Online Appendix: Mitigating Emissions Leakage in Incomplete Carbon Markets

A Optimal subsidy derivation

We assume a linear damage function over the relevant range of GHG emissions. We further assume the domestic producers are subject to a domestic carbon price of τ per unit of emissions, e_d, where τ is set equal to σ in the base case. This carbon price can represent either a carbon tax or the equilibrium permit price in a scenario where the industry under consideration is small relative to the larger carbon market.

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

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

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

The first-order conditions for profit-maximization:

$$C'_d(q_d) + \tau e_d - s = p(q_d + q_f), \tag{A.3}$$

$$C'_f(q_f) = p(q_d + q_f). \tag{A.4}$$

In this simple case, we continue to assume that the equilibrium emissions price is set equal to the externality, i.e., $\tau = \sigma$. Equilibrium quantities can be defined implicitly as a function of the subsidy using (A.3)-(A.4). Defining welfare as a function of s, $W(s)$, we characterize the regulator's maximization problem as:

$$\max_s \quad W(s) \equiv \underbrace{S\big(q_d(s) + q_f(s)\big)}_{\text{Consumer Surplus}} - \underbrace{C_d\big(q_d(s)\big)}_{\text{Domestic Costs}} - \underbrace{C_f\big(q_f(s)\big)}_{\text{Foreign Costs}} - \underbrace{\sigma\big(e_d q_d(s) + e_f q_f(s)\big)}_{\text{Emissions Externality}}. \tag{A.5}$$

The regulator chooses the subsidy that satisfies the first-order condition:

$$\frac{\partial W}{\partial q_d}\frac{\partial q_d}{\partial s} + \frac{\partial W}{\partial q_f}\frac{\partial q_f}{\partial s} = 0. \tag{A.6}$$

Substitutions involving first order conditions derived above imply:

$$\frac{\partial W}{\partial q_d}\frac{\partial q_d}{\partial s} = \big(p - C'_d(q_d) - \sigma e_d\big)\frac{\partial q_d}{\partial s} = -s\frac{\partial q_d}{\partial s}, \tag{A.7}$$

and,

$$\frac{\partial W}{\partial q_f}\frac{\partial q_f}{\partial s} = \left(p - C_f'(q_f) - \sigma e_f\right)\frac{\partial q_f}{\partial s} = -\sigma e_f \frac{\partial q_f}{\partial s}. \tag{A.8}$$

Solving for s, we obtain:

$$s^* = -\ \sigma\ e_f\ \frac{\frac{\partial q_f}{\partial s}}{\frac{\partial q_d}{\partial s}}. \tag{A.9}$$

A.1 Home vs. foreign preferences

In our baseline model, we assume that goods produced by domestic and foreign suppliers, respectively, are perfect substitutes. Under this assumption, the surplus function depends on the total amount produced, $S(q_d + q_f)$. In practice, however, many of the goods produced in GHG emitting industries are more accurately described as heterogeneous. Examples include food processing and garment manufacturing. It is, therefore, important to show how our derivation of the optimal subsidy schedule generalizes to the case where home and foreign production are imperfect substitutes.

Here we show that, as long as utility maximizing consumers equate marginal consumer surplus to product prices, our optimal subsidy formulation obtains.[47] Consider a more general surplus function $S(q_d, q_f)$. We assume that, in equilibrium, consumer choices are such that:

$$\frac{\partial S}{\partial q_d} = p_d,$$
$$\frac{\partial S}{\partial q_f} = p_f.$$

Under these conditions, the first order conditions in (A.3) and (A.4), are modified to reflect that the price of the domestic and the foreign goods are not necessarily the same. Making the substitutions as before, the product prices cancel and it follows that equations (A.7) and (A.8) still obtain.

One important difference in this formulation is that marginal costs of production across foreign and domestic producers need not be equal in equilibrium. Intuitively, differences in underlying preferences for foreign versus domestic production will lead to differences in marginal costs. To arrive at (A.7) and (A.8), we only require that the marginal rate of substitution is equalized across consumers and products. Our subsidy formulation is still

[47] A natural condition for this to hold is that consumers are price takers, which was already assumed in the baseline model.

valid in the presence of heterogeneous preferences as long as the market is competitive.

A.2 Adding exports

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

The profit function for a domestic price-taking firm is augmented to include revenues earned and cost incurred in the production of exports:

$$\pi(q_d, q_e) = p(q)(q_d + q_e) - C(q_d + q_e) - \tau e_d(q_d + q_e) + s(q_d + q_e). \tag{A.10}$$

We assume the domestic market and international markets are fully integrated, i.e., they obtain the same price and equalize their marginal costs, except due to potential wedges due to the carbon regulation.

Adding exports, the optimal subsidy becomes:

$$s^*_{export} = -\sigma e_f \left(\frac{\frac{\partial q_f}{\partial s} - \frac{\partial q_e}{\partial s}}{\frac{\partial q_d}{\partial s} + \frac{\partial q_e}{\partial s}} \right). \tag{A.11}$$

Compared to Equation (A.9), the optimal subsidy has an extra term in the numerator to account for exports that can offset foreign production. Thus, s^*_{export} is weakly larger than in Equation (A.9). Intuitively, the introduction of exports opens another leakage channel insofar as a policy-induced reduction in exports lead to increased foreign production and associated emissions.

The optimal subsidy in elasticity form becomes:

$$s^*_{export} = \sigma \ e_f \times \frac{|\eta_f| q^f + |\eta_e| q^e}{q^d + q^e}, \tag{A.12}$$

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

This formulation of the optimal subsidy implicitly assumes that exports are substitutes for, versus additional to, foreign production. This provides an upper bound on the exports subsidy, as it assumes reduced exports in the domestic market due to a carbon price are fully replaced by foreign production. In fact, some of the policy-induced reduction in exports may not be fully offset by increases in foreign production and associated foreign emissions. Here again, the optimal subsidy derived above may over-estimate the optimal subsidy.

A.3 Endogenous abatement

We assume that domestic producers emit GHGs at a constant rate of $e_d(A)$ per unit of q_d. This emissions intensity is decreasing and convex in the firm's choice of abatement A. The unit cost of abatement is k. The foreign firm emits at an exogenous and constant rate of e_f per unit of q_f. To mitigate emissions leakage, the regulator can introduce an output-based subsidy s to partially rebate carbon prices. This production subsidy works to offset the policy-induced increase in operating costs incurred by domestic producers.

The profit function for a representative domestic and foreign price-taking firm are thus:

$$\pi_d(q_d) = p(q)q_d - C_d(q_d) - kA - \tau e_d(A)q_d + sq_d, \tag{A.13}$$
$$\pi_f(q_f) = p(q)q_f - C_f(q_f). \tag{A.14}$$

The first-order conditions for profit-maximization:

$$C'_d(q_d) + \tau e_d(A) - s = p(q_d + q_f) \tag{A.15}$$
$$-k = \tau e'_d(A)q_d \tag{A.16}$$
$$C'_f(q_f) = p(q_d + q_f). \tag{A.17}$$

Domestic firms invest in abatement until the marginal abatement cost equals the marginal return on abatement investment (measured in terms of avoided compliance costs). This is a fairly stylized representation of abatement costs, but one that highlights the abatement incentive created by the emissions price τ.

As in the base case, domestic production can be defined implicitly as a function of the subsidy parameter s. We note that the subsidy affects foreign production and abatement in equilibrium only indirectly through the effect on domestic output. As before, one can implicitly define the equilibrium functions of these objects in terms of the subsidy level.

The regulator's maximization problem is given by:

$$\begin{aligned}\max_s \quad W(s) \equiv & \underbrace{S(q_d(s) + q_f(s))}_{\text{Consumer Surplus}} - \underbrace{C_d(q_d(s)) - kA(s)}_{\text{Domestic Costs}} - \underbrace{C_f(q_f(s))}_{\text{Foreign Costs}} \\ & - \underbrace{\sigma(e_d(A(s))(q_d(s) + e_f q_f(s))}_{\text{Emissions Externality}}.\end{aligned} \tag{A.18}$$

The regulator chooses the subsidy that satisfies the first-order condition:

$$\frac{\partial W}{\partial q_d}\frac{\partial q_d}{\partial s} + \frac{\partial W}{\partial q_f}\frac{\partial q_f}{\partial s} + \frac{\partial W}{\partial A}\frac{\partial A}{\partial s} = 0 \tag{A.19}$$

In this more general model, the $\frac{\partial q_d}{\partial s}$ term is intended to capture both direct output and indirect abatement adjustments. Substitutions involving first order conditions derived above imply:

$$\frac{\partial W}{\partial q_d}\frac{\partial q_d}{\partial s} = (p - C_d'(q_d) - \sigma e_d)\frac{\partial q_d}{\partial s} = -s\frac{\partial q_d}{\partial s}, \tag{A.20}$$

$$\frac{\partial W}{\partial q_f}\frac{\partial q_f}{\partial s} = \left(p - C_f'(q_f) - \sigma e_f\right)\frac{\partial q_f}{\partial s} = -\sigma e_f\frac{\partial q_f}{\partial s}, \tag{A.21}$$

$$\frac{\partial W}{\partial A}\frac{\partial A}{\partial s} = (-K - \sigma e_d'(A)q_d)\frac{\partial A}{\partial s} = 0. \tag{A.22}$$

Solving for s, we obtain (as above):

$$s^* = -\sigma\ e_f\ \frac{\frac{\partial q_f}{\partial s}}{\frac{\partial q_d}{\partial s}}. \tag{A.23}$$

Intuitively, if the carbon price reflects the emissions externality, the level of abatement will be efficient and the output based subsidy will be designed to mitigate emissions leakage exclusively.

