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Mitigating Emissions Leakage in Incomplete Carbon Markets

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Abstract

Policies regulating greenhouse gas emissions apply to a small subset of emitting sources. This raises a formidable concern: emissions can 'leak' from regulated to unregulated sources. We provide a theoretical basis for deriving industry-specific measures of leakage risk, and for calibrating the output-based subsidies which are currently used to mitigate leakage. Using U.S. energy price variation as a proxy for variation that would be induced by a domestic carbon price, we show how theoretically consistent leakage mitigating subsidies can be calibrated. We simulate the impacts of a domestic carbon price on U.S. manufacturing with and without these subsidies. Absent mitigation, emissions leakage is substantial. Output-based subsidies targeted on the basis of our leakage risk measures significantly reduce this leakage risk. In contrast, the current practice of coarsely targeting subsidies on the basis of emissions intensity and trade exposure delivers a small fraction of leakage mitigation benefits while incurring significant costs.

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Absent a globally coordinated effort to regulate greenhouse gas (GHG) emissions, some jurisdictions are moving ahead with unilateral climate policy initiatives. As of 2021, there are 64 carbon pricing initiatives covering an estimated 21.5 percent of global anthropogenic GHG emissions.[1] Although this expanding scope is encouraging, a majority of anthropogenic GHG emissions remain unpriced. This incomplete coverage is concerning given the global nature of the climate change problem.

If a regional GHG policy increases the operating costs incurred by regulated sources relative to their unregulated rivals, this can shift production- and associated emissions- outside the regulated jurisdiction. This 'leakage' of emissions will offset GHG emissions reductions achieved within the jurisdictions implementing the policy. In response to concerns about emissions leakage, jurisdictions are experimenting with measures designed to mitigate leakage risk. This paper aims to advance the theory and improve the practice of emissions leakage mitigation in incomplete carbon markets.

In theory, full auctioning of emissions allowances, together with some form of border carbon adjustment and export rebate, can be effective in mitigating emissions leakage (see, for example, Fischer and Fox (2012); Böhringer et al. (2017); Kortum and Weisbach (2020)). While the border adjustment concept is elegant in principle, this approach has been difficult to implement in practice (Cosbey et al. (2019); Morris (2018)). Across existing and planned carbon pricing programs, policymakers are more often choosing to subsidize those sectors deemed most exposed to leakage risk. In GHG emissions trading programs, this subsidy is conferred in the form of permits allocated for free on the basis of industrial output. Under a carbon tax, tax revenues can be rebated on the basis of output.

Output-based rebating offers a viable means of mitigating emissions leakage (Fischer and Fox (2007); Fowlie et al. (2016); Quirion (2009); Fischer and Fox (2012)). But this strategy has some notable side effects. First, an opportunity cost is incurred when allowances are allocated for free or tax revenues are recycled to industrial producers. Second, output-based rebating dilutes the carbon price signal received by firms receiving the subsidy. Under a binding cap, allocating leakage mitigating subsidies to a subset of industries shifts the abatement cost burden onto unsubsidized producers, thus increasing the abatement costs incurred to bring emissions below a given cap. Under a carbon tax, output-based subsidies reduce the amount of abatement delivered by sources subject to the tax. Given these efficiency and distributional considerations, it is important to judiciously allocate subsidies to industries truly at leakage risk.

Looking across existing carbon pricing regimes, the standard approach to assessing leak-

[1] The World Bank Carbon Pricing Dashboard tracks proposed and existing carbon pricing initiatives globally. https://carbonpricingdashboard.worldbank.org/map_data.

age risk and targeting subsidies relies upon industry-level measures of emissions intensity (EI) and trade exposure (TE).[2] An advantage of these measures is that they can be readily calibrated using publicly available data. But the tenuous connection between these metrics and true leakage risk has raised concerns about legitimacy and efficacy.[3] The appropriateness of these criteria as a basis for evaluating and mitigating leakage risk has been identified as an important research gap (Cosbey et al. (2019)).

In order to strengthen the link between economic theory and policy implementation, we derive more theoretically consistent leakage metrics and demonstrate how these can be calibrated and applied. We begin with a conceptual framework that elucidates the determinants of emissions leakage. Building on insights from Meunier et al. (2014), we derive expressions for efficient leakage mitigation under alternative policy objective functions. Theoretically consistent leakage risk metrics depart from standard practice in two ways. First, we identify a critical determinant of both leakage risk and the efficient leakage mitigating subsidy schedule that is not reflected in current metrics: the responsiveness of unregulated production to policy-induced changes in regulated production (i.e. the market transfer rate). Second, whereas standard leakage metrics are based on domestic emissions, the rate of emissions leakage depends more directly on *foreign* emissions intensities.

The theoretically consistent leakage risk metrics we derive will be of limited practical use if they cannot be operationalized. We show how industry-specific market transfer rates can be calibrated using publicly available data. We use variation in domestic (relative to foreign) energy prices over the past decade to mimic the impacts of an economy-wide carbon price on domestic production, imports, and exports. Combining industry-specific estimates of market transfer rates with corresponding measures of emissions intensity yields industry-specific measures of leakage risk.

Our calibrated risk metrics indicate that the rate of emissions leakage (i.e. units of emissions leaked per unit of emissions abated) is likely to be high in some emissions intensive industries. In contrast with standard metrics, however, we estimate low levels of leakage risk in emissions intensive industries with low trade exposure. To investigate the larger implica-

[2]For example, the European Union, Canada, and California use these two metrics in the implementation of GHG regulations.

[3]Policy makers and other stakeholders have emphasized the need to refine and improve upon existing leakage mitigation protocols. 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

tions of these estimates, we simulate the effects of a hypothetical, economy-wide carbon tax. We estimate that a significant fraction of the policy-induced reductions in domestic emissions could be offset by emissions leakage. Our median estimate of the aggregate leakage rate is 46%.

Having assessed the potential for emissions leakage, we use counterfactual policy simulations to consider some alternative leakage mitigation strategies. Output-based subsidies targeted on the basis of our industry-specific leakage risk metrics significantly reduce simulated emissions leakage. However, given the practical challenges associated with using nuanced economic analysis to calibrate industry-specific subsidies, policy makers will be inclined towards simpler approaches. We contrast our theoretically preferred subsidy schedule against coarser alternatives modeled after current policy practice. The simpler alternatives we consider incur comparable costs but deliver a fraction of the emissions leakage mitigation benefits.

Our analysis contributes to a growing literature which assesses the potential for GHG emissions leakage under incomplete GHG regulation. To date, Computable General Equilibrium (CGE) modeling has provided much of the evidence on the quantitative impacts of incomplete carbon pricing and the potential for leakage (see, for example, Carbone and Rivers (2017); Fischer and Fox (2012); Böhringer et al. (2015)).[4] CGE models are powerful tools, but limited in the extent to which industry-specific details can be incorporated. To address this limitation, a number of recent studies use more detailed models to assess the potential for emissions leakage and leakage mitigation in specific industry.[5] Taken together, this literature reveals significant potential for emissions leakage under incomplete carbon pricing. However, the link between economic research and real-world leakage mitigation practices remains tenuous. Our approach aims to strengthen this link.

This paper is also germane to the empirical trade literature where the responses of trade flows to price shocks play a central role in determining first-order economic outcomes (Imbs and Mejean, 2015), (Feenstra et al., 2018). In this literature, trade elasticities are typically estimated using highly aggregated data and identified using shocks to tastes, technologies, or

[4] Whereas most CGE studies estimate moderate leakage rates (in the range of 10 to 30 percent), attempts to incorporate more realistic assumptions have yielded significantly higher leakage rates (see, for example, Babiker (2005) who predicts leakage rates in excess of 100 percent.)

[5] In a U.S. context, estimates of leakage potential range from very low (e.g. Bushnell and Humber (2015) estimate leakage rates close to zero in the nitrogen fertilizer industry), to very high (e.g. Chen (2009) estimate a leakage rate of 90% in the electricity sector). In Europe, leakage rate estimates have been estimated in the range of 20 to 73 percent for the cement sector (Demailly and Quirion (2006, 2008); Ponssard and Walker (2008)) and 30 to 50 percent for the aluminum and steel sectors (Demailly and Quirion, 2008). Researchers have also surveyed firms about the potential impacts of carbon pricing and used these responses to assess leakage potential in different industries (see, for example, Anderson et al. (2011); Kenber et al. (2009); Petrick and Wagner (2014)).

trade costs. In contrast, we use variation in domestic versus foreign energy costs to estimate the responsiveness of foreign import supply and export demand at a more dis-aggregated industry-level. For our purposes, energy price variation has the advantage of being more closely tied to the variation that a domestic carbon price would induce.

Finally, we contribute to a rich empirical literature that examines how asymmetries in environmental regulations across trading partners can affect manufacturing outcomes and trade flows.[6] Early work was largely based on cross-sectional comparisons (e.g., Grossman and Krueger (1995) and Mani (1996)). More recent work uses panel data to analyze the impacts of environmental regulation on industrial activity (see, for example, Ederington et al. (2005); Kenber et al. (2009); Petrick and Wagner (2014); Kahn and Mansur (2013)). Our empirical approach builds most directly on the important work of Aldy and Pizer (2015) who use variation in domestic energy prices to estimate the likely effects of a U.S. carbon price on domestic manufacturing production and *net* imports. These authors estimate very small impacts on net imports, leading them to conclude the costs of leakage mitigation "may outweigh the benefits and justify no action". We reach a more nuanced conclusion. Although we estimate very small impacts on *net* imports, we find significant potential for emissions leakage. We show that targeted leakage mitigating subsidies could substantively reduce this leakage risk. In contrast, crudely targeted subsidies have limited impact on leakage and can impose substantial costs.

The rest of the paper proceeds as follows. Section 1 briefly characterizes the current policy context. Section 2 derives measures of leakage risk and associated mitigating subsidies in theory. Section 3 calibrates industry-specific measures of emissions intensity. Section 4 estimates the elasticity parameters needed to calibrate industry-specific market transfer rates. Section 5 evaluates consequences of counterfactual carbon pricing policies with and without leakage mitigation. Section 6 concludes.

1 Emissions Leakage and Leakage Mitigation

Emissions leakage is a first-order concern in jurisdictions that have implemented unilateral carbon pricing policies. The economics literature has identified several channels through which this leakage can occur.[7] We confine our attention to the trade channel which has

[6] For an excellent review of the broader literature on the competitiveness impacts of environmental regulations, see Dechezleprêtre and Sato (2017).

