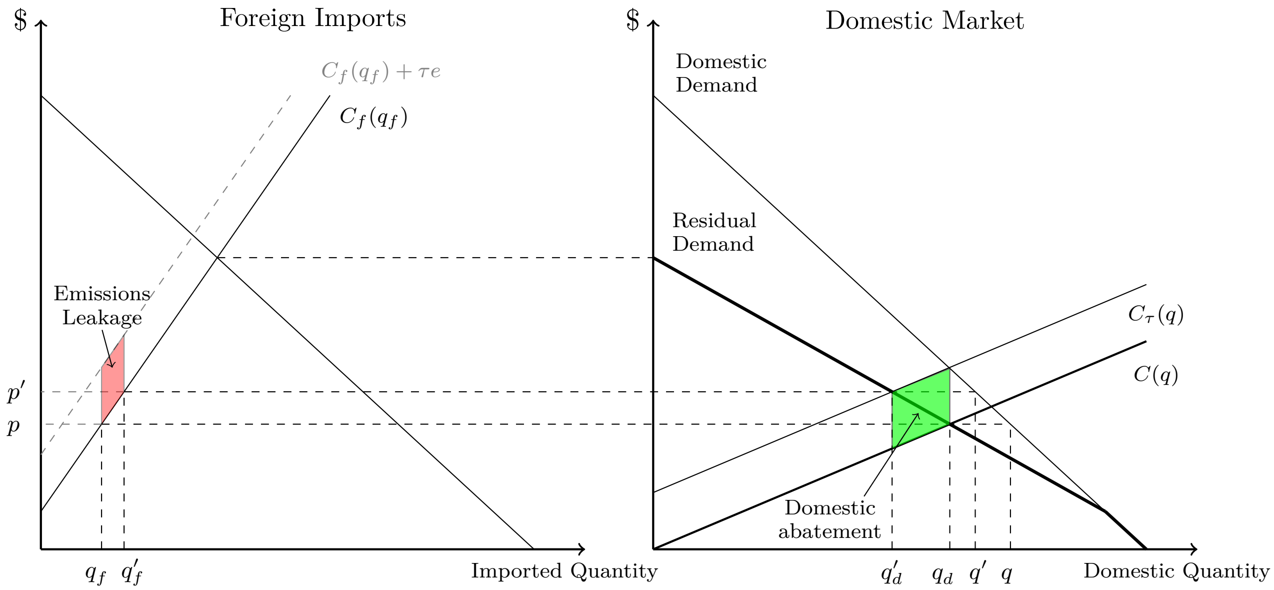



Figure 2: Leakage in Trade-Exposed Energy Intensive Industries

This figure shows equilibrium prices and quantities with and without a carbon price. In the presence of a carbon price, 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 carbon regulation.

international trade flows. Thus, we refer to the regulated jurisdiction as 'domestic' and the unregulated region as 'foreign'.

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 $\tau$ per metric ton of carbon dioxide (and equivalent greenhouse gases) to domestic producers. This carbon price is the equilibrium allowance value in an emissions trading program. The key assumption here is that firms take this carbon price $\tau$ as given. For ease of exposition, we assume a constant emissions rate per unit of output $e$ across domestic and foreign production. Under this policy, absent any output-based updating provisions, marginal operating costs 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 $\tau$). 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 can be used to more precisely define two important concepts:

- *Market transfer* of production from the regulated region to an unregulated region refers to the change in production absorbed by unregulated firms. 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.

- *Emissions leakage* refers to the policy-induced increase in emissions outside the jurisdiction imposing the regulation. This emissions leakage results when a policy-induced increase in domestic operating costs causes domestic producers to lose market share to their foreign competitors. In the figure, the dashed line in the left panel represents a measure of marginal cost of foreign producers that reflects emissions costs (valued at $\tau$). The shaded parallelogram therefore represents foreign emissions leakage valued at $\tau$.

The area of the orange parallelogram captures the costs or damages associated with the policy-induced increase in foreign emissions (valuing emissions-related damages at $\tau$ per unit of emissions). The graph highlights the key determinants of emissions leakage: the emissions intensity of the foreign firm, $e_f$, and 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.

Note that our analysis focuses exclusively on emissions leakage. 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 fraction 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"). Estimation of rent leakage, which requires detailed information about domestic ownership of foreign producer assets and industry structure, is beyond the scope of this study.

Although not explicitly represented in the figure, this graphical exposition helps to illustrate how an implicit subsidy conferred by an implicit production subsidy (either via tax revenue recycling or output-based permit allocations) can mitigate emissions leakage. If the industry receives additional allowances or revenues per unit of output, this will offset the extent of the policy-induced upward shift in the supply curve. This in turn will reduce the extent of market-transfer and associated emissions leakage.

## 3.1 MODEL

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 $q = q_d + q_f$. 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, $\sigma$. 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 $\tau$ per unit of emissions, $e_d$. 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. 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 $q_f(\tau)$.

One can see that 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 2, this transfer corresponds to $q'_f - q_f$.

To mitigate emissions leakage, the regulator can introduce an output-based subsidy to partially rebate carbon prices. The intuition for why this may be helpful can be seen in the first-order conditions above.

A production subsidy works to offset the policy-induced increase in operating costs $e_d\tau$. 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.

The model can be readily extended to allow domestic firms to also sell a quantity, $q_e$, into an export market. 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:

$$\pi(q_d, q_e) = p(q)q_d + p_e q_e - C(q_d + q_e) - \tau e_d(q_d + q_e) + s(q_d + q_e), \tag{4}$$

where $p_e$ is the price of the good in the foreign market.

Compared to the baseline model, the only change is that, in equilibrium, marginal revenue will be equalized across the domestic and export markets, as marginal cost is the same in the two markets. We augment the first-order conditions with marginal profits from exporting:

$$C_d'(q_d + q_e) + e_d\tau = p_e(q_e). \tag{5}$$

Given this system of first order conditions, equilibrium outcomes $q_d(\tau)$, $q_e(\tau)$, and $q_f(\tau)$ can all be expressed as a function of the carbon price. In the empirical analysis that follows, we estimate how changes in relative energy costs, which we use to proxy for changes in $\tau$, affect equilibrium levels of domestic production, domestic exports, and foreign imports, respectively.