In the more complicated case where the carbon price is constrained below the optimal tax level, the optimal subsidy will serve a dual purpose of leakage mitigation and compensating for the sub-optimal abatement incentive:

$$s^*_{constrained} = s^* - (\sigma - \tau)\left(e_d(A) + e_d'(A)q_d\frac{\frac{\partial A}{\partial s}}{\frac{\partial q_d}{\partial s}}\right). \tag{A.24}$$

To the extent that abatement increases with domestic production (and thus, the subsidy), the policymaker has an incentive to subsidize output in order to bring domestic abatement investment closer to the socially optimal level.

A.4 Endogenous permit prices, multiple sectors

We consider a two-sector economy where one sector is trade exposed and eligible for an output-based subsidy whereas the second sector is not. Let s_1 denote the subsidy per unit of output paid to sector one.

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

$$p_1 = C_1' + \lambda e_1 - s_1, \tag{A.25}$$
$$p_1 = C_f', \tag{A.26}$$
$$p_2 = C_2' + \lambda e_2. \tag{A.27}$$

where λ is the shadow value of the emissions cap or constraint and therefore equals the price in the cap-and-trade system. Assuming no direct complementarities between sectors, and conditional on an exogenously set cap $\overline{E}$, we can define production of q_2 implicitly as a function of q_1, i.e. $q_2 = \frac{\overline{E}-e_1 q_1}{e_2}$, and solve for the optimal subsidy. The subsidy drives a wedge in the equalization of marginal costs across sectors. Solving for the price of emissions λ and rearranging:

$$\frac{S_1' - C_1' + s_1}{e_1} = \frac{S_2' - C_2'}{e_2}. \tag{A.28}$$

The introduction of the subsidy shifts more of the abatement activity to the unsubsidized sector (as compared to the case where no subsidy is conferred but the emissions cap is the same). The expression, together with the emissions cap, gives an implicit function $q_1(s_1)$ and $q_2(s_1)$.

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

$$\max_{s_1} \quad S_1(s_1) + S_2(s_1) - C_1(s_1) - C_2(s_1) - C_f(s_1) - \sigma\Big(e_1 q_1(s_1) + e_2 q_2(s_1) + e_f q_f(s_1)\Big), \tag{A.29}$$

Note that the emissions constraint imposed by the cap is already implicitly defined by q_2. Both q_f (through product market) and q_2 (through the emissions market cap) can be expressed implicitly as a function of s_1. Solving for the welfare maximizing subsidy obtains:

$$s^{cross} = \sigma e_f \left| \frac{\frac{\partial q_f}{\partial s}}{\frac{\partial q_d}{\partial s}} \right|. \tag{A.30}$$

A.5 Supply chain linkages

We now extend the model to accommodate, albeit in a stylized way, multiple sectors that are linked not only via the permit market, but also in a competitive vertical supply relationships. We begin with a two-sector model that considers linkages between the electricity sector and a downstream sector that uses electricity as in input to production. We then explore alternative supply-chain relationships.

Electricity as an input. Suppose that the downstream Sector 1 consumes α units of electricity, denoted q_2, to produce a unit of q_1 in a Leontief-like production function. We assume that the electricity sector is not (directly) trade-exposed. The competitive first-order conditions for the two sectors can now be written as follows:

$$p_1 = C_1' + \alpha p_2 + \sigma e_1 - s_1, \tag{A.31}$$

$$p_1 = C_f', \tag{A.32}$$

$$p_2 = C_2' + \sigma e_2. \tag{A.33}$$

Assuming no factor substitution and perfect pass through of carbon prices in factor markets, we can show that this problem can be mapped directly onto our baseline model with only one sector if we define the emissions intensity in Sector 2 as $e_1 + \alpha e_2$.

Emissions embodied in factor inputs other than electricity are not typically captured by the emissions intensities used to assess leakage risk in downstream industries. These upstream emissions will be impacted by leakage mitigating subsidies if and only if the upstream domestic sector is itself trade exposed. In what follows, we revisit the derivation of optimal subsidies in contexts where supply-chain relationships implicate emissions-intensive factor inputs (other than electricity) in downstream, trade-exposed sectors.

As will be clear from these examples, it is hard to come up with a general formulation for the optimal subsidy schedule. Optimal leakage mitigation will depend critically on where in the supply chain the leakage occurs and how the production functions are specified. We will show the trade-off on how to set optimal subsidies by means of two extreme examples.

Trade-exposed upstream sector, trade-exposed downstream sector Consider a situation similar to the previous example, but now the upstream domestic sector is also trade exposed. For simplicity, we consider that the input is never exported. To further simplify, we also consider the emissions rate to be the same both in the foreign and the domestic jurisdiction. Producing a final good 1 requires α units of intermediary good 2. Thus, the comprehensive emissions rate becomes $e_1 + \alpha e_2$. In contrast to the previous example, the domestic producer can choose to source factor inputs from either a foreign or a domestic producer, although this has no general equilibrium effects in the input market. This configuration of supply relationships are summarized in Figure A.1.

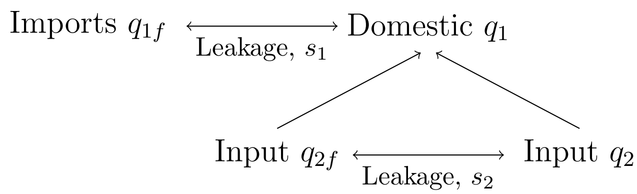


Figure A.1: Representation of IO flows in the extended model

Welfare is defined as:

$$\max W \equiv S(q_1 + q_{1f}) - C_1(q_1) - C_2(q_2) - C_{2f}(q_{2f}) - C_{1f}(q_{1f}) - \sigma(e_1 + \alpha e_2)(q_1 + q_{1f}),$$

subject to $q_2 + q_{2f} = \alpha q_1$. The regulator can only tax emissions within her jurisdiction: $e_1 q_1 + e_2 q_2$. We consider the second-best setting in which the regulator can set two different subsidies, s_1 and s_2, to address the potential for leakage risk.

The competitive first-order conditions for the two sectors of taxed based on direct emissions can now be written as follows:

$$p_1 = C_1' + \alpha p_2 + \sigma e_1 - s_1, \tag{A.34}$$

$$p_1 = C_{1f}', \tag{A.35}$$

$$p_2 = C_2' + \sigma e_2 - s_2, \tag{A.36}$$

$$p_2 = C_{2f}'. \tag{A.37}$$

We can see both the wedge in both sectors due to leakage, as well as the presence of good 2 as an input to good 1. These equations implicitly define q_1, q_2 and q_{1f} as a function of the subsidies, with $q_{2f} = \alpha q_1 - q_2$.

Back to the welfare function, the FOC components for s_1 are given by:

$$\frac{\partial W}{\partial q_1}\frac{\partial q_1}{\partial s_1} = \Big(- s_1 - \sigma\alpha e_2\Big)\frac{\partial q_1}{\partial s_1}, \tag{A.38}$$

$$\frac{\partial W}{\partial q_{1f}}\frac{\partial q_{1f}}{\partial s_1} = \Big(- \sigma e_f\Big)\frac{\partial q_{1f}}{\partial s_1}, \tag{A.39}$$

$$\frac{\partial W}{\partial q_2}\frac{\partial q_2}{\partial s_1} = \Big(\sigma e_2 - s_2\Big)\frac{\partial q_2}{\partial s_1}. \tag{A.40}$$

Similarly for s_2, the FOC components for s_2 are:

$$\frac{\partial W}{\partial q_1}\frac{\partial q_1}{\partial s_2} = \Big(- s_1 - \sigma\alpha e_2\Big)\frac{\partial q_1}{\partial s_2}, \tag{A.41}$$

$$\frac{\partial W}{\partial q_{1f}}\frac{\partial q_{1f}}{\partial s_2} = \Big(- \sigma e_f \Big) \frac{\partial q_{1f}}{\partial s_2}, \tag{A.42}$$

$$\frac{\partial W}{\partial q_2}\frac{\partial q_2}{\partial s_2} = \Big(\sigma e_2 - s_2 \Big) \frac{\partial q_2}{\partial s_2}. \tag{A.43}$$

Solving for this system of two equations ($\frac{dW}{ds_1} = 0$ and $\frac{dW}{ds_2} = 0$), we find:

$$s_1 = -\sigma e_f \frac{\frac{\partial q_2}{\partial s_1}\frac{\partial q_{1f}}{\partial s_2} - \frac{\partial q_2}{\partial s_2}\frac{\partial q_{1f}}{\partial s_1}}{\frac{\partial q_2}{\partial s_1}\frac{\partial q_1}{\partial s_2} - \frac{\partial q_2}{\partial s_2}\frac{\partial q_1}{\partial s_1}} - \alpha\sigma e_2, \tag{A.44}$$

$$s_2 = \sigma e_2 - \sigma e_f \frac{\frac{\partial q_1}{\partial s_1}\frac{\partial q_{1f}}{\partial s_2} - \frac{\partial q_1}{\partial s_2}\frac{\partial q_{1f}}{\partial s_1}}{\frac{\partial q_2}{\partial s_1}\frac{\partial q_1}{\partial s_2} - \frac{\partial q_2}{\partial s_2}\frac{\partial q_1}{\partial s_1}}. \tag{A.45}$$

Under the condition that $\frac{\partial q_{f1}/\partial s_1}{\partial q_1/\partial s_1} = \frac{\partial q_{f1}/\partial s_2}{\partial q_1/\partial s_2}$, i.e., the transfer rate for the final good is the same regardless of the subsidy used, the solution is subsidizing the input sector in full, i.e. $s_2 = \sigma e_2$.[48] Assuming that the foreign sector is as polluting as the domestic one, i.e., $e_f = e_1 + \alpha e_2$, the effective subsidy is given by the transfer rate of consumption times the comprehensive emissions rate, as in the case of electricity:

$$s_1 e_1 + \alpha s_2 e_2 = -\sigma \frac{\partial q_{1f}/\partial s_1}{\partial q_1/\partial s_1} e_1 - \alpha\sigma \frac{\partial q_{1f}/\partial s_1}{\partial q_1/\partial s_1} e_2.$$

Therefore, the optimal solution will tend to load the incidence on good 1, which is the one relevant for final consumption, while minimizing leakage distortions in good 2 by setting the effective tax to zero via the subsidy.[49]

How do these subsidies compare to the subsidy schedule we derive in the paper which is based on less comprehensive measures of embodied emissions? There are two major differences. First, the incidence between inputs and outputs is much more proportional than in the suggested optimal schedule. Second, the total effective subsidy is not necessarily the same. In this particular example, the total effective subsidy will be correct with respect to e_1 but sub-optimal with respect to e_2.