[7] When a large open economy reduces demand for carbon-intensive inputs (e.g. fossil fuels), global input prices fall. This can stimulate demand for these inputs in unregulated regions. Emissions leakage via this factor price channel has the potential to be economically significant. (see, for example, Fischer and Fox (2012), and Boehringer et al. (2010)). Other possible channels include an income channel wherein changing terms of trade can alter the distribution of global income (Karp, 2013); and technology spillovers from

received the most attention from policy makers. Through this channel, emissions leakage can manifest if the policy causes an increase in imports into –or a reduction in exports from– a jurisdiction imposing an incomplete GHG policy. If policy-induced changes in trade flows cause a net increase in foreign production, any associated increase in foreign emissions will offset emissions reductions within the jurisdiction imposing the policy.

The economics literature has emphasized two alternative approaches to mitigating emissions leakage: a border carbon adjustment (BCA) and output-based subsidies. Under a border tax adjustment, compliance with GATT exception requirements and administrative cost considerations makes targeting essential. Under an output-based subsidy regime, we will argue that targeting is also important. A failure to target these subsidies can significantly undermine leakage mitigation benefits.

Given the importance of targeting leakage mitigation measures at those industries where emissions leakage potential is high, a critical first step involves identifying those sectors that should be eligible for protection. Under current policies, leakage mitigation is targeted on the basis of trade-related leakage risk. Risk is assessed using two industry-level metrics: emissions (or energy) intensity and trade exposure.[8]

The *emissions intensity* (EI) of an industry is generally measured in terms of tons of $CO2_e$ per \$M value added. This intensity measure typically capture both direct emissions from onsite energy inputs as well as indirect emissions associated with the consumption of electricity. Direct emissions from non-energy industrial processes are often -but not always- reflected in EI measures. Given the complexity of upstream emissions accounting, leakage risk metrics generally ignore emissions embodied in factor inputs other than electricity.

Trade exposure (TE) metrics are designed to capture the extent to which production and consumption in a domestic industry depends on trade with outside jurisdictions. Prior work by Sato et al. (2015) finds that standard TE metrics can be a poor proxy for the ability of a firm or industry to pass through regulatory compliance costs.

An important practical advantage of using EI and TE to assess leakage risk is that these metrics can be calibrated at the industry in a methodologically consistent way using publicly available data. In general, industries associated with high emissions intensity and high trade exposure are classified as high leakage risk, although the specifics of this categorization vary

induced innovation which can result in *negative* leakage (Baylis et al., 2014; Fischer et al., 2017).

[8] Leakage protocols developed in the EU ETS, Australia, the proposed American Clean Energy and Security Act of 2009, and California's GHG Trading Program, use industry-specific measures of emissions intensity and trade share to gauge industry-level leakage risk and allocate leakage mitigating compensation. Emerging programs in China are following this example (Wang et al., 2017). Beginning in 2021, the EU will apply a more targeted permit allocation scheme based on the combination of trade intensity and emission intensity.

across policy regimes.[9]

Once industries have been classified, mitigating measures (either border adjustments or output-based subsidies) can be targeted at the most high risk industries. This mapping of leakage risk measures to subsidy levels would ideally balance the efficiency and distributional costs of conferring output subsidies against leakage mitigation benefits. In practice, this mapping has been ad hoc and highly political. In what follows, we develop a theoretically sound approach to leakage risk assessment and production subsidy calibration that can be applied in a methodologically consistent way across industries.[10]

2 Emissions Leakage Mitigation in Theory

In this section, we derive empirically tractable formulations for leakage mitigating subsidies under alternative assumptions and policy objectives. These output-based subsidies can be construed more generally as measures of leakage risk. We show how, across a varied set of assumptions and extensions, a foundational basis for leakage risk assessment emerges.

2.1 Baseline model

We consider a single industry in which domestic producers of a homogeneous good face competition from foreign producers, but do not export to foreign markets. Domestic and foreign producers are denoted by subscripts d and f, respectively. Domestic production generates an emissions externality σ at a constant rate of e_d per unit of q_d.[11] Foreign emission intensity is denoted e_f. In this baseline model, all emissions are assumed to be direct versus embodied in factor inputs.

We assume that the domestic policy maker can regulate domestic GHG emissions, but not the emissions associated with foreign production. Domestic producers face a carbon price of τ per unit of emissions. This exogenous price can represent either a carbon tax or the equilibrium permit price if the industry is small relative to the larger carbon market. To mitigate emissions leakage, a subsidy s per unit of output is conferred to domestic producers, with $s \leq \tau e_d$. We assume a linear damage function over the relevant range of GHG emissions.

[9] The American Clean Energy Security Act used a threshold of 5% emissions intensive and 15% trade intensive to identify sectors at leakage risk. California uses a series of thresholds to define low/medium/high risk categories. Figure E2 in the Appendix provides two specific examples from existing and proposed policies in the United States.

[10] Our theoretical approach abstracts away from political considerations in order to identify leakage mitigating subsidies that maximize welfare, conditional on a set of assumptions and policy objectives.

[11] We maintain that the marginal social cost of carbon is constant over the range of emissions reductions a domestic carbon pricing regime would induce.

In this base case, we also assume the carbon price fully internalizes the emissions externality.

The profit functions for a domestic and foreign price-taking firm are thus given by:

$$\pi_d(q_d) = p(q)q_d - C_d(q_d) - \tau e_d q_d + s q_d, \tag{1}$$

$$\pi_f(q_f) = p(q)q_f - C_f(q_f). \tag{2}$$

Profit-maximizing firms set marginal operating costs equal to the product market price. In the presence of a carbon tax, this introduces a wedge between domestic and foreign producers. The incomplete carbon pricing policy induces a shift, or "market transfer," to foreign producers. The associated increase in foreign emissions, $e_f q_f$, offsets emissions reductions achieved at home. Within this basic framework, emissions leakage is completely determined by two factors, the emissions intensity of foreign producers e_f and the policy-induced increase in foreign production: $dq_f/d\tau$.

Building on Meunier et al. (2014), we can frame the policy design problem in terms of social welfare maximization. Taking first order conditions of profit maximization, equilibrium quantities can be defined as implicit functions of the subsidy (see Appendix A). The regulator's welfare maximization problem becomes:

$$\max_s \quad W(s) \equiv \underbrace{S(q_d(s) + q_f(s))}_{\text{Consumer Surplus}} - \underbrace{C_d(q_d(s))}_{\text{Domestic Costs}} - \underbrace{C_f(q_f(s))}_{\text{Foreign Costs}} - \underbrace{\sigma(e_d q_d(s) + e_f q_f(s)).}_{\text{Emissions Externality}} \tag{3}$$

This formulation implicitly assumes that output based subsidies are designed to mitigate *emissions* leakage risk. When output-based subsidies (or border adjustments) are implemented as part of a carbon pricing regulation, international trade agreements (e.g. GATT) will limit the extent to which these subsidies favor domestic producers over foreign competition. Whereas subsidies to mitigate emissions leakage are admitted under GATT's General Exception provisions, these exceptions do not include preserving domestic competitiveness (Cosbey et al., 2019). In Equation 3, we shut off the protectionist incentive; we assume the domestic regulator values domestic and foreign rents equally. This focuses our attention on the environmental externality exclusively. Appendix 6 extends the model to accommodate protectionist objectives.

Maintaining our assumption that the carbon price τ is set at σ, we solve for the subsidy s^* that maximizes Equation (3) (see Appendix A):

$$s^* = -\,\sigma\; e_f\; \frac{\frac{\partial q_f}{\partial s}}{\frac{\partial q_d}{\partial s}}. \tag{4}$$

The welfare maximizing subsidy is the product of the externality σ, the foreign emissions intensity of imports e_f, and the rate at which equilibrium imports change in response to an incremental, policy-induced change in domestic production (i.e. the market transfer rate). Intuitively, the optimal subsidy internalizes, on an output basis, the reduced damages associated with displaced foreign emissions.

A reformulation of Equation (4) elucidates the relationship between the welfare maximizing subsidy we derive and the metrics that are currently used to assess leakage risk:

$$s^* = \sigma \underbrace{e_f}_{\substack{\text{Foreign}\\ \text{Emissions}\\ \text{Factor}}} \times \underbrace{|\eta_f|}_{\substack{\text{Foreign}\\ \text{Output}\\ \text{Elasticity}}} \times \underbrace{\frac{q_f}{q_d}}_{\substack{\text{Trade}\\ \text{Ratio}}}, \tag{5}$$

where η_f represents the equilibrium elasticity of the supply of imports to a change in domestic production induced by a change in domestic production costs.[12] Recall that leakage risk is currently assessed on the basis of domestic emissions (or energy) intensity and trade share. The former is likely to be correlated with (although not a perfect proxy for) the emissions intensity of imports e_f (Fowlie and Reguant, 2018). The latter corresponds to the ratio of foreign imports and domestic production $\frac{q_f}{q_d}$. Missing from the standard approach is a measure of the trade elasticity η_f.[13]

This optimal subsidy schedule, summarized by Equations (4) and (5), is robust to several extensions and generalizations. In Appendix A1, we release the assumption that foreign and domestically produced goods are perfect substitutes. We show that same optimal subsidy formulation obtains in the more general case of imperfect substitutes, provided that the marginal rates of substitution (between domestic and foreign production) are set equal to the ratio of the product (home versus foreign) prices. In Appendix A2, we extend the baseline model to accommodate domestic exports. The introduction of exports opens up a related leakage channel insofar as a policy-induced reduction in domestic exports can lead to increased foreign production and associated emissions. Incorporating exports, the optimal subsidy (in elasticity form) becomes:

$$s^*_{export} = \sigma \ e_f \times \frac{|\eta_f| q^f + |\eta_e| q^e}{q^d + q^e}. \tag{6}$$

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

[13] Our derivation of s^* has implicitly assumed that any policy-induced change in foreign imports to the domestic market is equal to the overall impact on aggregate foreign production. However, there are plausible scenarios in which this assumption will not hold. For example, an increase in foreign imports will over-estimate the net increase in foreign production if some of the increase in the supply of domestic imports is met via a reduction in supply to other locations. In this case, the estimated relationships between policy costs and (observable) trade flows will over-estimate the responsiveness of total foreign production (which is much harder to reliably measure).

Here, elasticities are defined relative to total domestic production, $q^d + q^e$.[14]

In Appendix A3, we release the assumption that the emissions intensity of production is determined outside the model. We allow domestic firms to make capital investments that reduce their emissions intensity. We show that the optimal subsidy formula is unchanged, although the partial derivative $\frac{\partial q_d}{\partial s}$ now captures the net effect of multiple margins of domestic adjustment (including any abatement investments). In what follows, we release several of the simplifying assumptions invoked thus far.