## 3.2 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.

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. It is not a priori obvious that these metrics provide a reliable proxy for market transfer and foreign emissions intensity. The extent to which industry-level emissions intensities and trade shares capture or correlate with the extent to which trade flows respond to changes in relative operating costs is an empirical question.

The goal of our empirical exercise is two fold. First, we construct more direct measures of how disaggregated trade flows (imports and exports) respond to changes in relative energy costs. We then examine the degree of correlation between our measures and standard leakage risk metrics.

# 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 CARB or 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. The majority of these industries are eligible for leakage mitigation under California's greenhouse gas Cap-and-Trade Program. 21 additional industries are included in our analysis; these are emissions intensive, trade exposed industries that would be presumptively eligible for leakage mitigation under federal regulation.

For the purpose of this report, the calibration and synthesis that follows our estimation exercise emphasizes the subset of industries targeted by California's leakage mitigation efforts. We also create a California-specific subsample of data in which domestic production is restricted to establishments in California, and the LFTTD is restricted to transactions with a port of entry or port of exit in California.

As noted above, our analysis of international market transfers and associated emissions leakage risk will be most relevant in those industries where trade flows in and out of California are large and the potential for international market transfers are significant.

Unfortunately, it is difficult to establish in the trade data the point of origin for U.S. exports and the final destination for U.S. imports. This makes it difficult to separately identify California trade flows. As a crude proxy for imports destined for California, we use imports entering via ports in California. As a crude proxy for exports originating in California, we use exports departing through ports in California. Table 3 summarizes annual flows of imports and exports through California ports. Normalizing these values by total domestic imports and exports, respectively, provides a sense of California import demand and export supply as a share of national totals.

## 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 4. 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 4, 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.

Manufacturing establishments in California account for 11 percent of the total value of shipments on average. However, this share is heterogeneous across the industries in our sample. Similarly, import and export volumes passing through California ports account for a similarly small share of total trade volumes, although these trade shares vary across industries.

## 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.[5] We calculate two measures of domestic energy prices, using different weights in the weighted averages, to allow 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

[5]Figure 3 shows the share of input costs attributed to electricity consumption and the share attributed to fuel costs across a wide range of industries.

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[6] 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.[7] 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 $\beta_{ijrst}$, 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. 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

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

[7] 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.

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 5 for both the full sample of EITE industries and the California subsample. In both samples 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. Under either measure of domestic energy price, the price in the California subsample is greater than the price in the full sample of 6-digit NAICS industries, driven largely by California's high electricity 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 5. 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. When restricting the sample to only transactions with a port of entry or exit in California, the foreign energy prices are roughly equal to those from the entire sample, suggesting that the trade flows through California ports are representative of all U.S. trade in terms of foreign energy prices. 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

$$\tilde{EI}_{jt} = \sum_{i \in j} \left( EI_{it} \times \tilde{\xi_i} \right).$$

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 5 displays summary statistics for these energy intensity measures. Energy intensity using contemporaneous shares is greater than energy intensity using baseline shares in both the full industrial sample and the California subsample. 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. The California subsample is less energy-intensive on average than the full sample, despite California having higher domestic energy prices. This can be explained by California establishments having greater energy efficiency or facing relatively higher costs for non-energy inputs. 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 4 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.[8] 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 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

[8] 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.

by the total MMBTUs consumed from electricity and primary fuels:[9]

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

Here, $q^{elec}_{irst}$ and $q^{fuels}_{irst}$ 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 $e^{elec}_{st}$ 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:

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

where $q^d_{irst}$ 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:

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

We summarize these three $CO_2$ intensities measures in Table 5 and, for selected industries, in Figure 3. 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. Average emissions intensities for establishments in California are substantially lower than the national average, due largely to California's relatively less carbon-intensive electricity mix.

## 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 4. Average wages in the California subsample are comparable to those in the full sample, and wage exhibits substantial heterogeneity in both samples.