Common input, leaky output. What happens in the above example if taxing input q_2 has general equilibrium effects also for the producers outside the regulated jurisdiction? This can happen naturally if foreigners are sourcing inputs from the same market, via q_{2f}, as shown in Figure A.2, and there are no frictions that keep such prices separate. The

[48]Given the Leontieff assumption in production and the fact that input prices have no general equilibrium effects for foreign producers in this example, this is true in our setting.

[49]Notice that this is not equivalent to removing the tax upstream. In a more general model, abatement is still encourage due to the output-based nature of the subsidy.

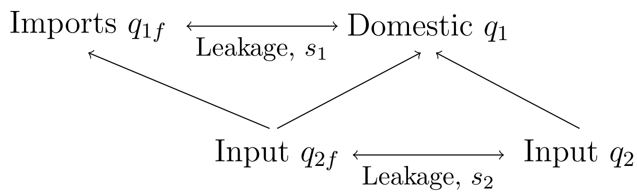


Figure A.2: Representation of IO flows in the extended model

equations for competitive behavior are similar to the previous example, but now the foreign producer first-order condition also includes the marginal cost of inputs, αp_2. The equilibrium equations for the optimal subsidies are still represented by (A.44)-(A.45) but crucially the equilibrium transfer rates are different in this example.

Importantly, both the foreign and domestic output face the same marginal cost of inputs regardless of the subsidy, which means that taxing the upstream producer implicitly taxes imports. Precisely for this reason, the finding from the previous section reverts. Under the same simplified linear marginal cost specification and Leontieff production function, the optimal effective subsidy is to subsidize the direct tax impact at the downstream (i.e., $s_1 = \sigma e_1$) and tax at the upstream level instead. The effective subsidy is equal to total emissions times the market transfer rate of inputs to the unregulated jurisdiction:

$$s_1 e_1 + \alpha s_2 e_2 = -\sigma \frac{\partial q_{2f}^1 / \partial s_2}{\partial q_2 / \partial s_2} e_1 - \alpha\sigma \frac{\partial q_{2f}^1 / \partial s_2}{\partial q_2 / \partial s_2} e_2,$$

where q_{2f}^1 is the domestic demand of foreign input—input leakage in Figure A.2. As in the previous example, the incidence of the subsidies is very different than under our proposed general formula. In this case, the direct incidence is focused on the input. The final incidence in the output is then determined by the full pass-through of prices. In this particular example, the total effective subsidy downstream based on our prescribed formula will be correct with respect to e_2 but suboptimal with respect to e_1.

Comparison to basic direct subsidies. Looking at the total effective subsidy, in both cases they are a function of total emissions rates and transfer rates (either of the final good or the intermediary). Our formula, instead, recommends an effective subsidy for the final good of:

$$s_1 e_1 + \alpha s_2 e_2 = \sigma \frac{\partial q_{1f} / \partial \tau}{\partial q_1 / \partial \tau} e_1 + \alpha\sigma \frac{\partial q_{2f}^1 / \partial \tau}{\partial q_2 / \partial \tau} e_2.$$

Furthermore, the incidence of the subsidy is also different depending on the example, whereas our proposed approach has a more symmetric treatment of inputs and outputs.

We could enrich the model further to consider the case in which inputs are also used as final goods, or the case in which both goods act as inputs and outputs, which we leave for future research. The above examples suggest that general conclusions about the optimal subsidies are likely depend substantially on the assumptions regarding the production function and the nature of leakage. Importantly, under reasonable conditions, subsidies to inputs are likely be different depending on the intended user of such inputs, something that we consider unlikely to be politically viable.

A.6 Rent leakage

The welfare function defined above values foreign and domestic producer surplus equally. This is appropriate when regulators have the authority to design production subsidies to mitigate emissions leakage only. However, policy makers may also be authorized to mitigate the loss of domestic surplus and profits, e.g., due to reduction in jobs. We thus consider the following policy objective function:

$$\widetilde{W}(s) \equiv \underbrace{S(q_d(s)+q_f(s))}_{\text{Gross Consumer Surplus}} - \underbrace{C_d(q_d(s))}_{\text{Domestic Costs}} - \underbrace{p(q_d(s)+q_f(s))q_f(s)}_{\text{Foreign Payments}} - \underbrace{\sigma(e_d q_d(s)+e_f q_f(s))}_{\text{Emissions Externality}}. \tag{A.46}$$

Here, foreign production costs have been replaced by the import costs incurred by domestic consumers. The subsidy that maximizes this objective function yields a subsidy that is designed to mitigate both emissions and rent leakage.

Deriving the optimal subsidy under this modified objective function:

$$s^*_{rent} = \underbrace{\sigma e_f \left|\frac{\partial q_f}{\partial q_h}\right|}_{\text{Emissions Leakage}} + \underbrace{\left|\frac{dp}{dq_h}\right| q_f}_{\text{Rent Leakage}}$$

Assuming that net domestic production increases with the subsidy, the optimal subsidy is higher than in the baseline case, i.e., $s^*_{rent} > s^*$. An increase in the subsidy will weakly reduce the market price, and thus weakly reduce the transfer of surplus to foreign suppliers.

A.7 Imperfect competition

The model can be extended to account for the potential exercise of market power in the domestic product market. To illustrate the implications of using one subsidy to simultaneously mitigate emissions leakage and the exercise of market power, we consider the extreme case in which the domestic firm is a monopolist facing a fringe of import competition. The profit-maximizing first-order condition becomes:

$$C_d'(q_d) + e_d\sigma - s = p(q) + p'(q)q_d. \tag{A.47}$$

This yields a modified subsidy which is designed to mitigate not only emissions leakage, but also distortons associated with the exercise of market power in the domestic market:

$$s^*_{monopoly} = s^* - p'(q)q_d. \tag{A.48}$$

Compared to the base subsidy, there is an additional term which increases the subsidy so as to reduce the monopolist pricing distortion. Thus, the subsidy which aims to address two distortions will be larger than the leakage mitigating subsidy derived for the competitive case: $s^*_{monopoly} > s^*$.

B Data Sources

We combine several public data sets to construct measures of leakage risk and calibrate corresponding output-based subsidies. Table B.1 summarizes the key data sets. The following paragraphs explain the data sources for variables used in our analysis.

Value of shipments, import transactions, and export transactions NBER-CES Manufacturing Industry Database (NBER-CES) has value of shipment from 1980-2011 and Annual Survey of Manufactures (ASM) combined with the Census of Manufacturers (CMF) has value of shipment from 2002 to 2017 at NAICS6-year level. We combine these 2 data sets to construct a series of shipments for all manufacturing industries from 1995-2016. Import and export data are from Schott (2008), available at NAICS6-year level from Schott (2008).

The North American Industry Classification System (NAICS) is the standard used by Federal statistical agencies in classifying business establishments. A 2-digit code refers to a sector, a 3-digit digit code refers to a sub-sector, and a 6-digit code refers to a industry. For example, 311221 is Wet Corn Milling indsutry, the first 2 digit of which suggests that it is from sector 31 (Manufacturing). The 3-digit subsector 311 is Food Manufacturing, the 4-digit industry group 3112 is Grain and Oilseed Milling, and the 5-digit naics5 industry code 31122 is Starch and Vegetable Fats and Oils Manufacturing. The main dataset of this paper is at NAICS6-year level.

NAICS industry codes are updated every five years. In the period of our analysis (1996-2015), 2 different versions (2007 version and 2012 version) of NAICS code are released. Our analysis uses the 2012 version. However, most of the raw data uses NAICS 2007 version as the industry id for the first several years and switches to NAICS 2012 version after the updated was released. The main changes from 2007 version to 2012 version is that some NAICS6 industries were aggregated into one new NAICS6 code in the 2012 version. For example, industry 311311 Sugarcane Mills and industry 311312 Cane Sugar Refining are aggregated into 1 industry 311314 Cane Sugar in NAICS 2012 code. For these industries, we aggregate the shipments, values of import and export, and energy consumption correspondingly. [50]

[50] The only exception is the Electronic Computer Manufacturing industry (33411). Industry 334113 (Computer Terminal Manufacturing) and most part of 334119 (Other Computer Peripheral Equipment Manufacturing - except digital camera manufacturing) from the 2007 version aggregate into 334118 (Computer Terminal and Other Computer Peripheral Equipment Manufacturing) in the 2012 version, while one establishment within 334119 (digital camera manufacturing) is grouped into industry 333316 (Photographic and Photocopying Equipment Manufacturing). Due to the lack of establishment level data, we ignore this problem and merge 334119 from the 2007 version with 334118 from the 2012 version.

Electricity and primary fuel prices From StateEnergy Data System (SEDS) we have domestic primary fuel prices and electricity prices by state and year. Based on these state-level prices, we construct a industry-year level price index by combining the SEDS data with industry level energy consumption data.