2.2 Indirect Emissions

Some of the GHG emissions associated with domestic industrial production are 'indirect' emissions embodied in factor inputs. Purchased electricity is, by far, the most important source of indirect emissions in domestic manufacturing. We therefore consider a downstream sector that consumes α units of electricity per unit of output in a Leontief-like production function. We assume that the electricity sector is not (directly) trade-exposed. We further assume perfect pass through of carbon prices in factor markets (see Fabra and Reguant (2014)). If we redefine the emissions intensity in Sector 1 as $e_1 + \alpha e_2$. (thus ruling out factor substitution), this scenario maps directly onto our baseline model.

In Appendix A5, we show that leakage can be efficiently mitigated by conferring the output-based subsidy defined in Equation (4) to the downstream sector, provided that the emissions intensity e_f reflects both direct emissions and the emissions embodied in electricity inputs to foreign production. This theoretical result implies that sectors with no direct emissions could be eligible for leakage-mitigating subsidies if a policy-induced increase in electricity input costs leads to emissions leakage. Notably, emissions intensity metrics used to assess leakage risk under existing cap-and-trade programs (e.g. in Europe and California) reflect both direct emissions and emissions associated with purchased electricity. The key difference (between our theory and policy practice) is that these used metrics reflect domestic- versus foreign- emissions intensities. We return to this issue in the proceeding section.[15]

Appendix A5 extends the model to consider more complicated supply-chain relationships that implicate emissions-intensive factor inputs other than electricity. Given the variety of

[14] For ease of exposition, subsequent extensions will build on the baseline model that considers only imports. But all results can generalize to the export-inclusive case.

[15] It is worth noting that, although leakage risk metrics are calibrated to capture emissions embodied in purchased electricity, output-based subsidies have been designed to reflect direct emissions only. In both California and Europe, indirect emissions leakage has been mitigated separately. This dual crediting process has come under criticism. And, in California, there is currently a proposal to consolidate leakage mitigation into one output-based subsidy designed to mitigate leakage risk associated with direct and indirect compliance costs (Staff Straw Proposal and Request for Input on Electric Investor-Owned Utility Cap-and-Trade Program Allowance Proceeds Use: 2021-2030)

forms that these vertical relationships could conceivably take, we are unable to derive a general formulation for the optimal subsidy schedule. In our subsequent calibrations and policy simulations, we will emphasize the formulation derived from the model that accommodates indirect emissions from electricity inputs only.

2.3 Constrained and Exogenous Carbon Price

Political constraints and other considerations can limit the ability of policy makers to set carbon prices at a level that reflects the full marginal damage.[16] We first consider the case where the carbon price is set explicitly (as in the case of a carbon tax). If the domestic carbon price is constrained to fall below σ, as is likely the case, this has implications for the welfare-maximizing subsidy.

We generalize the baseline model to consider the case where $\tau \neq \sigma$. We maintain the assumption that τ is exogenously determined (as in the case of an emissions tax). The optimal subsidy now becomes:

$$s^*_{tax} = s^* - (\sigma - \tau)e_d, \tag{7}$$

where, the *tax* subscript denotes optimization against an exogenously set tax and s^* is the subsidy derived above.

In Equation 7, the welfare maximizing subsidy serves two purposes. It mitigates the leakage externality and compensates for the fact that the tax has not been set optimally. In the likely scenario where the carbon price has been set below τ, $s^*_{tax} < s^*$. Intuitively, the subsidy is reduced to compensate for the fact that the emissions price is too low. Note that this adjustment restores the net compliance cost obtained in the baseline model: $\tau e_d - (s^* - (\sigma - \tau)e_d) = \sigma e_d - s^*$.

2.4 Multiple Sectors; Endogenous Carbon Price

The level of subsidy conferred on one sector can indirectly impact equilibrium outcomes in other sectors via a number of channels. Here we consider how equilibrium interactions in a GHG emissions market impact the choice of welfare maximizing subsidy.

We consider a case where two sectors are covered by an exogenously set emissions cap E, but only one sector is trade exposed and susceptible to emissions leakage. Let s_1 denote the subsidy conferred on the trade exposed sector which will impact the second sector via the equilibrium permit price. The emissions constraint imposed by the cap is now implicitly captured by q_2 such that the permit price is an endogenous parameter.

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

In Appendix A4, we show that if we assume away any direct complementarities between sector, and if we take as given the exogenously set cap $\overline{E}$, we obtain the same expression for the optimal subsidy:

$$s^{cross-rel} = \sigma e_f \left| \frac{\frac{\partial q_f}{\partial s}}{\frac{\partial q_1}{\partial s}} \right|. \tag{8}$$

This result may seem inconsistent with our previous finding that the optimal output-based subsidy should be defined to compensate for an *exogenous* carbon price that falls below (or exceeds) the true externality cost. However, because the endogenously determined permit price represents the shadow value of the exogenously imposed emissions constraint, any attempt to adjust the subsidy to compensate for a cap that is too low (too high) will drive the market-clearing price even lower (higher). Thus, the subsidy cannot be used to compensate for a cap that has been set too low or too high; it should be designed solely to mitigate leakage.[17]

2.5 Other extensions

Our characterization of the welfare maximizing subsidy, summarized in Eq. (4), is robust to several of the extensions we consider above. One notable exception is the case where the subsidy can be used to both mitigate leakage and compensate for an exogenous permit price that has not been optimally set. More generally, the optimal subsidy will depart from the prescribed formula when it is used to address multiple distortions or failures. Appendices A6 and A7 consider some additional examples along these lines.

This theoretical analysis helps to highlight some important differences between leakage risk metrics that are currently used to target ad hoc subsidies and those derived from a partial equilibrium optimal design perspective. Notably, the rate at which foreign production responds to policy-induced changes in domestic production plays an important role in determining our measure of leakage risk, but is not explicitly captured by standard metrics. Another difference is that our derived subsidies implicate the emissions intensity of foreign production whereas standard leakage metrics are calibrated to reflect variation in domestic emissions. Building on these insights, we turn to the task of operationalizing theoretically consistent measures of leakage risk for U.S. manufacturing sectors.

[17] Appendix A4 extends this simple model in two additional ways. First, we show that when the policy-maker is able to choose both the emissions cap and the optimal subsidy schedule, the subsidy formulation is given by (8) and the cap is set such that the equilibrium permit price equals σ. We also show that the subsidy derived in (8) holds in a scenario where sectors are linked not only via the permit market, but also in a competitive vertical input supply relationship.

3 Calibrating Measures of Emissions Intensity

To calibrate our theoretically derived measures of leakage risk, we need industry-specific estimates of the emissions intensity of the foreign production that responds to policy-induced reductions in domestic output (e_f). We also need estimates of how industrial production and trade flows respond to the introduction of a domestic carbon price. Measures of domestic energy intensity are directly implicated in the estimation of these market transfer rates. In what follows, we estimate both domestic and foreign energy and emissions intensities at the industry level.

3.1 Measures of domestic emissions intensity

Industries that generate domestic GHG emissions (directly or indirectly) will be impacted by a domestic carbon price. The emissions intensity metrics routinely used to assess these impacts capture greenhouse gases emitted directly from domestic sources (e.g. emissions from the combustion of primary fuels used as inputs to industrial production) and the emissions associated with purchased energy inputs (e.g. emissions from electricity generation).[18] We estimate these *domestic* industry-specific emissions intensities in two steps.

First, we estimate the *energy* intensity of production using the ratio of industry-level annual energy inputs and corresponding measures of annual shipment values from the Annual Survey of Manufactures (ASM). Appendix C.3.2 explains how we use these data to estimate annual energy inputs (measured in MMBtu) at the NAICS6 level. In a second step, we translate industry-specific energy intensities to carbon intensities using fuel-specific estimates of carbon content. This exercise yields industry-specific measures of the carbon intensity of energy inputs to production. We subsequently refer to these emissions intensity measures as 'partial' because they capture only the emissions embodied in energy inputs.

Table 1 summarizes these intensity estimates across 312 industries and twenty years. The distribution of domestic energy intensity estimates (measured in MMBtu inputs per \$1000) is right skewed. Whereas the average energy intensity is 3.1 MMBtu per \$1000 in manufacturing shipments, the most energy intensive industries (e.g. pulp mills, cement, lime manufacturing) consume more than 30 MMBtu/\$1000 shipments. Median CO_2 intensity is 386 tons/\$1000; the most carbon intensive industries exceed 3000 tons/\$1000. See Appendix C.3 for a more detailed discussion.

These industry-specific measures of domestic carbon intensity can be used to assess how carbon pricing would impact operating costs. However, these measures fail to capture emis-

[18] For example, in the European and California programs, emissions intensity metrics capture direct emissions plus a measure of the carbon emissions associated with purchased electricity inputs.

sions embodied in non-energy factors of production (such as chemicals, steel, etc). For example, whereas these intensity measures capture the emissions from the electricity and fuel used to process tomatoes in the U.S., they exclude the GHG emissions released during the upstream agricultural production, the manufacturing of food processing equipment, etc.

To calibrate more comprehensive measures of the domestic carbon emissions embodied in domestic production processes, we use domestic input-output (I-O) tables constructed by the Bureau of Economic Analysis (BEA) to summarize the carbon implications of domestic supply chain relationships. Taking the Leontief inverse of these BEA I-O tables, we can estimate the dollars of each domestically produced non-energy input, including those required to produce intermediate inputs, that are required to produce an additional dollar of final demand in each domestic manufacturing industry. We combine these inverted matrices with our 'partial' (energy-related) emissions intensities to estimate a more comprehensive measure of the the domestic CO_2 emissions embodied U.S. production.[19] Appendix C.4 describes this accounting exercise in detail.

Figure E.4 in the Appendix plots these more comprehensive measures of industrial emissions intensity against our partial emissions intensity measures. In some industries, the comprehensive CO_2 intensities are estimated at more than double our direct estimates. Among the most carbon intensive industries (e.g. lime, paper, cement, nitrogen fertilizer), however, the comprehensive intensities are all within 10 percent of the partial measures.[20]

Although it is conceptually appealing to use more comprehensive measures of carbon intensity in an assessment of carbon pricing impacts, there are formidable limitations with this approach. these estimates are based on static supply-chain relationships calibrated at high levels of sectoral aggregation. Given the potential for significant measurement and calibration error, our preferred empirical estimates use our partial measures of emissions intensities.

3.2 Calibrating measures of leakage risk

Our theoretically consistent measures of leakage risk (and associated subsidies) implicate marginal *foreign* emissions intensities. In contrast to domestic emissions data, detailed facility-level data are not collected in a consistent way across countries. To our knowledge, the best available source of international emissions data is a global Input-Output database

[19]We note that these comprehensive emissions intensity measures capture energy-related versus process emissions.