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

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

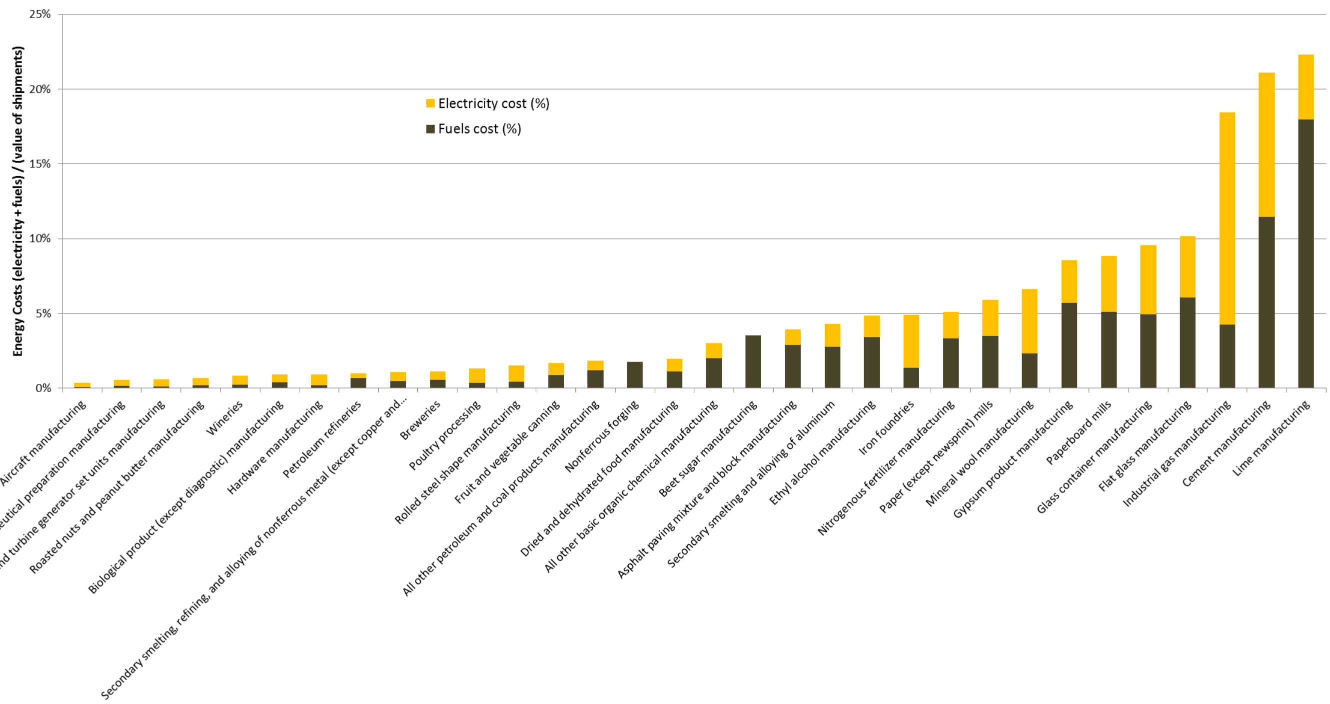



Figure 3: Energy Share and Composition Across Select Sectors

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.

duction 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 4. Average capital intensity in the California subsample is comparable to that in the full sample, and capital intensity also exhibits heterogeneity in both samples.

## 5 EMPIRICAL STRATEGY

The theoretical framework introduced in Section 3 provides an intuitive basis for our empirical analysis. In Figure 1, an increase in domestic energy prices relative to foreign energy prices is shown to reduce domestic production. Some of this reduction in domestic production is transferred to foreign jurisdictions. Likewise, if domestic producers export to foreign markets, an increase in relative domestic operating costs will weakly reduce export flows. Both margins of adjustment can lead to emissions leakage as foreign production responds to domestic regulation.

In sum, the responsiveness of trade flows to changes in relative operating costs is an important determinant of leakage risk. Our empirical objective, therefore, is to characterize the extent to which domestic production, imports and exports respond to changes in relative energy costs. We begin by summarizing some important challenges that complicate this kind of estimation exercise in general. We then present our estimation strategy and discuss how our approach responds to these challenges.

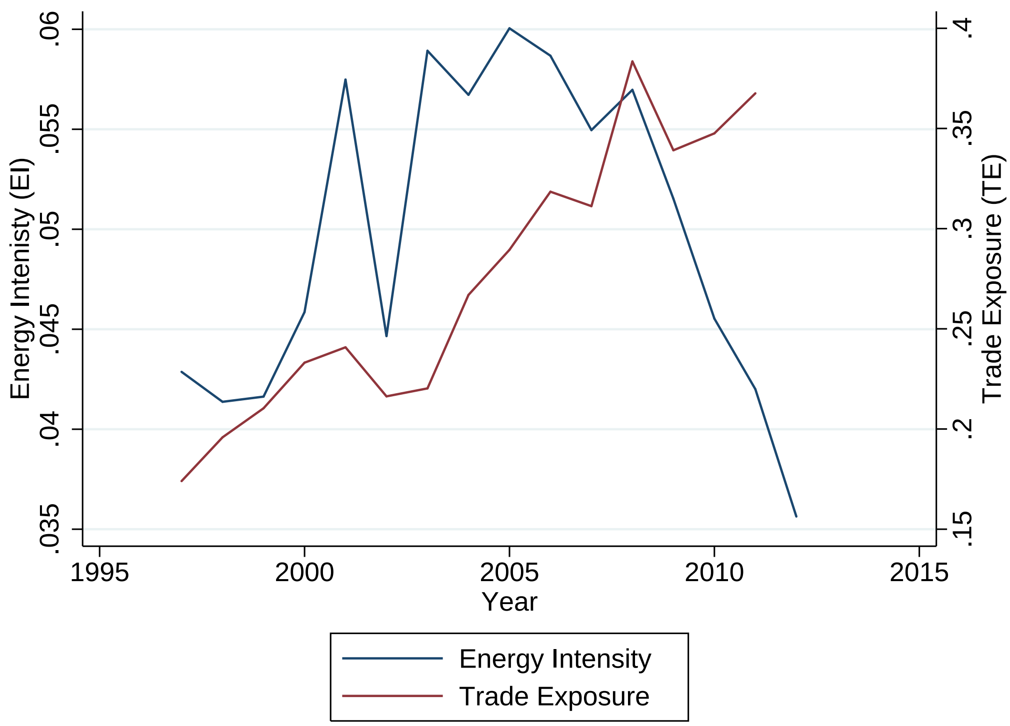



Figure 4: Evolution of Emissions Intensity and Trade Exposure Over Time

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.

## 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 ($\tau$). 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.[10] 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 complying with California's greenhouse gas Cap-and-Trade Program affects 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). This policy took effect in 2013, whereas our data end in 2012. We therefore need to 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:

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

where

$$\begin{aligned}
i &= \text{6-digit NAICS index,}\\
t &= \text{year index,}\\
y_{it} &= \text{aggregate outcome for industry } i \text{ in year } t,\\
p^d_{it} &= \text{domestic energy price,}\\
p^f_{it} &= \text{foreign energy price (a vector of foreign electricity and gas prices),}\\
X_{it} &= \text{Industry characteristics other than energy intensity (e.g., capital intensity),}\\
w_{it} &= \text{domestic wage,}\\
\phi_i &= \text{3-digit NAICS fixed effects,}
\end{aligned}$$

[10] When we narrow our focus to consider California, we focus exclusively on trade flows through California ports to proxy for imports to California and exports from California producers.

$\eta_{st}$ = 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 ($p^d_{it}$), foreign energy prices ($p^f_{it}$), and observable industry characteristics ($X_{it}$) such as energy intensity and capital intensity is summarized above as $f(p^d_{it}, p^f_{it}, X_{it}; \beta)$. We estimate several alternative forms of this relationship. The vector of parameters to be estimated is $\beta$. 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.[11] 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 estimation 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

[11] 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.