From Misato et al. (2019), we have foreign energy prices for each country. We construct industry-year level import and export energy price index by combining this data with industry level trade data.

Value and quantity of electricity purchased and primary fuel purchased We use value and quantity of electricity purchased and primary fuel purchased for each industry to aggregate the state-year level energy prices into industry-year level. These energy consumption variables are also used to estimate energy intensity for each industry. Calculation details are shown in section C.1 and C.3. These energy consumption variables are from Manufacturing Energy Consumption Survey (MECS) and mainly at naics-3-digit level.

Fortunately, there are 35 industries of which the data is available at naics-5-digit or naics-6-digit industry level. Most of these 35 industries are energy-intensive and are crucial to our analysis. Therefore, when constructing energy price index, energy intensity, and other energy variables, although we have to use naics-3-digit level data for most of the industries due to the limit of MECS data, for these 35 industries that MECS has naics-5-digit or naics-6-digit level available, we will use the corresponding finer level data. More details will be included in section C.1.

Although ASM has value and quantity of purchased fuels at a finer level than MECS (naics-6), it does not cover 1995-2001. Therefore, we use the index contructed using MECS data in our main analysis. We also construct another price index series using ASM data for year 2002-2017 to check the performance of our index. Summary statistics results suggest that the price index at naics-6-digit-year level constructed using MECS data is highly correlated with the ASM price series. We therefore believe that our price index captures the variation at NAICS6-year level successfully. For more explantion on how these price indexes are constructed, please see section C.1

Carbon intensity U.S. Energy Information Administration (EIA) has carbon emission coefficients for each fuel type. Emission and Generation Resource Integrated Database (eGrid) has state-specific carbon emission coefficients for electricity. We combine these coefficients with energy intensity of each industry to estimate the industry-level emission factor (section C.3).

Input-Output Tables When constructing emission factors, we want to account for the interaction between industries. We use the 2007 Input-Output Table from U.S. Bureau of Economics Analysis [51] to convert direct energy prices and energy intensities into embodies prices and intensities (see section C.4).

To construct foreign emission intensities, we need industry-specific imports and exports volume and direct emission intensities. From EXIOBASE, we have industry-specific I-O table describing the interaction between US and its trading partners in 2007.

Employment We include wages as a control variable in the empirical analysis. The series of industry-year level employment is from a combined data set of CMF-ASM (2002-2017) and NBER-CES (1995-2001). Employment at the state level from QCEW is also used to construct industry level prices (see section C.1).

Exchange Rate We obtain a time series of trade-weighted exchange rates from FRED. In particular, we use the TWEXB index.[52]

[51] See https://www.bea.gov/industry/input-output-accounts-data.
[52] See https://fred.stlouisfed.org/series/TWEXB.

Table B.1: Primary Data Sets

Data set	Variables	Aggregation	Years
Census of Manufacturers (CMF)	Value of shipments, value and quantity of electricity purchased, value of primary fuels purchased, wages, input costs, capital intensity	NAICS6-Year	2002, 2007, 2012, 2017
Annual Survey of Manufacturers (ASM)	Same as CMF	NAICS6-Year	2002–2017 (except CMF years)
NBER-CES Manufacturing Industry Database	Same as CMF	NAICS6-Year	1980–2011
Schott (2008)	Value of import transactions, value of export transactions	HS code-Port-Country	1993–2017
Quarterly Census of Employment and Wages (QCEW)	Value of wage, number of employment	NAICS6-State-Year	1995–2017
Manufacturing Energy Consumption Survey (MECS)	Primary energy consumption by fuel type	Industry-Region-Year	1998, 2002, 2006, 2010, 2014
State Energy Data System (SEDS)	Primary energy price by fuel type (domestic)	State-Year	1993–2016
Misato et al. (2019)	Energy price indices (international)	Country-Year-Sector	1995-2015
U.S. Energy Information Administration (EIA)	Carbon dioxide emissions coefficients by fuel	fuel type	
Emissions and Generation Resource Integrated Database (eGRID)	Carbon dioxide emissions rate (from electricity)	State	2016
EXIOBASE	Trade fraction data (import and export fractions)	Country-Industry	2007
Input-Output Accounts Data, Bureau of Economic Analysis (BEA)	Domestc Input-Output Table	Industry-Industry	2007

Notes: The degree of sectoral aggregation can depend on the dataset (NAICS6, industry, or sector). We create crosswalks across datasets that maintain the granularity of NAICS6 sectors whenever possible. Some NAICS6 sectors are aggregated at the NAICS5 level due to changes in NAICS definitions during the sample.

C Variable Construction

As explained in section 4, our analysis needs outcome variables (shipments, imports, and exports), energy price variables, and emission factors at industry-year level. The outcome variables are from public available data sets. This section will explain the construction of NAICS6-year level energy price indexes (domestic energy price index and foreign energy index) and emission-related variables (energy intensity, carbon intensity, and emission factor). For explanation on NAICS6 and naics code, please refer to section B.

C.1 Domestic energy price index (direct)

We construct domestic energy price indexes by weighted averaging over electricity price and fuel price of each industry, as shown in equations (C.1) and (C.2).

$$Price^{TV}_{ind,y} = share^{elec}_{naics3,y} \times Price^{elec}_{ind,y} + (1 - share^{elec}_{naics3,y}) \times Price^{fuel,TV}_{ind,y} \quad [\$/\text{mmBtu}] \tag{C.1}$$

$$Price^{TIV}_{ind,y} = share^{elec}_{naics3w,2007} \times Price^{elec}_{ind,y} + (1 - share^{elec}_{naics3,2007}) \times Price^{fuel,TIV}_{ind,y} \quad [\$/\text{mmBtu}] \tag{C.2}$$

$$share^{elec}_{naics3,y} = \frac{q^{elec}_{naics3,y}}{q^{elec}_{naics3,y} + q^{fuel}_{naics3,y}} \tag{C.3}$$

where

ind : Index for naics-6-digit industries

naics3: Index for naics-3-digit level subsectors.

y : Index for year

$Price^{elec}_{ind,y}$: Electricity price in year y. [$/mmBtu] (constructed in section C.1.1 equation (C.4))

$Price^{fuel}_{ind,y}$: Electricity price in year y. [$/mmBtu] (constructed in section C.1.2), with $Price^{fuel,TV}_{ind,y}$ in equation (C.6); and $Price^{fuel,TIV}_{ind,y}$ in equation (C.7).

$q^{elec}_{naics3,y}$: Quantity of purchased electricity for subsector $naics3$ in year y [mmBtu] from MECS.

$q^{fuel}_{naics3,y}$: Quantity of purchased fuel for subsector $naics3$ in year y [mmBtu] from MECS. As explained in section B, for the 35 industries that MECS has $naics5$ or $NAICS6$ level data available, $q^{elec}_{naics3,y}$ and $q^{fuel}_{naics3,y}$ will be replaced to the corresponding finer level.

The weight is share of quantity of purchased electricity in total energy consumption of each industry. Two price indexes are constructed for each industry using different estimates of the share: *Price Index weighted by time-variant fuel share* uses contemporaneous ratio of the quantity of purchased electricity to quantity of total purchased energy, as shown in equation (C.1); *Price Index weighted by time-invariant fuel share* uses the share of electricity in the reference year (2007), as shown in equation (C.2).

The electricity price and fuel price in the equation are constructed using energy expenditure data from MECS, state-level energy price data from SEDS, and several other data sets. Details are included in the following two sub-sections.

C.1.1 Industry-year level domestic electricity price (direct)

From SEDS we have primary fuel prices by state and year. From QCEW we have data on annual total employment at naics-6-state-year level. Using these 2 variables, we construct *domestic electricity price* at industry-year level. The process of calculating electricity price for each NAICS6-year is shown in equation (C.4).

$$Price^{elec}_{ind,y} = \frac{\sum_{s=1}^{52} Price^{elec}_{s,y} \times empl_{s,ind,y}}{\sum_{s=1}^{52} empl_{sjt}} \qquad [\$/\text{mmBtu}] \qquad (C.4)$$

where

s :	Index for state, 1-52
$Price^{elec}_{s,y}$:	Electricity price in state s, year y [$ / mmBtu] from SEDS
$empl_{s,ind,y}$:	Employment of naics-6-digit industry ind, state s, year y [1 person] from QCEW

Because we do not have industry-level energy price data from the raw data set, we need a way to weight state-level electricity prices. We use employment level (publicly available annually by industry by state from QCEW) to proxy for the distribution of productive activity across states in a given industry/year.