[20]This ratio of partial and comprehensive emissions intensity measures the share of embodied emissions that are directly related to energy inputs. This ratio is related to measures of 'upstreamness' which capture the economic distance from final customers (see, for example, (Shapiro, 2020)

called Exiobase.[21] These foreign emissions data are very highly aggregated across sectors and regions. Appendix C.5 documents several issues with these foreign emissions data.

Given the numerous limitations, we elect to use our estimates of domestic emissions intensities to proxy for foreign emissions intensities. The advantage of this approach is that domestic data are reliably collected in a uniform way across all manufacturing sectors. One drawback is that domestic producers that could differ substantively from foreign producers. Another limitation is that estimates of average emissions intensity could under- or over-state marginal emissions intensities. These challenges are discussed in Fowlie and Reguant (2018).

4 Calibrating Market Transfer Rates

Market transfer rates measure the net change in foreign production caused by an incremental change in domestic production. Ideally we would use exogenous variation in climate policy compliance costs (e.g. variation in federal carbon prices) to estimate these parameters. To mimic the effects of carbon price variation we do not observe, we leverage the fact that a domestic carbon price would primarily affect manufacturing operations via increased domestic energy costs.[22]

Variation in domestic energy prices in recent years has generated cost variation similar to that which would be induced by a unilateral domestic carbon price. Appendix Figure E.1 shows the significant drop in domestic energy prices relative to international foreign prices since 2007. This structural break can be attributed to the technological innovation in horizontal drilling and hydraulic fracturing which led to a significant increase in domestic natural gas and oil production. The associated energy price shock has been largely confined to the domestic market because natural gas is costly and complicated to export overseas. Our empirical strategy is premised on the idea that we can use some of this variation in relative energy costs (i.e. domestic versus foreign) to estimate the industrial production and trade flow response.

To calibrate industry-specific market transfer rates empirically, we decompose these rates into parts.[23] Our preferred decomposition is as follows:

[21] We thank Joe Shapiro for drawing our attention to this data source and sharing some of the code he uses to construct foreign emissions intensity metrics. Shapiro's approach is described in detail in Shapiro (2019)

[22] Over 90 percent of industrial GHG emissions come from direct fossil fuel combustion or electricity consumption. Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. US EPA, Washington DC.

[23] To estimate these rates directly, one could regress foreign net imports on domestic production to obtain a direct measure of transfer rates. However, there are many reasons why foreign production could be correlated with domestic production, either positively through common shocks or negatively due to substitution. It is difficult to think of an approach that would properly isolate the response of foreign production to domestic

$$TransferRate_j = \frac{|\epsilon_j^{Imp}| \cdot Imp_j + |\epsilon_j^{Exp}| \cdot Exp_j}{|\epsilon_j^{Prod}| \cdot Prod_j} = \frac{dq_{fj}}{dq_{dj}}. \tag{9}$$

The elasticity parameters, denoted by ϵ_j, capture the responsiveness of domestic production and trade flow values to variation in domestic energy prices. These are estimated econometrically.[24] The remaining parameters (i.e. import value (Imp), export value (Exp), and domestic shipments ($Prod$)) are calibrated using publicly available data in the baseline year (2007).

4.1 Data

In the interest of demonstrating an approach that could be applied in real-world policy settings, we restrict ourselves to using public data sources that cover all manufacturing sectors. Our data are comprised of observations from 312 U.S. manufacturing sectors over the period 1995-2017. Industries are defined using the six-digit North American Industry Classification System (NAICS). Appendix Table B.1 summarizes our data sources in detail.

4.1.1 Outcome variables

The outcomes of primary interest include domestic production (shipment values), the value of import transactions, and the value of domestic export transactions. These outcomes are reported annually, in nominal value terms, in the Annual Survey of Manufacturers (ASM) and the Census of Manufacturers.[25] Table 1 summarizes these outcome variables at the NAICS6-year level.

4.1.2 Domestic energy prices

For each industry–year, we estimate the average price paid per MMBtu of energy inputs. We use electricity consumption and expenditures reported in the Census of Manufactures(CM) and Annual Survey of Manufactures (ASM), respectively, to construct industry-year specific estimates of average electricity input prices. Primary industrial fuel prices are estimated

production due to an energy cost shock.

[24] The elasticity parameters we estimate are related to -but conceptually distinct from- the elasticity parameters in Equation (9). The theoretical formulation is defined in terms of quantities of production quantities. Our estimated elasticities are defined in terms of value added.

[25] Our theoretical framework calls for using output in quantities, not value. Unfortunately, quantity data is not available in the ASM or Census, and it would be impossible to obtain from alternative sources for a wide range of NAICS codes. We considered using industry-specific deflators to have a measure of physical output, although there is not consistent coverage throughout the sample. Furthermore, for most sectors, heterogeneity in output makes measuring quantities with industry deflators an ill-posed exercise that is not well defined.

at the state level in the State Energy Data System (SEDS). To weight prices of different fuels used in a given industry-year, we use industry-region-year fuel shares as reported in the Manufacturing Energy Consumption Survey (MECS). With these components, we estimate weighted average energy prices using the industry-specific fuel shares as weights:

$$P_{jt}^{energy} = share_{naics3}^{elec} \times Price_{jt}^{elec} + (1 - share_{naics3}^{elec}) \times Price_{jt}^{fuel}, \tag{10}$$

where j denotes industry and t denotes year.

We also construct the domestic energy price index analog to our more comprehensive energy intensity indices. More precisely, we use the elements of the inverse domestic Leontief matrix described in Section 4 to construct a weighted average of industry-specific direct price indices. For each industry, these more comprehensive price indices account proportionately for the energy costs reflected in non-energy factor prices (under a strong assumption of full pass through), in addition to direct energy input costs. Appendix C.1 explains the construction of these energy price indices in detail.

Direct and total domestic energy price indices are summarized in the middle panel of Table 1. All prices are deflated to 2007 U.S. dollars. Average price indices are weighted by 2007 domestic shipment values. The weighted average direct energy price is \$11.26/MMBtu. The more comprehensive total price index (reflecting both direct and embodied energy input prices proportional to value added) is lower on average at \$9.79/MMBtu.

In addition to reporting mean values, the table decomposes the variance in these energy price indices. Notably, a significant fraction of the energy price variation remains after we remove industry and time fixed effects. It is this residual variation that we will use to estimate the elasticity parameters. To put this residual variation into perspective, a carbon price of \$25 would increase industrial natural gas prices by approximately \$1.33/MMBtu. This falls within two standard deviations of the residual energy price variation.

4.1.3 Foreign energy prices:

In order to isolate the effects of relative variation in domestic energy input costs, we need to control for variation in foreign energy prices. We build on the work of Sato et al. (2019) who have constructed weighted averages of fuel-specific prices for 48 regions and 12 sectors over 1995-2015. We use these estimates to construct industry-specific average price indices using import or export trade volumes as weights. See Appendix C.2 for details.

Three alternative measures of foreign energy price indices are summarized in Table 1. Measures differ in terms of the trade volume weights. Energy prices in countries where U.S. exports are shipped are somewhat lower on average as compared to the average foreign energy prices in countries where U.S. imports are sourced. This implies that the U.S. manufacturing sector exports disproportionately to countries with higher energy prices, while importing relatively more from countries with lower energy input costs. Although fuel prices are highly correlated across countries, substantial variation remains within 6-digit NAICS industries, even after sweeping out common time trends..

4.1.4 Other controls

We include additional variables in our regression specifications to control for other potential confounds. These variables include industry-year wages and a time series of a trade weighted US dollar index from FRED. These control variables are also summarized in Table 1.

4.2 Empirical strategy

A host of factors determine how industrial production, imports, and exports in different manufacturing sectors evolve over time. The complexity of these relationships makes it challenging to isolate the *causal* effects of domestic energy price variation on manufacturing production and trade flows. Our empirical strategy aims to strike a balance between controlling for potential confounds, and retaining sufficient variation in relative energy prices to identify the elasticity parameters with some degree of precision.

Our primary empirical objective is to estimate the industry-specific elasticity parameters needed to calibrate Equation (9). Data limitations prevent us from estimating relationships between energy cost variation and the outcomes of interest separately for each industry. Instead, we pool data across 312 U.S. manufacturing industries and specify estimating equations that accommodate systematic variation in the elasticity parameters along observable dimensions. The following general form serves to motivate our basic approach:

$$\ln y_{jt} = \alpha_j + \beta_j^d \cdot EI_j \cdot \ln p_{jt}^d + \beta_j^f \cdot EI_j \cdot \ln p_{jt}^f + \gamma' X_{jt} + \eta_t + \varepsilon_{jt}, \tag{11}$$

where j indexes 6-digit NAICS industries, t indexes years, and the dependent variable y_{it} is one of four outcomes (production, imports, exports, and net trade) associated with industry j in year t.

The NAICS6 industry fixed effects, α_j, capture time invariant factors that generate variation in economic outcome variables across industries. Year fixed effects capture macroeconomic trends over time that affect all sectors similarly. The X_{jt} represent other time-variant factors that vary across industries and could play a significant role in determining outcomes (such as industry-specific wage dynamics, tariffs, or exchange rate fluctuations).

The domestic energy price index is p^d_{jt} and the foreign energy price index is p^f_{jt}. These industry-specific indices are interacted with corresponding measures of energy intensity (measured in terms of MMBtu/$). This assumes that an industry which uses no energy inputs is affected only indirectly by energy price variation via common macroeconomic trends and a constant elasticity with respect to energy costs.[26] We calibrate these energy price indices and intensities in a number of ways. One set of estimating equations uses our partial measures. Another set of equations use our more comprehensive measures. Some specifications use contemporaneous energy prices to capture the immediate impacts of variation in relative energy costs. Recognizing that domestic production decisions and trade flows could take years to adjust, we also estimate specifications using lagged energy prices. All equations are estimated as weighted regressions.[27] Standard errors are heteroskedasticity robust, clustered at the NAICS6 level.[28]

The β^d parameters are identified using the residual variation in domestic energy prices: deviations from industry specific average energy prices after adjusting for variation in foreign energy prices, annual shocks common to all industries, and other controls. As in Hausman and Kellogg (2015), we leverage variation in natural gas prices induced by the boom in hydraulic fracturing which generated substantial differences in relative energy prices. Some of the intra-industry residual variation is spatially driven because the domestic energy supply expansion affected different regional market prices differently. Differences in the spatial distribution of plants in an industry thus generates variation in our industry-year price indices across industries. Another source of variation comes from pre-existing (and sustained) differences in industry-specific fuel shares.

We instrument for energy prices using electricity prices. The rationale behind this instrumentation strategy is as follows. Given how we construct the energy price indices, our energy price indices are measured with error. Electricity prices are more precisely reported and reflect more exogenous regional variation. In contrast to other fuel prices which are heavily commoditized, there is a more limited scope for electricity trading across regions. Thus, whereas all U.S. electricity prices have been impacted by the fracking boom, the extent

[26] Our attempts to estimate more flexible functional forms generated unrealistically large effects for sectors with very low energy intensity. This appears to be driven by the collinearity of foreign and domestic prices for these sectors and the limited signal in their cost shocks.