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, capital intensity, and California share of production/trade volumes. Capital intensity serves as a proxy for immobility; highly capital-intensive firms tend to be harder to relocate. Allowing the responsiveness parameters to vary systematically with the California share measure facilitates a test of whether industries with a large share of California production react differently to domestic energy price shocks.

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 overestimate the market transfer. We will return to this point in the interpretation of our results.

6. *Energy price variation as a proxy for a California 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.

A second important consideration is that the relative energy price changes we observe are nationwide, whereas California policy makers are interested in anticipating the effect of an emissions policy confined to California and Québec. In those sectors where California producers comprise the vast majority of domestic market (e.g., tomato processing), our estimates are directly relevant to the California case. In other cases, our estimates likely overstate the impacts of a California Cap-and-Trade Program.

# 6 ESTIMATION RESULTS

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.

## 6.1 ILLUSTRATIVE REGRESSIONS

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.[12] 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 6 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 6 summarizes the results the regression equations that analyze variation in domestic production across time and across industries. Across all specifications, an increase

[12]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.

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 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 6 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 7 presents the estimates. The qualitative results are similar to those in Table 6. Estimated elasticity parameters are generally smaller in absolute value. This makes intuitive sense. The results summarized by Table 6 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 7, underlying specifications hold these margins of adjustment fixed at pre-period levels.

As another way of summarizing the output from our regressions, Figure 5 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 5.), 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.

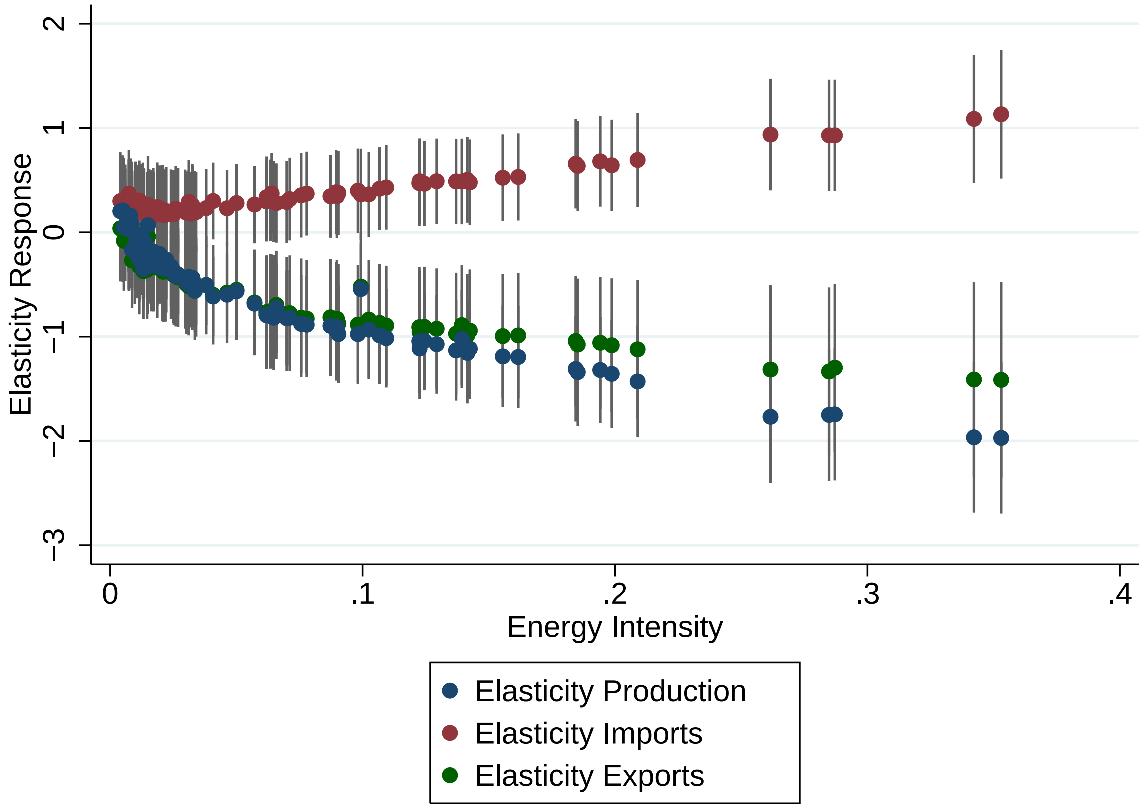



Figure 5: Coefficient Estimates along Energy Intensity

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.

One can also see that domestic production is the most responsive to changes in domestic energy prices (in elasticity 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. Additionally, and given our focus on California, we investigate whether these elasticity parameters vary systematically with the extent to which industrial activity (i.e., production, imports or exports) is concentrated in California.

Table 8 summarizes the estimation results associated with these more flexible specifications that incorporate these additional interactions. The table pools estimates from across multiple specifications. Examining these interaction terms, we find that industries with a larger presence in California (either a larger share of domestic production, or a larger share of imports/exports flowing through California ports) tend to be somewhat more responsive to a change in relative energy costs. However, these interaction effects translate into small, statistically-indistinguishable differences in the distributions of trade responsiveness parameters. Overall, the inclusion of additional interactions does not significantly affect the distribution of calibrated parameters summarized by the coefficients for P25, P50, and P75.

In what follows, we will evaluate the impacts of a Cap-and-Trade Program carbon price using a range of specifications, including those that accommodate a systematically different response among industries with a larger California presence. The inclusion of these interactions does not significantly influence our estimated impacts and conclusions.