To assess the performance of this proxy, we also generated price series using ASM data in which annual average electricity prices are reported at the naics-5-digit or naics-6-digit level (see equation (C.5)). This series spans 2002-2016 and covers all naics-5-digit industries and about 80% of naics-6-level industries. It is sufficient for comparison purpose but not enough to cover our entire study period. Across the 15 years with both ASM and MECS data available, the correlation of ASM electricity price series and $Price^{elec}_{ind,y}$ from equation (C.4) is 0.63. Within different naics-3-digit sub-sector, the correlation varies from 0.53 to 0.91.

$$Price^{elec,ASM}_{ind,y} = \frac{expen^{elec}_{ind,y}}{q^{elec}_{ind,y}} \qquad [\$/\text{mmBtu}] \qquad (C.5)$$

$expen^{elec}_{ind,y}$:	Electricity expenditure of industry ind in year y [$] from ASM
$q^{elec,asm}_{ind,y}$:	Quantity of purchased electricity of industry ind in year y [kWh, equivalent to 3.41×10^{-3} mmBtu] from ASM

C.1.2 Industry-year level domestic fuel price (direct)

Naics6-year level fuel price index is constructed as weighted average of state-level fuel prices. Fuel mixes vary across industries, so weighted average fuel prices reflect not only regional differences, but also differences in fuel composition.

$$Price^{fuel,TV}_{ind,y} = \frac{\sum_{s=1}^{52}(\sum_f price^f_{s,y} \times share^f_{naics3,y}) \times empl_{s,ind,t}}{\sum_{s=1}^{52} empl_{s,ind,t}} \qquad [\$/\text{mmBtu}] \qquad (C.6)$$

$$Price^{fuel,TIV}_{ind,y} = \frac{\sum_{s=1}^{52}(\sum_f price^f_{s,y} \times share^f_{naics3,2007}) \times empl_{s,ind,t}}{\sum_{s=1}^{52} empl_{s,ind,t}} \qquad [\$/\text{mmBtu}] \qquad (C.7)$$

where

f : Index for fuel (e.g., distillate fuel oil, residual fuel oil, natural gas, HGL, coal, coke, other (biofuel))

$price^f_{s,y}$: Price of fuel type f in state s, year y. [\$/mmBtu] from SEDS

$empl_{s,ind,y}$: Employment of naics-6-digit industry ind, state s, year y [1 person] from QCEW

$share^f_{naics3,y}$: Ratio of quantity of purchased fuel type f to total quantity of purchased fuel for sub-sector $naics3$ in year y. This is calculated in the same spirit as equation (C.3) but focused on the shares of different fuels. The purchased quantity for each fuel type are from MECS and are in [mmBtu]. For the 35 industries that MECS has $naics5$ or $NAICS6$ level data available, this variable will be replaced to the corresponding finer level.

Note that SEDS provides 26 different prices for the 26 types of fuel. We only use 7 out of the 26 prices because MECS only records industry expenditures for these 7 types of fuel: distillate fuel oil, residual fuel oil, natural gas, HGL, coal, coke, other (biofuel). To construct a fuel price for each NAICS6-state-year, we should use NAICS6-specific fuel usage to weight the state-year level fuel prices. However, MECS only have naics-3-digit level expenditure data for most of the industries. Thus variable $share^f$ is at naics3-year level for most of the industries. After getting the naics3-state-year to NAICS6-state-year level fuel price index, we aggregate it to industry-year level using employment of each industry-state as the weight. Therefore, even though $share^f$ does not differ across NAICS6 industries within the same naics3 subsector, the NAICS6-state level employment gives NAICS6 level variation.

C.2 Foreign energy price index

We include foreign energy prices in our analysis to capture differences in the energy prices faced by domestic and foreign producers. The relevant foreign energy prices to consider are the prices in countries where imports originate and where exports are destined. We calculate a set of foreign energy price indices for each industry based on industry-specific trade partners. From Misato et al. (2019), we get energy prices for around 40 countries. They uses IEA data and supplement the data with other governmental data where missing. We calculate a weighted average of country-sector level prices with the weight equaling to the average import or export trading volume for each industry, as shown in equation (C.8), (C.9) and (C.10).

$$Price^{foreign}_{ind,y} = \frac{Price^{imp}_{ind,y} \times imp_{ind,y} + Price^{exp}_{ind,y} \times exp_{ind,y}}{imp_{ind,y} + exp_{ind,y}} \qquad [\$/\text{mmBtu}] \tag{C.8}$$

Import price and export price for each NAICS6-year are generated using equation (C.9) and (C.10):

$$Price^{imp}_{ind,y} = \frac{\sum_c p^{sector}_{c,y} \times imp_{c,ind,y}}{\sum_c imp_{c,ind,y}} \qquad [\$/\text{mmBtu}] \tag{C.9}$$

$$Price^{exp}_{ind,y} = \frac{\sum_c p^{sector}_{c,y} \times exp_{c,ind,y}}{\sum_c exp_{c,ind,y}} \qquad [\$/\text{mmBtu}] \tag{C.10}$$

c : Index for trading partner countries.

sector : 1-10, based on IEA classification of all the manufacture industries. In our analysis, we map each of the section 1-10 with multiple naics-3-digit sub-sections.

$p^{sector}_{c,y}$: Energy prices at country c, year y, for sector *sector*. [\$/TOE, equivalent to 2.52×10^{-2}] from Misato et al (2019). For countries that we do not have energy prices, we use regional price index $Price_{region,y}$ generated from equation (C.11) below.

$imp_{c,ind,y}$: Imports value of industry *ind*, year y, from country c. [\$] from Schott (2008)

$exp_{c,ind,y}$: Exports value of industry *ind*, year y, to country c. [\$] from Schott (2008)

We only have energy prices available for 46 countries from 1995-2009 (with holes) (from Misato et al. 2009). And for 33 of these countries, we have energy prices available from 1995-2015. Therefore, we classify the countries into 5 regions and generate a set of region level foreign prices index: For countries not included in Misato et al. (2019), we plug in this regional foreign price index to equation (C.9) and (C.10) in replace of $p^{sector}_{c,y}$.

$$Price^{sector}_{region,y} = \frac{\sum_{c \in region} Price^{sector}_{c,y} \times \overline{Imports_{c,sector}}}{\sum_{c \in region} \overline{Imports_{c,sector}}} \tag{C.11}$$

$$\overline{Imports_{c,sector}} = \frac{1}{21} \sum_{y=1995}^{2015} Imports_{c,sector,y} \tag{C.12}$$

The above variable $Price^{sector}_{region,y}$ will be plugged into equation (C.9). A similar variable $Price^{sector,exp}_{region,y}$, constructed in the same sense as equation (C.11) above but using export volume as the weight, will be used for equation (C.10).

Table C.1: Number of countries with prices available from 1995-2015 in each region

region	year	countries
Africa	1995-2014	South Africa (missing 2015)
Asia & Pacific	1995-2015	AUS, JPN, KOR, NZL
CAN	1995-2015	Canada
Europe	1995-2015	27 countries
Central America	1995-2015	MEX
South America	1995-2015	BRA (& CHL for Food and Tobacco sector only)

C.3 Domestic emissions intensity (direct)

To estimate the emissions leakage from each industry, we need a domestic carbon emissions intensity (in [Kg/$m shipment]) for each industry to convert the changes in production into changes in emission. (For more details, see section 2.) This domestic emissions intensity e^d_{ind} is constructed following equation (C.13):

$$e^d_{ind} = CI_{ind} \times EI_{ind} \qquad \text{[Kg/\$m shipment]} \qquad \text{(C.13)}$$

where CI_{ind} is carbon intensity in [Kg/mmBtu] for naics-6-digit industry *ind* in reference year (2007) and EI_{ind} is energy intensity in [mmBtu/$m shipment] for naics-6-digit industry *ind* in reference year (2007). The next 2 sub-sections explain the methodology for constructing these 2 variables.

C.3.1 Industry-year level domestic carbon intensity

We construct carbon intensities [Kilograms CO_2 per million Btu] for each industry-year using equation (C.14). The carbon intensity for reference year (2007) will be plugged into equation (C.13) to estimate the emissions factor.

$$CI_{ind,y} = \sum_f CI^f \times share^f_{naics3,y} + CI^{elec}_{ind,y} \times share^{elec}_{naics3,year} \qquad \text{[Kg/mmBtu]} \qquad \text{(C.14)}$$

$$CI^{elec}_{ind,y} = \frac{\sum_{s=1}^{52} CI^{elec}_{s,y} \times empl_{s,ind,y}}{\sum_{s=1}^{52} empl_{s,ind,y}} \qquad \text{[Kg/mmBtu]} \qquad \text{(C.15)}$$

f : Index for fuel (e.g., distillate fuel oil, residual fuel oil, natural gas, HGL, coal, coke, other (biofuel))

s : Index for state, 1-52

CI^f : Carbon intensity for fuel type f [Kg/mmBtu] from EIA

$CI^{elec}_{s,y}$: State annual CO2 non-baseload output emissions rate [lb/MWh, equivalent to 7.52×10^{-3} kg CO_2/mmBtu] from eGRID

$empl_{s,ind,y}$: Employment of industry ind, state s, year y [1 person] from QCEW

$share^{elec}_{naics3,y}$: Ratio of quantity of purchased electricity to total quantity of purchased energy. See equation (C.3) for the construction for this variable.

$share^{f}_{naics3,y}$: Ratio of quantity of purchased fuel type f to total quantity of purchased energy, calculated in the same sense as equation (C.3). The purchased quantity for electricity and each fuel type are from MECS and are in [$mmBtu$]. For the 35 industries that MECS has $naics5$ or $NAICS6$ level data available, $share^{elec}_{naics3,y}$ and $share^{f}_{naics3,y}$ are replaced to the corresponding finer level.

C.3.2 industry-year level domestic energy intensity

Energy intensity in [mmBtu/$m shipment] for each industry-year is constructed using equation (C.16). The energy intensity for reference year (2007) will be plugged into equation (C.13) to estimate the emissions factor.

$$EI_{ind,y} = \frac{q\_energy_{ind,y}}{shipment_{ind,y}} \qquad \text{[mmBtu/\$m shipment]} \tag{C.16}$$

$$q\_energy_{ind,y} = \begin{cases} q\_energy^{MECS}_{ind,y} & \text{if } ind \text{ at NAICS6 level in MECS} \\ q^{elec,ASM}_{ind,y} + \dfrac{expend^{fuel,ASM}_{ind,y}}{Price^{fuel,TV}_{ind,y}} & \text{if } y \geq 2002 \\ \dfrac{expend^{NBER}_{ind,y}}{Price^{TV}_{ind,y}} & \text{if } y \in [1995, 2001] \end{cases} \tag{C.17}$$

$q\_energy_{ind,y}$: Industry-year level total energy consumption in Btu, generated by equation (C.17)

$shipment_{ind,y}$: Industry-year level shipments in USD. The sources of shipments will be consistent with the data source of total energy usage (ASM or NBER).