[27] This is standard practice because, in an unweighted regression, industries with very small shipments/import/export values will have disproportionate effects on estimates. 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)). We examine the sensitivity of our results to several alternative weighting strategies.

[28] On another technical note, we find that some of our estimates are sensitive to a small number of outlying observations. We follow the literature (e.g., Ederington et al. (2005)) and use an approach suggested by Hadi (1994) to identify outliers in our data set and examine the sensitivity of the results to their inclusion.

of the impact depends on the generating fuel mix of the region and the proximity to the fracking shales.[29]

Ultimately, our ability to extract forward looking policy implications is predicated on the assumption that a careful analysis of how firms have historically responded to the short/medium run variation in relative energy costs we have isolated can inform our understanding of how a carbon price would impact industrial production and international trade flows. Although there are important similarities between our identifying variation and the variation in operating costs that would be induced by an economy-wide domestic carbon price, there are also differences. First, because we sweep out industry fixed effects, time trends, and some other potentially confounding sources of variation in outcomes, the residual variation in energy prices that we use for identification is more idiosyncratic than the variation that would be generated by a carbon pricing regime. Moreover, the identifying variation is driven primarily by *reductions* in domestic energy prices below foreign energy prices whereas a carbon price would induce a relative increase.[30] Another important consideration is that the carbon pricing regime we want to understand will generate government revenues that would presumably be put to good use. We explicitly evaluate the impacts of one use: leakage mitigation via output-based subsidies. But there are other uses, such as revenue recycling to households or the reduction of distortionary taxes on other inputs to production, which our identifying variation does not capture. This omission could lead us, for example, to overstate the impacts of a domestic pricing regime on domestic manufacturing outcomes (see, for example, Goulder (2013)).

4.3 Elasticity estimates

The regression equations are designed to isolate the response of manufacturing shipments, foreign imports, and domestic exports to changes in relative energy costs. Specifying these equations involves many design choices, some of which are ad hoc.[31] From a policy perspective, it will be important to understand the extent to which our estimates vary across specification alternatives. We thus report results from a range of estimating equations which differ in terms of regression weights, control variables, treatment of outliers, and measures

[29] See a similar approach in Ganapati et al. (2020).

[30] 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. However, if capacity constraints or other considerations generate asymmetry in response to changes in relative energy prices, our estimates will be less informative about the responses we should expect in response to a policy-induced increase in relative prices.

[31] For example, there are a variety of ways to specify our conditioning strategy or weight our regression observations.

of energy intensity.[32]

Figure 1 focuses on the most important parameters: elasticities with respect to domestic energy costs. We report elasticity estimates across 48 specifications (96 for the trade related variables because all specifications are weighted both by domestic production and the relevant trade volumes, respectively), showing the point estimates and 95 percent confidence intervals for each.[33] The left panel reports on specifications that use contemporaneous energy price variation. The right panel pertains to specifications that use lagged energy prices. All specifications in Figure 1 use direct measures of energy intensities and price indices. Appendix D summarizes the corresponding results generated using our more comprehensive measures that incorporate direct and upstream energy inputs.

The lack of precision (illustrated by wide confidence intervals) is unfortunate but inevitable given the residual variation we are working with. Across specifications, the sign of the estimated elasticities are generally consistent with economic theory.[34] Exports are found to be more responsive (in absolute terms) to domestic energy price variation as compared to imports. This is consistent with recent work (Feenstra et al., 2018) which finds that "micro" elasticities of substitution between foreign sources tend to be larger than "macro" elasticities of substitution between domestic and imported goods. This underscores the importance of estimating separately the response of imports and exports.

4.4 Calibrated market transfer rates and leakage risk

We use the elasticity estimates summarized in Figure 1 to calibrate industry-specific market transfer rates. This calibration proceeds in two steps. First, we construct *industry-specific* elasticity parameter estimates (i.e. the ϵ_j parameters in Equation (9)) using the product of the estimated β^d coefficients and the corresponding industry-specific measures of energy intensity EI_j (calibrated to the baseline year 2007). Next, we multiply these cost elasticities by the corresponding baseline annual import values, export values, and values of shipments to estimate level changes in these outcomes. The numerator in Equation (9) estimates industry-specific increase in foreign imports associated with a unit change in domestic energy costs plus any reduction in domestic exports (measured in dollar terms). The denominator

[32]The universe of possible estimating equations extends beyond those we summarize here. We did experiment with more saturated fixed effects and more flexible functional forms. Given the limited variation in domestic energy prices we have to work with, and collinearity between foreign and domestic energy prices, more flexible and/or saturated models do not perform well.

[33]All specifications use the price of electricity interacted with energy intensity as an instrument for the domestic energy price interaction.

[34]Imports (Panel c) are an exception. The estimated impact of domestic energy cost variation on import flows is negative for some specifications that use import values to weight the regression (versus the total value of shipments).

estimates the corresponding change in domestic production (also measured at the industry level in dollar terms).

Because our regression equations pool observations across industries, industry-specific market transfer rates are coarse and approximate. Another important consideration pertains to our trade transaction data. We use changes in U.S. imports and export values as a proxy measure for changes in total output. This assumes that domestic imports are purely additional (i.e., when domestic demand for imports falls, foreign production falls one-for-one) and domestic exports displace foreign production one-for-one. If an increase in domestic imports crowds represents a reallocation of global supply, and/or if a reduction in foreign exports is not replaced one-for-one by foreign production, our estimated impacts on trade flows will over-estimate the market transfer (and associated emissions leakage).

With hundreds of industries and over a hundred empirical specifications, we generate thousands of market transfer rate estimates. Overall, the median of the full distribution of transfer rate estimates (across industries and specifications) is 37%. But the average value is higher (46%) because there is a subset of regression specifications that imply very high transfer rates.

Panel (a) of Figure 2 provides a graphical summary of how these calibrated market transfer rates vary with standard leakage risk metrics: emissions intensity and trade exposure. We regress our calibrated market transfer rates (across all empirical specifications and methods) on industry-specific measures of emissions intensity, trade share, and their interaction. The markers in Figure 2 represent the 312 industries in our data. We use regression-based extrapolation to fill in the gaps between industry-specific observations.

Calibrated transfer rates vary across industries due to compositional differences with respect to imports and exports, and differences in the relative importance of trade flow values vis a vis domestic production. The heat map shows how calibrated market transfer rates are highest in the more trade exposed and energy intensive sectors. This result is consistent with the current policy practice that confers larger subsidies to very trade exposed industries (see Appendix Figure D.1). Notably, we estimate moderate to low market transfer rates in energy intensive industries with low trade shares. Intuitively, we should not expect to see high leakage risk in industries where we see low or no response in trade flows when domestic production responds to changes in domestic energy prices.

Given the formidable challenges associated with estimating foreign emissions (discussed in Appendix C.5), we use *domestic* emissions intensities to proxy for foreign emissions. To calibrate measures of leakage risk, we multiply industry-specific market transfer rates by the corresponding measures of domestic emissions intensity. This yields industry-specific emissions leakage rates (measured in terms of emissions leaked per dollar reduction in domestic shipments). In Panel (b) of Figure 2, we regress these leakage rates on emissions intensity, trade exposure, and their interaction.

Emissions leakage rates are increasing in both emissions intensity and trade exposure. An important difference between the patterns we estimate and current policy applications concerns highly energy intensive sectors that are *not* trade exposed. Under existing and planned carbon pricing programs, policy makers confer the highest levels of leakage protection to all emissions intensive sectors, regardless of the level of trade exposure. In contrast, we estimate relatively low leakage risk among emissions intensive industries that are not trade exposed.

5 Carbon pricing counterfactuals

In this section, we use our regression-based estimates to assess how an economy-wide, domestic carbon price would operate through energy prices to impact manufacturing sector outcomes. We simulate – albeit in a stylized way– the effects of a $25/ metric ton CO_2 price on domestic energy prices in 312 manufacturing industries.[35] In what follows, we emphasize the direct impacts of policies on energy input costs. Appendix D reports on a companion set of simulations using our more comprehensive measures of embodied energy costs and intensities.

A $25 carbon price is at the lower end of estimates of the social cost of carbon, but higher than carbon prices observed in many existing regional programs. Given the residual variation in domestic energy prices that we have to work with, we are limited in our ability to simulate the impacts of higher prices.[36] We first evaluate the effects of a $25 carbon price introduced without any attempt to mitigate leakage. We then incorporate output-based subsidies.

A full welfare analysis of these policy scenarios would require estimating production cost and demand parameters for hundreds of industries. This is beyond our scope. But we are well-positioned to investigate some emissions implications and policy design trade offs. First, we assess the impacts of the $25 carbon price on domestic production, trade flows, emissions, and leakage. Second, we assess the leakage mitigation benefits and distributional implications of our theoretically consistent subsidies. Finally, we acknowledge that policy

[35] Our focus on energy price impacts will lead us to *underestimate* policy impacts in the small number of industries where 'process' emissions (i.e. GHG emissions that are not generated by fossil fuel combustion) are significant.

[36] Proposed taxes range from $10 to $52/ton CO2e. Carbon pricing proposals introduced in the 116th Congress (2019–2020) are summarized at: https://www.c2es.org/document/carbon-pricing-proposals-in-the-116th-congress/.

makers face important trade offs between keeping subsidy calibration simple and targeting subsidies towards high leakage-risk sectors. We contrast our theory-based subsidy schedule against coarser, more categorical subsidy schedules.

5.1 Carbon pricing with no leakage mitigation

To simulate the direct effects a domestic carbon price on industrial energy costs, we introduce some additional assumptions. We assume complete carbon price pass-through by energy suppliers (Fabra and Reguant, 2014) and hold industry-specific fuel shares constant. Conditional on these assumptions, and ignoring any general equilibrium effects, we estimate that a \$25/ton carbon price increases baseline domestic energy price indices by more than 20% on average. These energy cost impacts are higher (lower) in industries that use a relatively more (less) carbon intensive fuel mix.

Industry-specific energy cost increases are combined with our regression-based energy cost elasticities to simulate the impacts of the carbon price on annual domestic manufacturing shipment values, imports, and exports. Results for all 312 industries are generated using the full suite of empirical specifications summarized in Figure 1. Table 2 reports results from the carbon tax regime. Table 3 corresponds to the cap-and-trade program. Absent output-based subsidies, these simulations of the tax and trading regimes deliver equivalent outcomes by design because the cap is defined to equal the level of domestic emissions that obtains under the \$25 tax.