## 6.2 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.

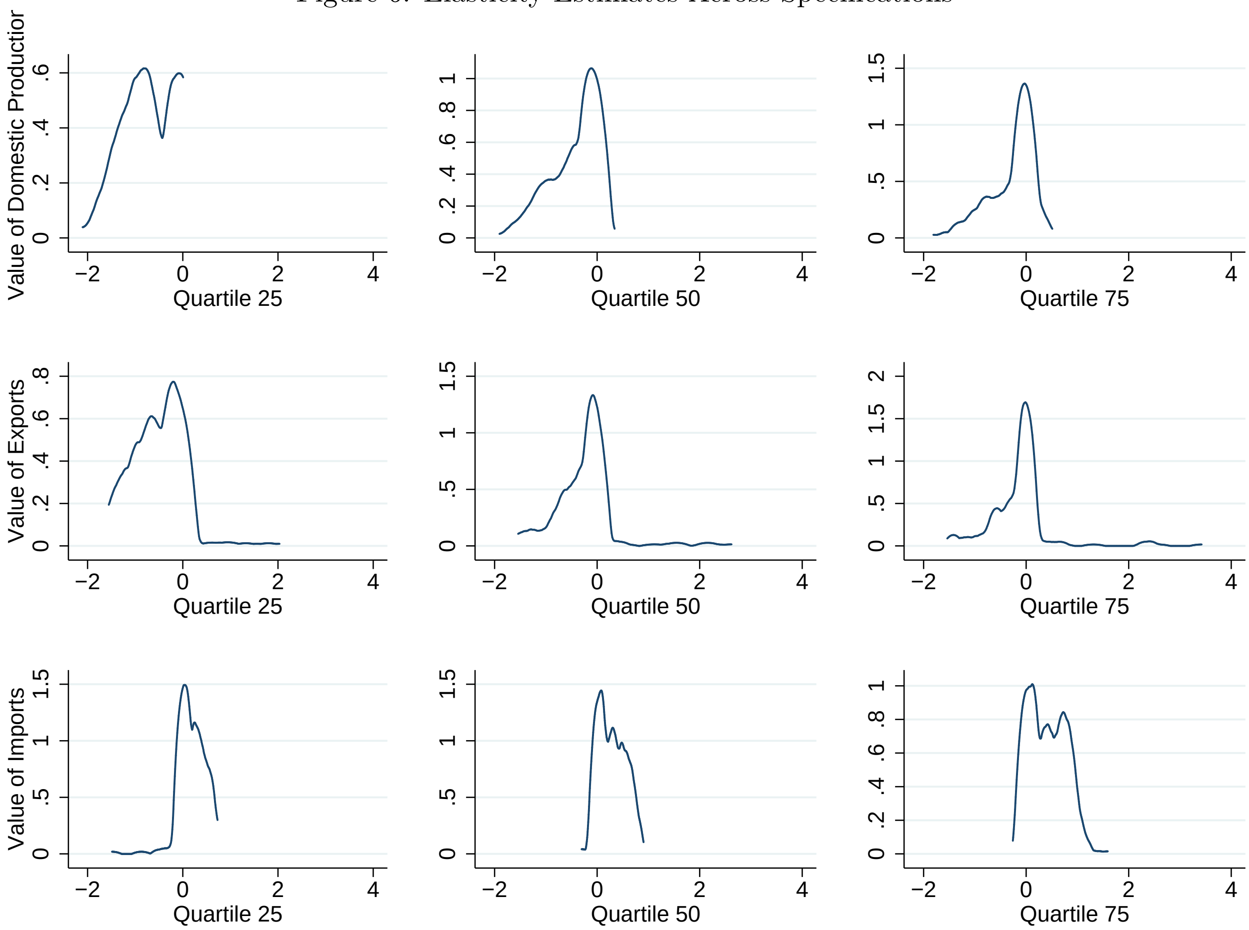
Figure 6 provides a graphical summary of the range of estimates we obtain. These figures plot the distribution of elasticity estimates at each of three percentiles (25, 50, and 75) across 192 different model specifications. In the first row, we present density plots for domestic production elasticities 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.[13]

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.

[13] 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.

Figure 6: Elasticity Estimates Across Specifications




This figure displays the density plots of the estimated elasticities over 192 different 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.[14]

In the third row, we show the estimated effects for imports. Because these impacts are positive (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 9 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

[14]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.

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.

### 6.3 SIMULATED POLICY IMPACTS

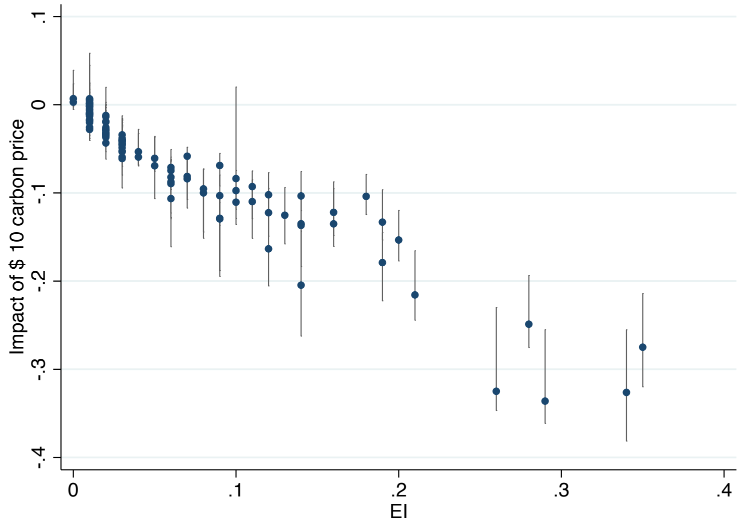
These estimates can be used to simulate the effects of a carbon price on domestic production, imports, and exports. Assuming complete pass-through by energy suppliers, we can calculate the effect of a given carbon price on industry-specific energy prices by multiplying the carbon price (measured in $ 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.