$q\_energy^{MECS}_{ind,y}$: Industry-year level total energy consumption in Btu from MECS. Only available for 35 NAICS6 industries.

$q^{elec,ASM}_{ind,y}$: Quantity of purchased electricity of industry *ind* in year *y* [kWh, equivalent to 3.41×10^{-3} mmBtu) from ASM.

$expend^{fuel,ASM}_{ind,y}$: Value of purchased fuel of industry *ind* in year *y* [\$] from ASM.

$expend^{NBER}_{ind,y}$: Total energy expenditure of industry *ind* in year *y* [\$] from NBER.

$Price^{fuel,TV}_{ind,y}$: [\$/mmBtu] From equation (C.6)

$Price^{TV}_{ind,y}$: [\$/mmBtu] From equation (C.1)

As explained in section B, although the energy consumption variables from Manufacturing Energy Consumption Survey (MECS) are more relevant to our purpose, it is mainly at naics-3-digit level. And there are only 35 industries of which the consumption data is available at naics-5-digit or naics-6-digit industry level. Because most of these 35 industries are energy-intensive and are crucial to our analysis, we use $q\_energy^{MECS}_{ind,y}$ in equation C.17 whenever available. For the rest of industries, we use NBER or ASM data to approximate the energy consumption in Btu.

C.4 Direct and embodied energy intensities and energy price index

To capture how a carbon price might impact operating costs, we should be concerned with not only direct energy inputs, but also the emissions embodied in other factors to production. Domestic input-output (I-O) tables summarize how industrial production value flows through domestic supply chains as intermediate inputs. We use these tables,[53] together with estimates of direct energy intensities and direct energy prices, to estimate the domestic emissions and energy costs embodied in intermediate inputs along the supply chain.

To distinguish these terms, we call the domestic energy price index from section C.1, foreign energy price index from section C.2, and domestic energy intensity from section C.3.2 direct domestic energy price index, direct foreign energy price index, and direct domestic energy intensity, respectively. This section will construct the corresponding embodied domestic energy price index, embodied foreign energy price index, and embodied energy intensity,

[53] We use the 2007 domestic requirements tables released by Bureau of Economic Analysis in 2017.

which account for the emissions and energy costs along the supply chain.

Naics-6-digit Industry Level I-O Table The interaction across industries is explained by matrix X in equation (C.18). Each element in the matrix $x_{i,j}$ means the proportion of units of industry i consumed by industry j as a proportion of its gross output.[54]

$$X = \begin{pmatrix} x_{1,1} & x_{1,2} & \dots & x_{1,N} \\ x_{2,1} & x_{2,2} & \dots & x_{2,N} \\ \vdots & \vdots & & \vdots \\ \vdots & x_{i,j} & \dots & \vdots \\ \vdots & \vdots & & \vdots \\ x_{N,1} & x_{N,2} & \dots & x_{N,N} \end{pmatrix} \tag{C.18}$$

$$Prod = \begin{pmatrix} prod_1 \\ prod_2 \\ \vdots \\ prod_i \\ \vdots \\ prod_N \end{pmatrix} \qquad Demand = \begin{pmatrix} d_1 \\ d_2 \\ \vdots \\ d_i \\ \vdots \\ d_N \end{pmatrix} \tag{C.19}$$

Let $Prod$ be the production vector, each element of which stands for the production of an industry, and $Demand$ be the demand vector for final goods, as shown in equation (C.19). Then for each industry i, its total amount of production should equal the amount of its production used as input by other industries plus the final demand of this industry's product. Therefore, we get equation (C.20):

$$prod_i = \sum_{j=1}^{N} x_{i,j} \times prod_j + demand_i \tag{C.20}$$

From each industry, we can get one equation like equation (C.20). Combing all the equations from N=472 manufacturing industries, we get the following matrix representation (equation (C.21)) of this system of equation:

$$Prod = X \times Prod + Demand \tag{C.21}$$

[54]When all sectors of the economy are included, including one input as value added, each column j in this table should sum up to 1, $\sum_{i=1}^{N} x_{i,j} = 1 \ \forall j$.

$$\implies Prod = (I - X)^{-1} Demand \tag{C.22}$$

$$IOTable := (I - X)^{-1} = \begin{pmatrix} l_{1,1} & l_{1,2} & \dots & l_{1,N} \\ \vdots & \vdots & & \vdots \\ \vdots & l_{i,j} & \dots & \vdots \\ \vdots & \vdots & & \vdots \\ l_{N,1} & l_{N,2} & \dots & l_{N,N} \end{pmatrix} \tag{C.23}$$

As shown in equation (C.22), to solve for the indirect production using the demand vector, we need the Leontief inverse of X. This Leontief inverse matrix is called an I-O Table. Each row i of the I-O Table contains the value of the production of industry i needed as intermediate goods, in order to produce one unit of *final* demand in industry js. For each industry j, the corresponding column contains all the industry i served as intermediate goods provides.

From Bureau of Economic Analysis (BEA), we get the I-O Table for 2007, which is set to be the reference year of our analysis. We remove all non-manufacturing industries from the I-O Table in order to construct, for each industry, a vector of all the intermediate manufactured inputs required to produce a dollar of final demand in that industry. There are 472 naics-6-digit manufacturing industries. However, the I-O Table released by Bureau of Economic Analysis includes 288 industries based on its own classification.

We expand the BEA I-O table to naics-6-digit level for all manufacturing industries using naics-6-digit level shipment from NBER-CES Manufacturing Industry Database. For each element $l_{i,j}$ in the original I-O table (288-by-288), we apply the following downscaling: $l_{i_n j_m} = \left(l_{ij} - \mathbf{1}\{i = j\}\right) * \frac{shipment_{i_n}}{\sum_{\nu}^{N} shipment_{i_\nu}} + \mathbf{1}\{i_n = j_m\}$, where i and j are the rows and columns of the original Leontief matrix (288x288), i_n and j_m are the rows and columns of the new Leontief matrix(472x472), $l_{i,j}$ are the original total requirements in the original Leontief matrix, x_{i_n} is the shipments for industry $shipment_{i_n}$ for 2007, and $\mathbf{1}\{i = j\}$ is an indicator function $= 1$ if $i = j$.

After this cleaning process, we get a 472-by-472 naics-6-digit industry level I-O Table, denoted $IOTable$ in equation (C.23). Each element $l_{i,j}$ in this matrix stands for the required production for i from j. So $l_{i,j}$, $i \neq j$ considers i as an intermediate goods provider for industry j. And $l_{j,j}$ is the production from j itself to serve industry j's own final demand. For each industry j, the corresponding column contains the value of required intermediate goods production from industry i, $\forall i \in$ manufacturing, 1-472, in order to produce one unit of final demand in j.

Embodied Energy Intensities (Domestic and Foreign) For industry j, we estimate the embodied energy intensity by summing up its own direct energy intensity (ei_j^{dir}) and energy intensities of all the other industry is that provides intermediate goods for industry j.

$$ei_j^{emb} = \sum_{i=1}^{472} ei_i^{dir} * l_{ij} \tag{C.24}$$

where

ei_i^{dir} : Direct energy intensities of industry i [mmBtu/$m shipment]

l_{ij}: The i, j element from the I-O table. This is the requirement for intermediate industry i from final industry j, so that industry j is able to produce one unit of final demand [$m shipment/$m shipment].

Let EI^{dir} denote a vector of direct energy intensities for the 472 industries and EI^{emb} denote a vector of embodies energy intensity. We convert the system of equatiomns into a matrix representation as in equation (C.25):

$$EI^{emb} = \begin{pmatrix} ei_1^{emb} \\ \cdots \\ ei_{ind}^{emb} \\ \cdots \\ ei_N^{emb} \end{pmatrix} = IOTable^T \times \begin{pmatrix} ei_1^{dir} \\ \cdots \\ ei_{ind}^{dir} \\ \cdots \\ ei_N^{dir} \end{pmatrix} = IOTable^T \times EI^{dir} \tag{C.25}$$

Embodied Energy Prices (domestic and foreign) We use both the I-O Table, which accounts for the proportion of intermediate goods needed for an output good, and direct energy intensities, which acoount for which intermediate goods are more energy intensive. For industry j, the indirect energy price index is constructed by a weighted summation of all the direct energy price pass-though from other industry is (including j itself):

$$price_j^{emb} = \sum_{i=1}^{472} price_i \times \frac{ei_i^{dir} * l_{ij}}{\sum_{\eta=1}^{472} \left[e_\eta^{dir} * l_{\eta j} \right]} \tag{C.26}$$

where

$price_i$: Direct energy prices from section C.1 and C.2.

l_{ij}: The i, j element from the I-O table. This is the requirement for intermediate industry i from final industry j, so that industry j is able to produce one unit of final demand [$m shipment/$m shipment].

ei_i^{dir} : Direct energy intensities of intermediate industry i [mmBtu/$m shipment]

For each industry i, as an intermediate goods provider for industry j, the weight for this industry i is proportional to its domestic energy intensity (ei_i^{dir} in [mmBtu/$m shipment]) and its contribution to industry j ($l_{i,j}$ in [$m shipment/$m shipment]). This weight can be interpreted as the contribution of industry i's energy consumption in the embodied energy intensity of industry j.

C.5 Foreign carbon intensity (direct)

To capture the emissions leakage caused by international trade, we construct foreign carbon intensities for each industry based on industry-specific trading volume and the emissions factor of trading partner countries. Due to limited data availability, we only construct the foreign carbon intensity for 98 NAICS6 industries.

Following a similar approach as section C.4, we use industry-specific I-O table, describing the trading interaction across countries, to convert direct energy intensities into foreign energy intensities.