Domestic manufacturing shipments: The median estimated reduction in domestic manufacturing shipments (annual) induced by a \$25 carbon price is 1.6%. Although estimates are quite stable across empirical specifications, variation in simulated estimates across industries is significant. Figure 3 summarizes the extent of this inter-industry variation. Each point corresponds to an industry; the lines denote the inter-quartile range of estimates across empirical specifications. For the majority industries, impacts on domestic shipments are small. However, among some of the most energy intensive industries (e.g. cement manufacturing, lime manufacturing, paper board mills, and pulp mills), reductions in shipment values are large (above 20%).

Trade flows: Estimated reductions in domestic exports are in the range of 1-3 percent (with a median value of 1.9%). Panel (b) of Figure 3 summarizes the industry-level estimates. Impacts are small in a majority of industries, but substantial among a small group of relatively emissions intensive exporting industries. Simulated increases in foreign import values are notably smaller in absolute value. The range of simulated outcomes include some *decreases* in imports because some of our empirical specifications (summarized in Fig. 1) yield *negative* estimates of the energy cost elasticity of imports.[37]

Domestic emissions and leakage: Panel B of Tables 2 and 3 summarizes simulated impacts on domestic emissions and emissions leakage. Our median estimate of domestic emissions abatement is 7.1%. Abatement estimates are moderately sensitive to the range of empirical specifications we consider.

Emissions leakage is estimated by multiplying changes in trade flows (increases in imports plus decreases in exports) by the corresponding, industry-specific emissions intensities. As we note above, this approach will over-estimate the extent of leakage risk if changes in foreign exports and domestic exports overstate changes in global production. Using domestic emissions intensities to proxy for foreign emissions introduces an additional margin of error.[38]

Subtracting emissions leakage from domestic emissions abatement estimates yields an estimate of the abatement induced by the carbon price *net of leakage*. Absent leakage mitigation, the median estimate of net abatement is 3.8%. Emissions leakage can alternatively be characterized terms of the rate at which emissions leakage offsets domestic emissions abatement.

For each empirical specification we estimate, we construct the ratio of the net increase in foreign emissions and the decrease in domestic emissions. The median leakage rate is 46%. This implies that for each ton of CO_2 abated domestically, almost half a ton 'leaks'. This estimate varies significantly across empirical specifications because the ratio is sensitive to changes in the energy cost elasticities in the numerator and denominator.

Figure E.5 in Appendix E summarizes industry-level estimates of emissions abatement and emissions leakage (measured in thousands of tons per year). Industries that deliver the largest emissions reductions are among the most energy intensive. Some –but not all– of the emissions intensive industries that deliver a large abatement response are associated with significant levels of emissions leakage.

5.2 Carbon pricing with leakage mitigating subsidies

In this section, we assess the implications of deploying a theoretically consistent (albeit coarsely calibrated) leakage mitigation strategy. We consider first a policy regime that combines the carbon tax with leakage mitigating subsidies. We then consider a cap and

[37]We also simulate the impacts of carbon pricing on imports *net of exports*. Previous research (e.g. (Aldy and Pizer, 2015)) find no statistically significant impact of a simulated carbon price on net imports. Our results are qualitatively similar. Although Table 2 shows how these net import estimates mask more significant export responses.

[38]As we note in Section 4, our estimates of foreign emissions intensities suffer from severe aggregation bias and other calibration errors. For this reason, we use domestic emissions intensities to proxy for foreign emissions intensities.

trade program with an endogenous carbon price.

Exogenous carbon price. To calibrate output-based subsidies for each industry, we use the industry-specific median transfer rate estimate. We multiply this median estimate by the corresponding industry-specific emissions intensity (which varies across simulations) and the \$25 carbon value. In other words, whereas the subsidy schedule is held fixed across simulations, estimated energy cost elasticities vary. This approach captures, to some extent, the fact that regulators must rely on imprecisely estimated elasticities to calibrate output-based subsidies. We re-simulate outcomes under the \$25 carbon tax, now adjusting industry specific costs to reflect the offsetting effects of the output-based subsidies.[39]

Column 2 of Table 2 summarizes outcomes simulated under this augmented tax regime. Because the subsidy partly offsets the costs imposed by a carbon tax, impacts on domestic manufacturing activity, imports, and exports are attenuated relative to the carbon tax only scenario. Our median estimate of domestic emissions abatement falls from 7.1% (under the tax) to 4.6% (under the tax + subsidy). The emissions leakage rate falls from 46% to 17%.

A comparison of columns (1) and (2) in Table 2 shows how the targeted, output-based subsidies substantively reduce emissions leakage. This leakage mitigation comes at some cost. One of these costs is summarized in the last row of Table 2 which reports government tax revenues net of the output-based subsidy outlay. A significant share of carbon tax revenues are recycled to industry as output-based subsidies. These foregone revenues amount to a substantial (\$19 B per year) opportunity cost.

Results in Table 2 are predicated on the assumption that the true social cost of CO_2 emissions is \$25/ton. By Equation (7), these subsidies will be too high if the true social cost of carbon exceeds the tax. Suppose, for example, that the true social cost of carbon is \$50, but the tax is constrained to equal \$25. Under this scenario, if the subsidy schedule was calibrated to address both emissions leakage and the sub-optimal tax, only about half of the industries should be subsidized.[40]

Endogenous carbon price. Domestic emissions are constrained by the emissions cap under a cap-and-trade program. The introduction of output-based subsidies in a subset of industries partly offsets the permit price signal in those industries. To the extent that this

[39] This approach assumes that the carbon price of \$25/ton reflects the true social cost per ton of CO_2 emitted. We later discuss the implications of releasing this assumption.

[40] To see this, note that the subsidy an industry receives is $\sigma \times TR \times e_f - (\sigma - \tau)e_d$. Under the imposed assumption that $TR \in [0, 1]$ and $e_f = e_d$, any industry with a transfer rate of less than half (which is approximately the median), should receive no subsidy. Instead, it should receive an additional tax to compensate for the low carbon prices, which we rule out due to political constraints.

results in less abatement in these industries, the permit price must increase to obtain the abatement needed to meet the cap.

Under the cap-and-trade scenario, output-based subsidies are defined as the product of the industry-specific emissions intensity, the corresponding market transfer rate, and the social cost of carbon (which is set to $25 for ease of comparison with the tax regime). Under this subsidy schedule, we find that the simulated permit price must increase to $34 to clear the market. The impact of the subsidies on domestic production and trade flows are thus more significant under the trading regime due to the higher permit price. These results are summarized in Column (2) of Table 3.

The introduction of the output-based subsidy increases *net* abatement to 5.1% (from 3.8%) by reducing the median leakage rate to 27% (from 46%). As compared to the tax regime, the level of government revenues collected is less impacted by leakage mitigation because of the offsetting permit price increase and the fact that the optimal subsidy is based on the social cost of carbon of $25, not the equilibrium price of $34.

Intuitively, the introduction of output-based subsidies reduces abatement in industries where leakage risk is high, but increases abatement activity in industries where the increase in the permit price more than offsets the effect of the subsidies. The subsidy-induced reduction in emissions leakage is relatively more significant under the tax regime as compared to the cap and trade scenario. However, the net effect on our measure of 'total' emissions is largest under the trading regime that incorporates the leakage mitigating subsidy.

5.3 A targeting/transparency tradeoff

Given the practical challenges associated with using nuanced economic modeling and econometric analysis to allocate valuable subsidies across industries, existing programs have opted for simpler approaches that assign industries to coarse risk categories for the purpose of subsidy calibration. Industries deemed to be at low risk receive no subsidies. Industries classified as high-risk receive subsidies based on an industry-specific emissions intensity metric scaled by an allocation factor.[41]

The clear benefit of this approach is ease of implementation. But there are potential costs if simpler approaches result in sloppier targeting. To investigate this trade off, we compare the outcomes simulated under our industry-specific subsidies (summarized in Column (2) of Tables 2 and 3) against simpler alternatives modeled after current policy practices.

Figure 2 graphically illustrates the two alternative approaches we evaluate. These figures summarize how the allocation factor varies with the two standard leakage risk metrics. In

[41]In practice, the emissions intensity measures used to calibrate subsidies are based not on the industry average, but on a relatively clean benchmark.

subsection 5.2, the allocation factor is defined as the industry-specific estimated market transfer rates. Panel (a) of Figure 2 shows how these transfer rates vary with standard leakage metrics.

Panel (c), our first alternative subsidy rate, takes a more categorical approach to calibrating output-based subsidies. Industries are assigned to one of two leakage risk categories. Risk classification is made on the basis of our calibrated leakage risk measures. Low risk industries receive no subsidy. The top 15% of industries (47 in total) are deemed to be high risk and are assigned an allocation factor of 80%. This basic design (assigning 15% of industries and 80% allocation factor) is comparable to existing and proposed programs.[42]

Panel (d) of Figure 2, our second alternative, summarizes an even coarser approach that is more consistent with current policy practice. Leakage risk assessment is based on two readily observable metrics: emissions intensity and trade exposure. Industries that are in the top decile of emissions intensity, regardless of their trade exposure, are assigned the 80% allocation factor. We also classify those in the top decile of trade exposure as high risk so long as emissions intensity is above the 25 percentile.

Using these alternative approaches to calibrating allocation factors (and associated output-based subsidies), we re-simulate the impacts of a $25 carbon price. Column (3) in Table 2 corresponds to a carbon tax regime in which industries are assigned to one of two leakage risk categories on the basis of our theoretically derived leakage risk metrics (LR). Relative to our baseline subsidy schedule, the number of industries receiving subsidies decreases from 312 to 47. With fewer industries receiving leakage protection, reductions in export demand are more pronounced (relative to the baseline subsidy schedule), but imports are unchanged in aggregate. Domestic abatement is *reduced* while the leakage rate increases; net abatement falls. In other words, sloppier targeting comes at a cost of higher emissions leakage and reduced domestic abatement.

Column (4) summarizes simulated outcomes under the tax regime in which leakage risk is determined directly on the basis of emissions intensity and trade exposure thresholds (EITE). Although the number of industries receiving output-based subsidies is the same as Column (3) the composition is different. This group now includes industries that are emissions intensive but not at high leakage risk (and excludes industries that are less emissions intensive but high risk). With sloppier targeting, we see a significant increase in the rate of emissions leakage and a decrease in net abatement. The leakage rate increases to 0.45 (up from 0.17 under the baseline subsidies). This approaches the leakage rate under the tax scenario that

[42]For example, 36 industries were categorically eligible for leakage mitigating subsidies under the proposed Waxman-Markey (as reported by Houser, 2009). 46 industries are classified as high or medium risk under California's GHG emissions trading program.

confers no subsidies (0.49). Moreover, because this regime confers large subsidies to the most emissions intensive industries, domestic abatement falls to 1.8%.