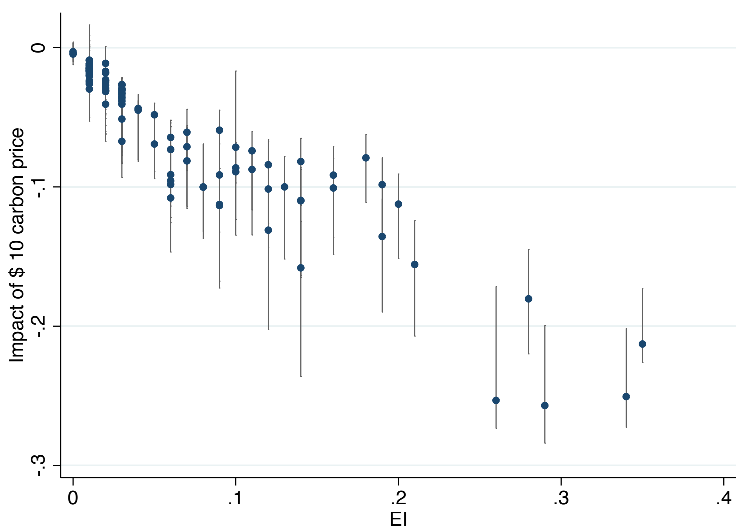
Figure 7 displays the results for the subset of industries that currently eligible for output-based allowance allocations in California (including fruit and vegetable processors). The bars represent the interquartile range across all specifications. Domestic production impacts are clearly more negative for more energy-intensive industries. The estimated impacts range from zero to a 30 percent reduction in domestic production. The estimated reduction in domestic production for an industry with an about average energy intensity is approximately 5 percent. Exports effects are also negative, although somewhat smaller (note effects are measured on a smaller scale), with the largest effects being around 25 percent. Imports are expected to increase with a $10 per metric ton of $CO_2$carbon price, with the largest estimates being around 15 percent.

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.

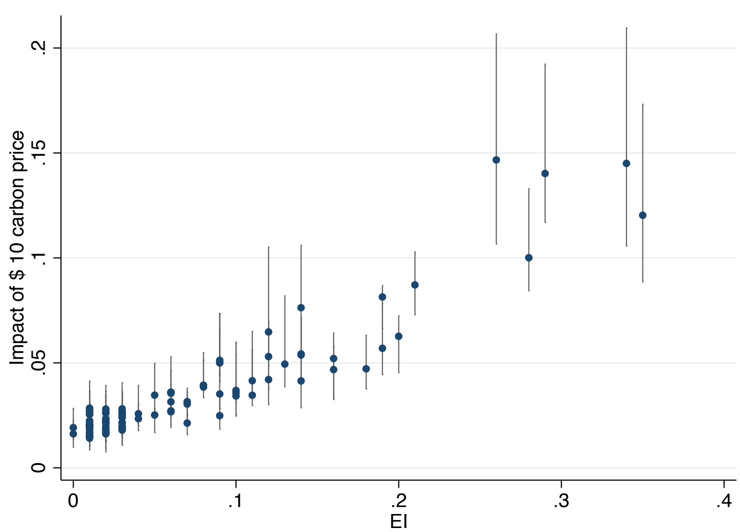
Table 10 summarizes these results in greater detail. For each industry, we summarize the distribution of elasticity estimates obtained across the 192 specifications we evaluate. Starting with the estimated




(a) Domestic production




(b) Exports




(c) Imports

Figure 7: 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.

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).

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 11 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.

## 6.4 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:

$$\text{output-based leakage rate} = e_f \cdot \frac{q_f}{q_d}$$

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:

$$\text{emissions-based leakage rate} = \frac{e_f}{e_d} \cdot \frac{q_f}{q_d}$$

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. Whereas exports out of, and imports into, the U.S. are precisely recorded, foreign exports from California producers, or foreign import transactions that have California as the final destination, are hard to separate. Presumably, some exports exiting (or entering) through California's ports originated (or are destined for) some other state. Similarly, not all of California's imports and exports come through California ports. For this reason, 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. In industries where California comprises a relatively small share of import demand and export supply, we should expect smaller impacts. 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 8 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. Consistent with CARB's policy, 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

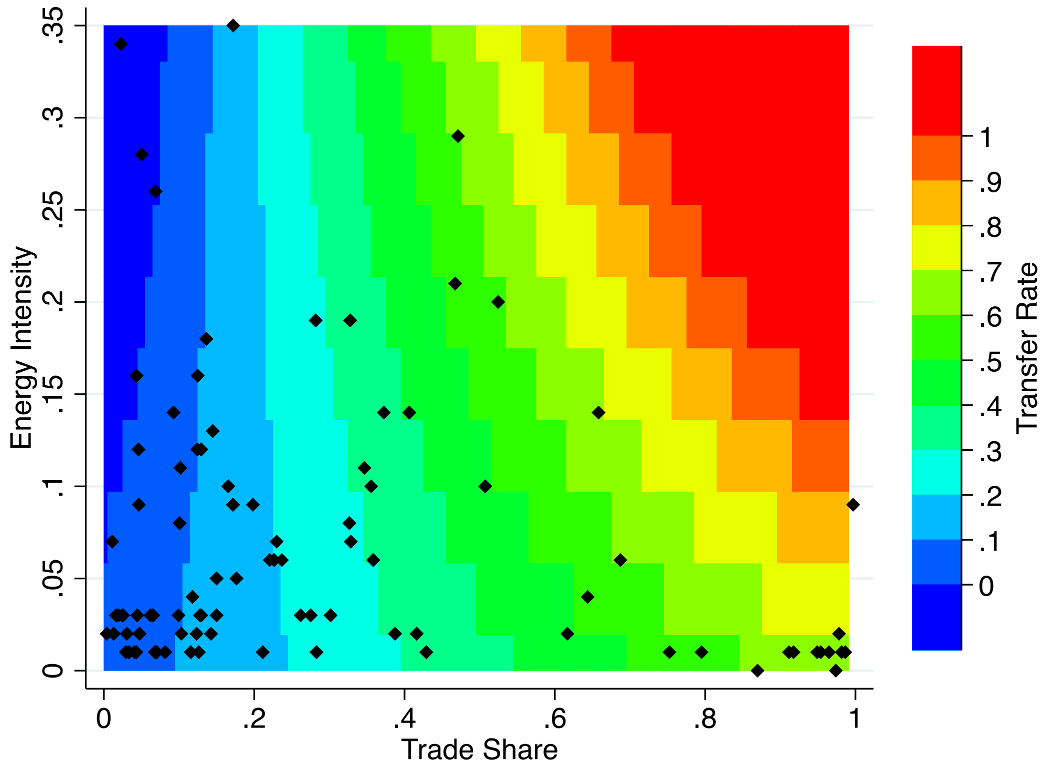



Figure 8: Heat Map of Transfer Rates

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.