Step 1: Construct total emission factor for each industry-country The I-O table from EXIOBASE, denoted X, shows the proportion of units of country $c1$ imported from country $c2$ as a proportion of its gross output. (Notice that in section C.4, what we call "I-O Table" is the Leontief inverse of the interaction table X. This is because Bureau of Economic Analysis (BEA) calls the Leontief inverse an I-O table.)

$$X_{ind} = \begin{pmatrix} x_{c1,c1} & x_{c1,c2} & \dots & x_{c1,cN} \\ x_{c2,c1} & x_{c2,c2} & \dots & x_{c2,cN} \\ \vdots & \vdots & & \vdots \\ \vdots & x_{ci,cj} & \dots & \vdots \\ \vdots & \vdots & & \vdots \\ x_{cN,c1} & x_{cN,c2} & \dots & x_{cN,cN} \end{pmatrix} \tag{C.27}$$

$$DirectE_{ind} = \begin{pmatrix} de_{c1} \\ de_{c2} \\ \vdots \\ de_{ci} \\ \vdots \\ de_{cN} \end{pmatrix} \tag{C.28}$$

Let $DirectE_{ind}$ denote the industry-specific direct emissions rate of each country (from EXIOBASE). Analogous to equation C.20-C.23, we get equation C.29, showing the construction of industry-specific foreign emissions rate.

$$\begin{aligned} E_{ind,-US} &= (I - X_{ind})^{-1} DirectE_{-US} \\ &= L_{ind,-US} \times DirectE_{-US} \qquad \forall ind \end{aligned} \tag{C.29}$$

where $E_{ind,-US}$ is the total emissions rate vector with the US rates removed, $DirectE_{-US}$ is a transpose of the direct emissions rate vector with the US rates removed, and L_{-US} is the Leontief inverse matrix with the US rows and columns removed (this means that it ignores any upstream emissions that come from the US).

Step 2: Get industry-country level indirect demand from industry-country level direct final demand From EXIOBASE we have a matrix of final demand of each country from each country-indsutry, denoted $Demand^{dir}$. Let M = 98 be the total number of industries. This final demand matrix is $N \times M$-by-N, where N is number countries. Each element $d_{(ci,ind),cj}$ with row index (ci, ind) and column index cj stands for the final demand of country cj (importer) from country ci (exporter) industry ind.

$$Demand^{dir} = \begin{pmatrix} d_{(c1,ind1),c1} & d_{(c1,ind1),c2} & \cdots & d_{(c1,ind1),cN} \\ d_{(c1,ind2),c1} & d_{(c1,ind2),c2} & \cdots & d_{(c1,ind2),cN} \\ \vdots & \vdots & & \vdots \\ \vdots & d_{(c,ind),c2} & \cdots & \vdots \\ \vdots & \vdots & & \vdots \\ d_{(cN,indM),c1} & d_{(cN,indM),c2} & \cdots & d_{(cN,indM),cN} \end{pmatrix} \tag{C.30}$$

From the I-O table, we can calculate indirect (upstream) demand by equation C.31. The indirect demand matrix will be in the same shape as the direct final demand matrix.

$$D^{indirect} = Demand^{dir} \times L^T \tag{C.31}$$

Step 3: Calculate the import/export weighted emissions factors for each industry We now aggregate the industry-country level emissions factor from step 1 into industry level foreign emission factors.

The weights is constructed using the demand matrix from step 2. Recall each element in either the direct or indirect demand is $d_{(ci,ind),cj}$, where ind is industry, ci is country of origin (exporter) and the column index cj is country of consumption (importer). The import weight for each industry ind, trading partner country c is:

$$w_{ind,c}^{ind} = \frac{d_{i,c,US}}{\sum_s^C d_{i,s,US}} \text{ , where, } s \in C \neq US$$

And the export weight for each industry ind, trading partner c is:

$$w_{ind,c}^{exp} = \frac{d_{i,US,c}}{\sum_s^C d_{i,US,s}} \text{ , where, } s \in C \neq US$$

Then we use import or export weighted summation of industry-country level emissions factors from step 1 ($E_{ind,-US} = (e_{ind,c1}^{indirect}, e_{ind,c2}^{indirect}, \ldots, e_{ind,cN}^{indirect})^T$) to estimate industry level foreign emissions factor:

$$ei_{ind}^{imp} = \left(w_{ind,c1}^{imp}, w_{ind,c2}^{imp}, \ldots, w_{ind,cN}^{imp}\right) \times E_{ind,-US} \qquad \forall ind \tag{C.32}$$

$$ei_{ind}^{exp} = \left(w_{ind,c1}^{exp}, w_{ind,c2}^{exp}, \ldots, w_{ind,cN}^{exp}\right) \times E_{ind,-US} \qquad \forall ind \tag{C.33}$$

$$e_i^{impexp} = \frac{e_i^{imp} \times imp_{ind} + e_i^{exp} \times exp_{ind}}{imp_{ind} + exp_{ind}} \qquad \forall ind \tag{C.34}$$

$$imp_{ind} = \sum_{c \neq US} d_{(c,ind),US} \tag{C.35}$$

$$exp_{ind} = \sum_{c \neq US} d_{(US,ind),c} \tag{C.36}$$

C.6 Labor inputs

Wages are calculated as the ratio of an industry's payroll to the industry's total number of employees, giving the average annual salary in the industry. The CMF and ASM report payroll and employees for each establishment-year, and we sum over all establishments in an industry to get industry totals. Wages are summarized in Table 1.

D Alternative results with embodied carbon intensities

In the paper, we report on regression specifications and policy simulations that are based on our direct measures of energy intensity and energy costs. Here we summarize the companion set of policy simulations which use our more comprehensive measures of embodied energy inputs and energy price indices. These simulations are designed to capture both the direct and indirect impacts of energy cost increases. However, because our embodied energy estimates are, at best, approximate, these results are more suggestive.

This more comprehensive analysis of direct and indirect impacts begins with the same set of regression specifications as are summarized in the paper. The only difference is that we replace the domestic and foreign energy price indices and intensities with our more comprehensive measures. Figure D.1 summarizes the regression coefficients we obtain with these specifications. The most important difference between these estimates and those reported in the paper is that our export elasticities are smaller in absolute value. This difference has implications for estimated rates of market transfer and emissions leakage.

Following the same process we describe in the paper, we combine these energy cost elasticities, together with baseline values of imports, exports, and domestic manufacturing production, to construct industry-specific market transfer rates. Figure D.2 (a) summarizes the relationships between calibrated rates and standard leakage metrics. On average, the market transfer rates associated with our more comprehensive measures of energy costs and intensities are lower (relative to those implied by more direct measures). This is primarily because export elasticities are smaller in absolute and relative terms. Figure D.2 (b) extends this analysis to the associated leakage metrics. Overall, leakage risk estimates are lower as compared to the rates we obtain using direct energy cost elasticities.

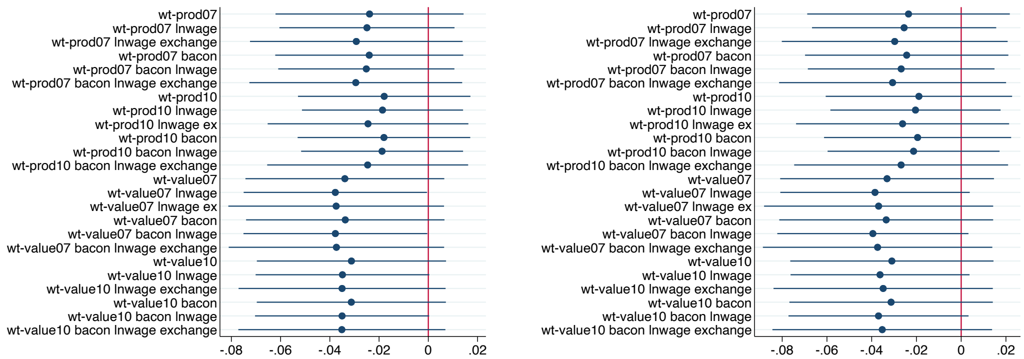
Next, we implement a companion set of policy simulations. The policy scenarios we analyze are analogous to those we introduce in the main paper. However, the execution is more complicated because we must account for both the direct and upstream impacts of the carbon price and output-based subsidies. We use input-output tables to estimate how a given set of policy incentives (i.e. the tax and the subsidy schedule) impacts operating costs along domestic supply chains. We continue to assume full energy cost pass through. And we rule out factor input re-allocations and general equilibrium effects.

Tables D.1 and D.2 summarize results from these policy simulations. Results from the policy scenario that features a carbon price in isolation are reported in the first column of each table. These results are identical across the tax and trading regimes by design (because the cap is calibrated to deliver an equilibrium permit price of $25/ton). Contrasting these results with Tables 2 and 3 in the paper, we see that impacts of the carbon price on domestic production are larger in absolute value while impacts on exports are somewhat smaller. These differences translate into higher rates of domestic abatement and lower median estimates of emissions leakage overall (0.31 versus 0.49). In this case, as in the simulations that focus more narrowly on direct energy cost impacts, the range of simulated leakage rates is wide because market transfer rates are sensitive to variation in energy cost elasticity estimates across specifications.