Table 3 illustrates how coarser targeting of subsidies impacts outcomes under the cap-and-trade (versus tax) regime. Under a binding emissions cap (set equal to the emissions under the $25 carbon tax), equilibrium carbon prices must rise above $40 to deliver sufficient levels of domestic abatement. This price increase is due to the fact that some of the heavy emitters receive more generous subsidies; permit prices must increase to generate sufficient reductions from the unsubsidized sectors. Similar to the tax regime, leakage rates associated with the sloppiest targeting (EITE) are close to the leakage rates obtained in the absence of subsidies. Across both the tax and the trading regimes, domestic abatement net of leakage is maximized under the optimal subsidy scheme but not substantially improved under the coarser EITE subsidies, highlighting again the benefits of a more sophisticated subsidy scheme.

As we note above, we use median market transfer rates to calibrate industry-specific subsidies. Thus, our 'targeted subsidy' scenario is not precisely targeted because the subsidies are never perfectly aligned with the assumed elasticities. In practice, challenges associated with estimating market transfer rates and foreign emissions intensities will only compound the extent of this mis-calibration. This caveat notwithstanding, our simulation results suggest potentially high returns to targeting leakage mitigation on the basis of more refined measures of leakage risk.[43]

6 Conclusion

Regional carbon pricing programs must strike a balance between reducing emissions covered by the regulation and mitigating emissions leakage to sources that are out of regulatory reach. Policymakers have been experimenting with approaches that combine carbon pricing with output-based subsidies targeted at industries deemed to be at high leakage risk. In existing and proposed programs, leakage risk is assessed on the basis of two key metrics: emissions intensity and trade exposure. The tenuous connection between these metrics and the fundamental drivers of leakage risk has raised concerns about policy effectiveness.

Our analysis uncovers some important differences between theoretically consistent measures of leakage risk and the standard measures used under existing and proposed policies. In particular, we highlight the importance of 'market transfer rates' which capture the responsiveness of foreign production to policy-induced changes in domestic operating costs. In theory, the rate of market transfer plays an important role in determining the level output-

[43] As we note above, absent information on demand and supply functions, we cannot evaluate the overall welfare impacts of these policy design alternatives.

based compensation that should be conferred to mitigate international emissions leakage. In practice, standard leakage metrics fail to capture this parameter.

We investigate how a U.S. economy-wide domestic carbon price would operate through domestic energy prices to impact manufacturing production, trade flows, domestic emissions, and emissions leakage. Consistent with the prior literature, we find substantial emissions leakage risk in the U.S. manufacturing sector. When carbon pricing is combined with targeted production subsidies, this emissions leakage is substantially reduced. Noting the practical challenges associated with implementing our theory-based subsidy schedule, we evaluate a coarser, categorical approach modeled after current policy practices. We find that subsidies targeted on the basis of standard leakage risk metrics incur much of the costs of leakage mitigation while delivering only a fraction of the benefits.

These findings should be interpreted with care in light of some caveats we have highlighted throughout the paper. These caveats notwithstanding, our approach provides a link between economic fundamentals and applied policy design challenges. We demonstrate and evaluate an approach to allocating subsidies on the basis of theoretically consistent leakage measures. Targeting appears to matter, which suggests that trade-offs between transparency and targeting of emissions leakage mitigation merit further attention. Overall, our findings illustrate both the possibilities and the challenges of real-world leakage mitigation.

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Table 1: Summary Statistics of Main Variables

	N	Mean	SD	SD within NAICS6	SD within yr and NAICS6
ln Value of shipments (MUSD)	6221	10.280	1.381	0.306	0.291
ln Value of imports (MUSD)	6221	8.166	2.120	0.488	0.374
ln Value of exports (MUSD)	6221	7.998	1.920	0.586	0.512
ln Value of consumption (MUSD)	6212	10.337	1.384	0.306	0.282
Net trade (M-X)/(M+S)	6221	0.035	0.151	0.070	0.068
ln Wage (KUSD)	6209	4.089	0.388	0.132	0.113
Trade Weighted U.S. Dollar Index: Broad, Goods	6221	109.412	9.108	9.107	0.000
Domestic energy price (USD/MMBtu)	6209	11.253	3.360	1.913	0.790
Domestic energy price, embodied (USD/MMBtu)	6221	9.783	2.441	1.996	0.618
Foreign energy price (USD/MMBtu)	6221	13.462	4.201	3.196	1.410
Import energy price (USD/MMBtu)	6221	14.042	5.066	3.782	1.920
Export energy price (USD/MMBtu)	6221	12.524	3.722	2.718	1.235
Trade exposure (M+X)/(M+S)	6221	0.320	0.249		
Energy intensity (MMBtu/000 USD)	6221	3.141	5.134		
Energy intensity, embodied (MMBtu/000 USD)	6221	5.573	5.845		
Carbon intensity (tons/MMBtu)	6209	0.108	0.026		
Tons per value (tons/000 USD)	6209	0.290	0.494		

Notes: All values deflated to 2007 U.S. dollars. Variables weighted by shipment values in 2007. Measures of energy intensity and trade exposure are held fixed at their 2007 values. The data covers 312 manufacturing NAICS6 sectors over twenty years (1996-2015). A few sectors are missing BLS wages for a few years thus leading to a few missing values that get transmitted to energy prices and carbon intensity. A few sectors have negative consumption, thus also leading to a few missing values in the log of consumption.

Table 2: Simulated Impacts of a $25/ton CO2e Carbon Tax

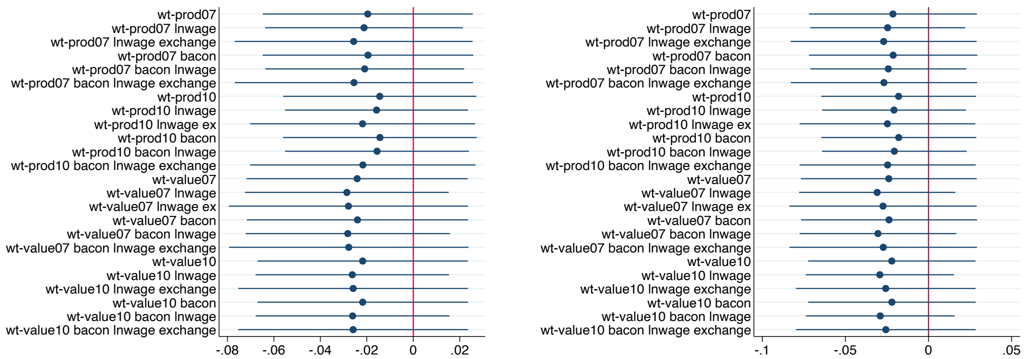
	Carbon Tax (USD $25)	Tax and Subsidy		
		Baseline	Alternative 1	Alternative 2
	(1)	(2)	(3)	(4)
A: Impacts on Domestic Shipments, Imports, Exports (%)				
$\%\Delta Prod$	-1.6	-1.0	-0.7	-0.8
	$[-2.0, -1.0]$	$[-1.2, -0.6]$	$[-0.9, -0.5]$	$[-1.1, -0.5]$
$\%\Delta Exp$	-1.9	-0.6	-0.7	-0.9
	$[-3.3, -0.9]$	$[-1.0, -0.3]$	$[-1.3, -0.4]$	$[-1.5, -0.4]$
$\%\Delta Imp$	0.9	0.3	0.4	0.4
	$[-1.2, 1.6]$	$[-0.4, 0.6]$	$[-0.4, 0.6]$	$[-0.5, 0.8]$
B: Annual Emission Abatement and Emissions Leakage (%)				
% Abatement	7.1	4.6	2.7	1.9
	$[4.5, 9.0]$	$[2.9, 5.8]$	$[1.7, 3.5]$	$[1.2, 2.4]$
% Net abatement	3.8	3.7	1.9	1.1
	$[0.4, 7.4]$	$[1.9, 4.9]$	$[0.8, 2.7]$	$[0.2, 2.0]$
Leakage rate	0.46	0.17	0.27	0.42
	$[-0.06, 0.90]$	$[-0.03, 0.35]$	$[-0.03, 0.53]$	$[-0.05, 0.83]$
Net Tax Revenue ($ B)	31.7	18.9	16.6	19.1
	$[31.1, 32.6]$	$[18.5, 19.3]$	$[16.4, 16.8]$	$[19.0, 19.2]$
Median allocation factor	0.00	0.52	0.80	0.80
N subsidized industries	0	312	47	47

This table uses the direct energy cost elasticity estimates summarized in Figure 2 to simulate the impacts of a $25 per metric ton of CO_2 carbon price on manufacturing shipments, imports, exports, domestic emissions, and emissions leakage. We report the median, 5th, and 95th percentile of the distribution of simulated outcomes. All impacts are summarized in percentage terms relative to the base year (2007). The first column corresponds to a policy simulation in which a $25 carbon tax is applied to all domestic energy inputs. The subsequent three columns combine this $25 price with industry-specific output-based subsidies. Subsidy schedules vary across columns (2), (3), (4). See text and Figure 2 for details.

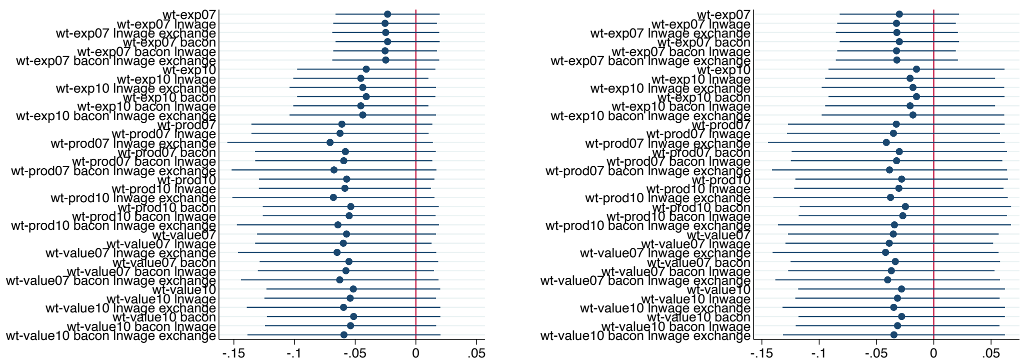
Table 3: Simulated Impacts under a Cap And Trade Program