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.

# 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). Note that, given data limitations, our results are best interpreted as estimating the impacts of a nation-wide carbon regulation. In sectors where California establishments account for a small share of total foreign import demand or export supply, our estimates are almost certainly over estimates.

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 currently eligible for leakage protection in California. 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 CARB's policy, the leakage estimates are highest for those industries classified under the Cap-and-Trade Program 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: California Import and Export Flows

| | Export value | | Import value | | Export Share | | Import Share | |
|---|---|---|---|---|---|---|---|---|
| | mean | SD | mean | SD | mean | SD | mean | SD |
| NAICS6 | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 311230 | 48.60 | 8.58 | 92.95 | 8.34 | 0.08 | 0.01 | 0.16 | 0.01 |
| 311310 | 66.19 | 23.83 | 348.15 | 65.68 | 0.17 | 0.06 | 0.15 | 0.01 |
| 311421 | 668.47 | 156.60 | 1234.14 | 75.18 | 0.24 | 0.03 | 0.23 | 0.01 |
| 311423 | 626.33 | 45.75 | 183.37 | 19.33 | 0.70 | 0.01 | 0.32 | 0.01 |
| 311512 | 120.36 | 51.40 | 11.19 | 5.70 | 0.53 | 0.05 | 0.12 | 0.02 |
| 311513 | 537.26 | 182.74 | 71.20 | 5.74 | 0.44 | 0.03 | 0.06 | 0.01 |
| 311514 | 1494.03 | 432.37 | 140.24 | 38.48 | 0.39 | 0.03 | 0.11 | 0.03 |
| 311611 | 6812.04 | 930.07 | 1361.20 | 395.47 | 0.47 | 0.01 | 0.18 | 0.01 |
| 311613 | 146.28 | 11.68 | 88.74 | 22.80 | 0.12 | 0.02 | 0.22 | 0.03 |
| 311615 | 424.57 | 102.49 | 17.55 | 7.17 | 0.09 | 0.02 | 0.05 | 0.02 |
| 311911 | 204.77 | 124.38 | 63.78 | 7.63 | 0.30 | 0.07 | 0.20 | 0.05 |
| 311919 | 142.86 | 20.87 | 34.80 | 11.11 | 0.25 | 0.01 | 0.14 | 0.04 |
| 311999 | 1408.74 | 285.36 | 397.75 | 52.94 | 0.32 | 0.03 | 0.11 | 0.04 |
| 312120 | 874.63 | 263.67 | 534.30 | 13.85 | 0.30 | 0.04 | 0.13 | 0.01 |
| 312130 | 881.45 | 125.50 | 1418.45 | 137.33 | 0.60 | 0.02 | 0.22 | 0.02 |
| 322121 | 187.45 | 13.99 | 492.38 | 49.33 | 0.06 | 0.01 | 0.12 | 0.01 |
| 322130 | 297.53 | 62.70 | 212.61 | 12.01 | 0.06 | 0.01 | 0.11 | 0.01 |
| 324110 | 5653.63 | 1161.50 | 5043.65 | 519.06 | 0.06 | 0.01 | 0.06 | 0.01 |
| 324121 | 30.53 | 3.86 | 12.37 | 13.20 | 0.22 | 0.05 | 0.07 | 0.07 |
| 324199 | 3.19 | 2.80 | 0.40 | 0.32 | 0.10 | 0.06 | 0.05 | 0.04 |
| 325120 | 191.02 | 13.80 | 7.79 | 2.25 | 0.36 | 0.03 | 0.04 | 0.01 |
| 325188 | 735.00 | 1139.76 | 160.57 | 259.55 | 0.24 | 0.01 | 0.04 | 0.01 |
| 325193 | 1.25 | 0.47 | 152.07 | 157.00 | 0.00 | 0.00 | 0.12 | 0.09 |
| 325199 | 3141.69 | 454.92 | 2548.20 | 600.89 | 0.09 | 0.01 | 0.08 | 0.01 |
| 325311 | 29.38 | 4.84 | 420.04 | 95.10 | 0.04 | 0.00 | 0.06 | 0.01 |
| 325412 | 1455.58 | 646.45 | 2738.57 | 390.79 | 0.05 | 0.03 | 0.04 | 0.01 |
| 325414 | 1412.68 | 325.98 | 642.52 | 142.95 | 0.11 | 0.02 | 0.05 | 0.01 |
| 327211 | 245.03 | 103.63 | 209.98 | 39.12 | 0.21 | 0.08 | 0.27 | 0.02 |
| 327213 | 8.72 | 1.68 | 398.98 | 88.28 | 0.03 | 0.01 | 0.30 | 0.02 |
| 327310 | 9.63 | 2.24 | 17.69 | 8.18 | 0.04 | 0.01 | 0.03 | 0.01 |
| 327410 | 0.39 | 0.12 | 0.45 | 0.14 | 0.01 | 0.00 | 0.01 | 0.00 |
| 327420 | 20.98 | 4.01 | 1.47 | 0.59 | 0.08 | 0.01 | 0.02 | 0.01 |
| 327993 | 146.65 | 16.64 | 115.19 | 14.98 | 0.16 | 0.01 | 0.18 | 0.02 |
| 331111 | 340.69 | 528.25 | 841.40 | 1329.49 | 0.07 | 0.00 | 0.08 | 0.00 |
| 331221 | 4.94 | 4.05 | 5.95 | 4.68 | 0.05 | 0.01 | 0.05 | 0.00 |
| 331314 | 19.05 | 8.77 | 1.62 | 2.67 | 0.24 | 0.15 | 0.03 | 0.06 |
| 331492 | 55.11 | 25.74 | 27.47 | 6.85 | 0.06 | 0.02 | 0.04 | 0.01 |
| 331511 | 70.27 | 17.47 | 176.36 | 53.68 | 0.08 | 0.02 | 0.16 | 0.03 |
| 332112 | 54.24 | 42.71 | 2.21 | 1.84 | 0.46 | 0.03 | 0.09 | 0.02 |
| 332510 | 313.51 | 26.24 | 1462.06 | 154.97 | 0.14 | 0.01 | 0.23 | 0.01 |
| 333611 | 927.21 | 136.80 | 578.06 | 214.45 | 0.09 | 0.01 | 0.12 | 0.03 |
| 336411 | 148.22 | 175.98 | 233.69 | 166.12 | 0.04 | 0.05 | 0.02 | 0.01 |
| 336414 | 146.77 | 151.38 | 12.68 | 20.54 | 0.11 | 0.10 | 0.65 | 0.31 |

Notes: Import and export transaction data are available at the 6-digit NAICS level disaggregated by port from USA trade online. This table summarizes trade transactions over the years 2010-2015. To construct a proxy measure for California imports and exports, respectively, we aggregate trade flows through the three California ports: Los Angeles, San Diego, and San Francisco. Columns (2) and (3) summarize annual domestic export values leaving these three California ports. Columns (4) and (5) summarize annual foreign import values (cif) entering the U.S. through the three California ports. Columns (5)-(8) summarize export and import shares, where shares are defined as California values divided by U.S. totals.

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

Panel A: United States

| | Mean | SD | SD within NAICS3 | SD NAICS3 & yr × 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 |

Panel B: California Only

| | Mean | SD | SD within NAICS3 | SD NAICS3 & yr × NAICS2 |
|---|---|---|---|---|
| ln Value of shipments | 19.91 | 2.33 | 2.07 | 2.03 |
| ln Value of imports | 18.10 | 3.05 | 2.57 | 2.52 |
| ln Value of exports | 18.30 | 2.04 | 1.88 | 1.83 |
| Domestic energy price | 16.56 | 8.39 | 7.62 | 7.13 |
| Foreign electricity price (exp) | 8.16 | 2.30 | 2.25 | 1.14 |
| Foreign electricity price (imp) | 7.73 | 2.91 | 2.77 | 1.62 |
| Foreign gas price (exp) | 2.20 | 0.85 | 0.83 | 0.45 |
| Foreign gas price (imp) | 1.85 | 0.93 | 0.87 | 0.57 |
| Energy intensity | 0.05 | 0.07 | 0.06 | 0.06 |
| Capital intensity | 0.73 | 1.55 | 1.52 | 1.50 |
| ln Wage | 54.56 | 18.03 | 13.07 | 12.63 |

*Notes:* All values deflated to 2010 U.S. dollars.

Table 5: Summary Statistics of Energy Variables (U.S./CA)

Panel A: United States

| | 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 | |

Panel B: California Only

| | Mean (SD) | SD within NAICS3 | SD NAICS3 & yr × NAICS2 |
|---|---|---|---|
| Domestic energy price (\$/MMBtu), using contemporaneous shares | 16.559 (8.385) | 7.619 | 7.126 |
| Domestic energy price (\$/MMBtu), using baseline shares | 20.445 (83.909) | 83.466 | 80.446 |
| Energy intensity (share of inputs), using contemporaneous shares | 0.053 (0.074) | 0.059 | 0.059 |
| Energy intensity (share of inputs), using baseline shares | 0.049 (0.076) | 0.059 | 0.059 |
| Average $CO_2$ emissions (tons per MMBtu) | 0.089 (0.015) | 0.013 | |
| Average $CO_2$ intensity (tons per \$1,000 value) | 0.210 (0.314) | 0.235 | |
| Average direct $CO_2$ intensity (tons per \$1,000 value) | 0.146 (0.260) | 0.193 | |

*Notes:* All values deflated to 2010 U.S. dollars.

Table 6: 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 7: 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 8: Regression Results with Capital Intensity Interactions

| Interaction | Value of Production CA | Value of Production Capital | Value of Exports CA | Value of Exports Capital | Value of Imports CA | Value of Imports Capital |
|---|---|---|---|---|---|---|
| P25 | $-0.870^{***}$ | $-0.994^{***}$ | $-0.816^{***}$ | $-0.858^{***}$ | 0.147 | 0.207 |
| | (0.239) | (0.238) | (0.283) | (0.291) | (0.204) | (0.211) |
| P50 | $-0.397^{**}$ | $-0.479^{**}$ | $-0.469^{*}$ | $-0.453^{*}$ | 0.284 | 0.268 |
| | (0.196) | (0.193) | (0.252) | (0.245) | (0.212) | (0.201) |
| P75 | $-0.154$ | $-0.252$ | $-0.277$ | $-0.274$ | $0.420^{**}$ | $0.404^{*}$ |
| | (0.194) | (0.191) | (0.228) | (0.237) | (0.210) | (0.212) |
| Interaction | $-0.316^{***}$ | $-0.005^{*}$ | $-0.317^{**}$ | 0.004 | $0.942^{***}$ | $-0.003$ |
| | (0.118) | (0.008) | (0.141) | (0.018) | (0.180) | (0.005) |
| R2 | 0.69 | 0.69 | 0.70 | 0.70 | 0.43 | 0.42 |
| Obs. | 1,524 | 1,524 | 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 industry-specific measures of energy intensity as well as California share (CA) 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 9: 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 5 and 6 at the NAICS6 level.

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

| | $CO_2$ / | P | Production | | | Exports | | | Imports | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NAICS6 | MMBtu | ($/MMBtu) | P25 | P50 | P75 | P25 | P50 | P75 | P25 | P50 | 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 7 at the 6-digit NAICS level for a $10 carbon price per metric ton of $CO_2$ in 2010 U.S. dollars.

Table 11: Impact of a $10 per Metric Ton of $CO_2$ Carbon Price with Process Emissions

| NAICS6 | Industry | Production P50 | | Exports P50 | | Imports P50 | |
|---|---|---|---|---|---|---|---|
| | | No process | Process | No process | Process | No process | 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 10, and including them ("Process").