	Carbon Tax	CAT and Subsidy		
		Baseline	Alternative 1	Alternative 2
	(USD $25)	(USD $34)	(USD $40)	(USD $43)
	(1)	(2)	(3)	(4)
A: Impacts on Domestic Shipments, Imports, Exports (%)				
$\%\Delta Prod$	-1.6	-1.5	-1.7	-1.9
	$[-2.0, -1.0]$	$[-1.9, -1.0]$	$[-2.1, -1.0]$	$[-2.5, -1.2]$
$\%\Delta Exp$	-1.9	-1.3	-1.9	-2.2
	$[-3.3, -0.9]$	$[-2.2, -0.6]$	$[-3.3, -0.9]$	$[-3.9, -1.1]$
$\%\Delta Imp$	0.9	0.7	0.9	1.1
	$[-1.2, 1.6]$	$[-0.8, 1.1]$	$[-1.1, 1.6]$	$[-1.4, 1.9]$
B: Annual Emission Abatement and Emissions Leakage (%)				
% Abatement	7.1	7.2	7.0	7.0
	$[4.5, 9.0]$	$[4.5, 9.1]$	$[4.4, 8.8]$	$[4.4, 8.9]$
% Net abatement	3.8	5.1	4.3	3.8
	$[0.4, 7.4]$	$[2.0, 7.3]$	$[1.1, 7.2]$	$[0.5, 7.3]$
Leakage rate	0.46	0.27	0.38	0.45
	$[-0.06, 0.90]$	$[-0.04, 0.54]$	$[-0.05, 0.75]$	$[-0.06, 0.88]$
Net Tax Revenue ($ B)	31.7	29.7	35.1	41.5
	$[31.1, 32.6]$	$[29.0, 30.7]$	$[34.4, 36.1]$	$[40.8, 42.4]$
Median allocation factor	0.00	0.52	0.80	0.80
N subsidized industries	0	312	47	47

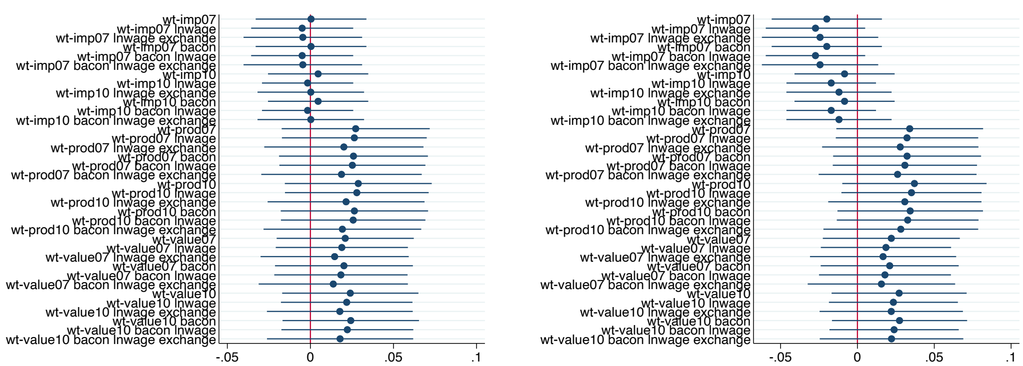
This table uses the direct energy cost elasticity estimates summarized in Figure 2 to simulate the impacts of a $25 per metric ton of CO_2 carbon price on manufacturing shipments, imports, exports, domestic emissions, and emissions leakage. All impacts are summarized in percentage terms relative to the base year (2007). The first column corresponds to a policy simulation in which a $25 carbon tax is applied to all domestic energy inputs. The subsequent three columns combine industry-specific output-based subsidies with a cap-and-trade price determined to (approximately) equal abatement to the baseline. Subsidy schedules vary across columns (2), (3), (4). See text and Figure 2 for details.



(a) Domestic shipments



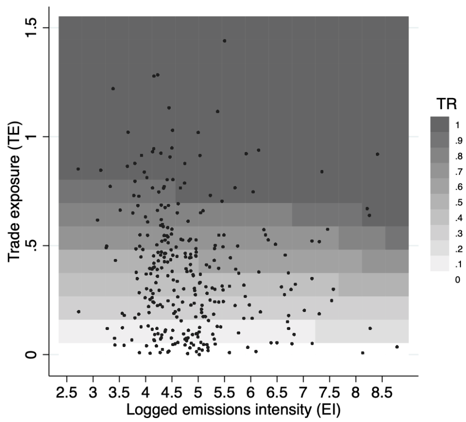
(b) Exports



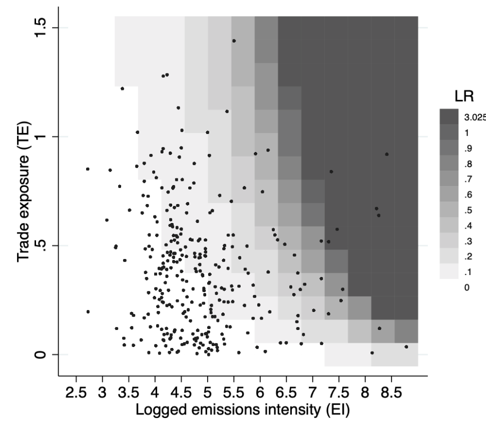
(c) Imports

Figure 1: Regression coefficients

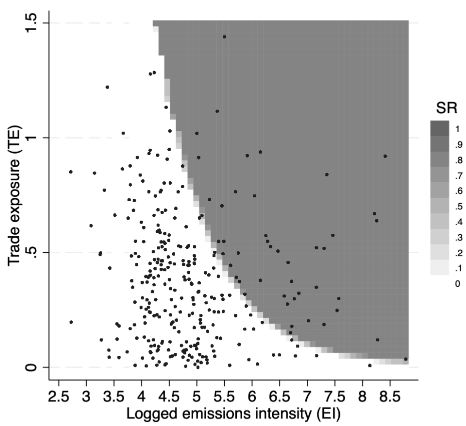
This figure displays the regression estimates of the impact of domestic energy prices interacted with energy intensity for several specifications, nested in this order: (i) treatment of outliers (no trim/bacon), (ii) regression weights (shipment value in 2007 and 2010, total value in 2007 and 2010, and an additional set of weights for imports (imports in 2007 and 2010), exports (exports in 2007 and 2010), and net trade (imports plus exports in 2007 and 2010)), and (iii) non-energy related control variables (none, log of wage, and log of wage plus trade exposure interacted with industry exchange rates). All specifications use the price of electricity interacted with energy intensity as an instrument. The left column features contemporaneous energy prices. The right panel features regressions using one-year lagged energy prices. All regressions include NAICS6 and year fixed effects. The lines represent the 95% confidence interval using robust standard errors.



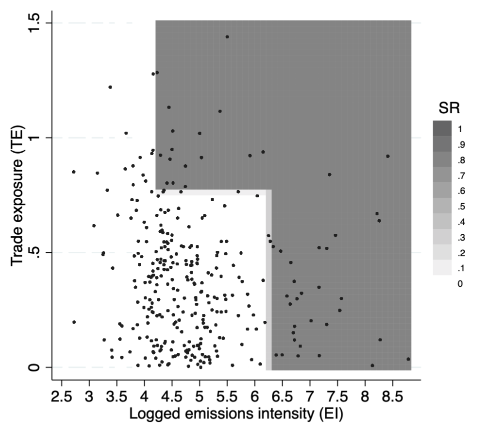
(a) Transfer rate (TR)



(b) Leakage rate (LR)



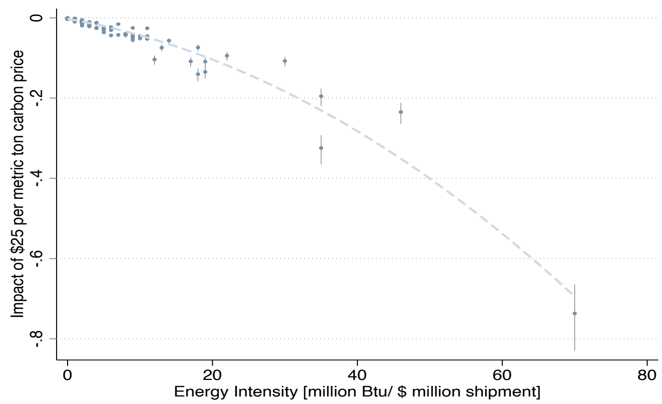
(c) Alternative subsidy rate 1



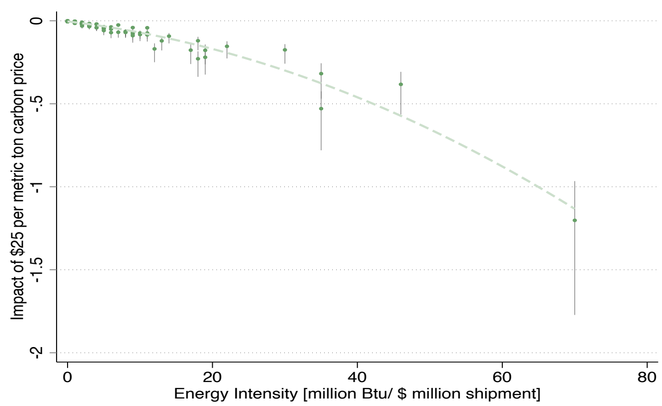
(d) Alternative subsidy rate 2

Figure 2: Quantifying transfer and leakage rates (change in foreign output and emissions per change in domestic output)

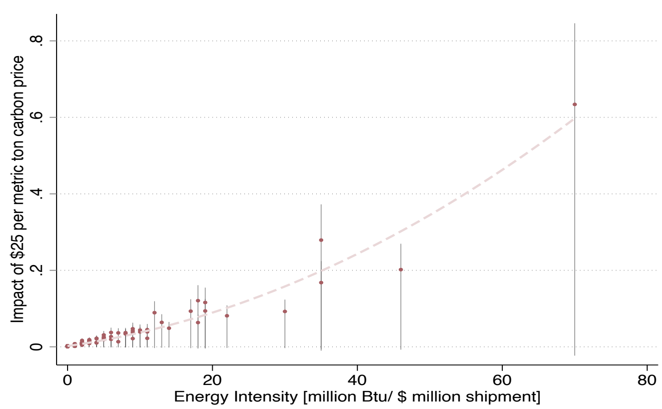
This figure displays calibrated transfer rates and leakage rates (upper panel) approximated as a function of direct emissions intensity and trade exposure, as defined in the text. Rates are smoothed over EITE characteristics, by regressing predicted transfer and leakage rates at the NAICS6 level on emissions intensity, trade shares, and their interaction. The lower panel shows alternative coarser transfer rates inspired by subsidies used in current policies, as discussed in Section 5.



(a) Production impacts



(b) Export impacts



(c) Import impacts

Figure 3: Simulated Impacts on Domestic Production and Trade Flows

This figure displays the simulated impacts of a $25 per metric ton of CO_2 carbon price. All impacts are summarized in percentage terms. Each marker corresponds to a NAICS6 industry. Bars denote the interquartile range across specifications. Base year is calibrated to 2007.