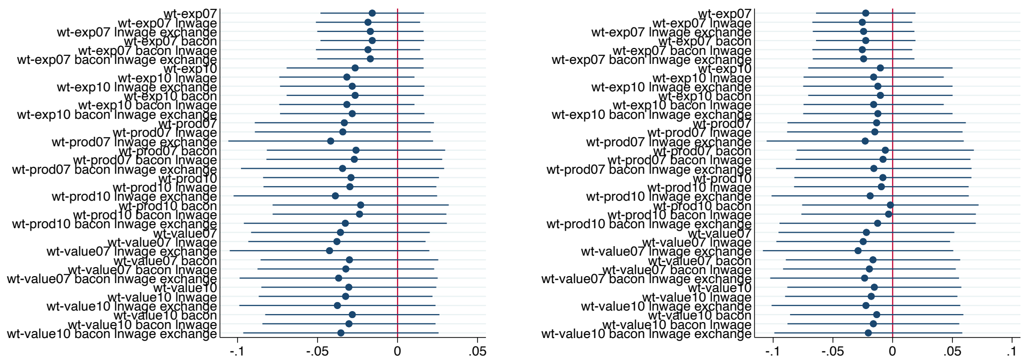
Next, we introduce our theoretically consistent subsidy schedule (in column (2)). Intuitively, the targeted output-based subsidy attenuates the impacts of the carbon price on manufacturing production and trade flows. Under the tax, the leakage mitigation subsidies drive median leakage estimates down to 0.05. Tax revenues collected by the government are reduced by almost half. Under the cap-and-trade program, impacts on leakage rates are offset by the higher permit price.

Qualitatively, the simulated results under coarser targeting are similar to results summarized in the main paper. Leakage is minimized and net abatement is maximized under our targeted subsidy schedule. The coarser targeting based on standard EI and TE metrics deliver a fraction of the leakage mitigation benefits (or none under cap-and-trade) while incurring substantive costs. Under the tax regime, almost 13$B is spent on annual subsidies. Under the emissions trading program, the permit price must rise to $43/ton to induce sufficient abatement.

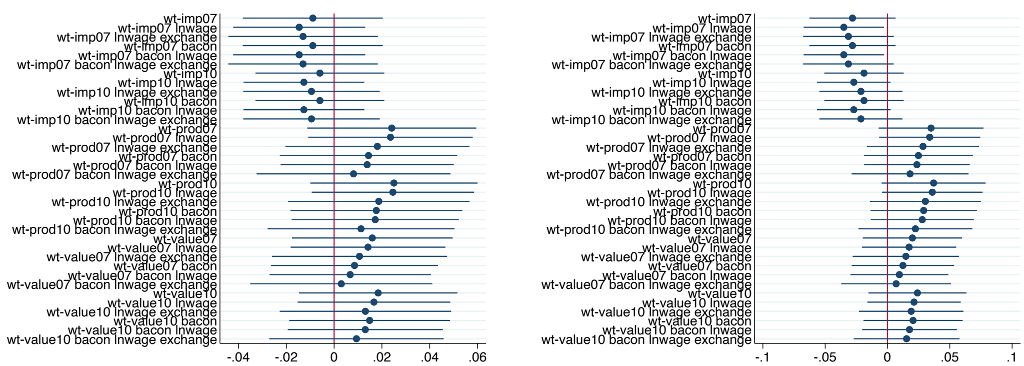
In sum, although there are some quantitative differences across simulations that focus on direct energy impacts and those that seek to account for direct and embodied energy cost impacts, the qualitative conclusions are the same. Absent leakage mitigation, the emissions leakage potential under a a moderate carbon price is substantial in the manufacturing sector. Targeted output-based subsidies can deliver significant reductions in emissions leakage risk. But coarsely targeted subsidies delivers limited -if any- leakage mitigation while incurring substantial costs.



(a) Domestic shipments



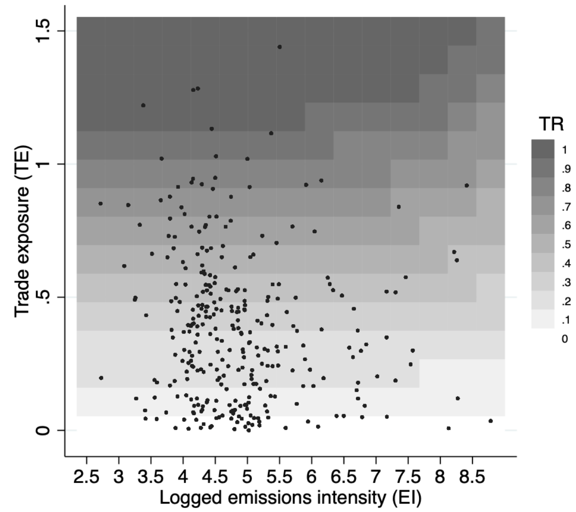
(b) Exports



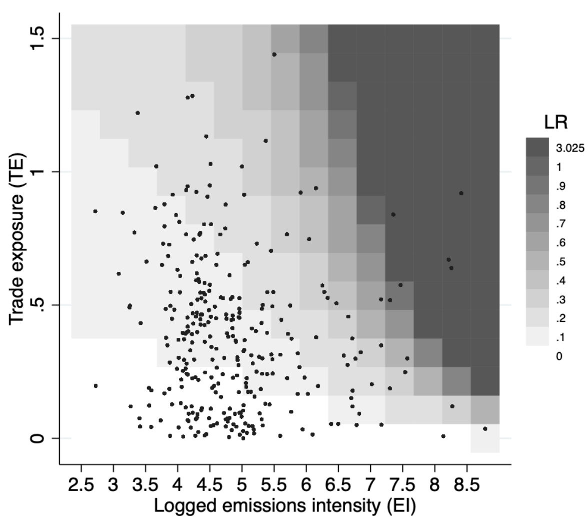
(c) Imports

Figure D.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)

Figure D.2: Quantifying transfer and leakage rates – Direct and Indirect Emissions

This figure displays calibrated transfer rates and leakage rates approximated as a function of energy 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 energy intensity, trade shares, and their interaction. The measures are derived using embodied intensity measures.

Table D.1: Simulated Impacts of a \$25/ton CO2e Carbon Tax with Embodied Emissions Intensities

	Carbon Tax (USD \$25) (1)	Tax and Subsidy: Baseline (2)	Tax and Subsidy: Alternative 1 (3)	Tax and Subsidy: Alternative 2 (4)
A: Impacts on Domestic Shipments, Imports, Exports (%)				
$\%\Delta Prod$	-2.9	-1.9	-1.4	-1.0
	$[-4.2, -2.0]$	$[-2.6, -1.3]$	$[-2.0, -1.0]$	$[-1.5, -0.7]$
$\%\Delta Exp$	-2.1	-0.6	-0.5	-0.5
	$[-3.3, -0.7]$	$[-1.1, -0.2]$	$[-0.9, -0.2]$	$[-0.8, -0.2]$
$\%\Delta Imp$	1.1	0.3	0.3	0.3
	$[-2.5, 2.7]$	$[-0.7, 0.8]$	$[-0.8, 0.8]$	$[-0.7, 0.8]$
B: Annual Emission Abatement and Emissions Leakage (%)				
% Abatement	9.8	7.1	4.3	1.7
	[6.6, 13.9]	[4.8, 10.1]	[2.9, 6.1]	[1.1, 2.4]
% Net abatement	7.1	5.8	3.6	1.3
	[2.2, 10.3]	[2.9, 7.7]	[1.9, 4.7]	[0.4, 1.8]
Leakage rate	0.29	0.15	0.12	0.26
	$[-0.23, 0.66]$	$[-0.14, 0.36]$	$[-0.12, 0.29]$	$[-0.24, 0.62]$
Net Tax Revenue (\$ B)	30.8	17.2	17.2	15.1
	[29.4, 31.9]	[16.3, 17.9]	[16.6, 17.6]	[14.9, 15.2]
Median allocation factor	0.00	0.25	0.80	0.80
N subsidized industries	0	312	47	47

This table uses the total energy cost elasticity estimates summarized in Figure D.1 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 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 D.2: Simulated Impacts under GHG Cap and Trade with Embodied Emissions Intensities

	Carbon Tax	CAT and Subsidy		
		Baseline	Alternative 1	Alternative 2
	(USD \$25)	(USD \$32)	(USD \$39)	(USD \$45)
	(1)	(2)	(3)	(4)
A: Impacts on Domestic Shipments, Imports, Exports (%)				
$\%\Delta Prod$	-2.9	-2.7	-3.1	-3.4
	$[-4.2, -2.0]$	$[-3.8, -1.8]$	$[-4.4, -2.1]$	$[-4.8, -2.3]$
$\%\Delta Exp$	-2.1	-1.2	-1.7	-2.1
	$[-3.3, -0.7]$	$[-2.0, -0.4]$	$[-2.7, -0.6]$	$[-3.5, -0.7]$
$\%\Delta Imp$	1.1	0.6	0.9	1.2
	$[-2.5, 2.7]$	$[-1.4, 1.6]$	$[-2.2, 2.4]$	$[-2.8, 3.0]$
B: Annual Emission Abatement and Emissions Leakage (%)				
% Abatement	9.8	9.9	9.7	9.5
	$[6.6, 13.9]$	$[6.7, 14.0]$	$[6.6, 13.9]$	$[6.5, 13.5]$
% Net abatement	7.1	7.8	7.5	7.0
	$[2.2, 10.3]$	$[3.6, 10.5]$	$[3.3, 10.2]$	$[2.2, 10.0]$
Leakage rate	0.29	0.19	0.22	0.29
	$[-0.23, 0.66]$	$[-0.16, 0.44]$	$[-0.18, 0.49]$	$[-0.23, 0.65]$
Net Tax Revenue (\$ B)	30.8	25.2	33.7	39.3
	$[29.4, 31.9]$	$[23.6, 26.4]$	$[32.0, 34.9]$	$[37.8, 40.4]$
Median allocation factor	0.00	0.25	0.80	0.80
N subsidized industries	0	312	47	47

This table uses the total energy cost elasticity estimates summarized in Figure D.1 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. he 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. Note that domestic abatement does not exactly match 9.3% across scenarios due to the discrete nature of our carbon prices.

E Additional Tables and Figures

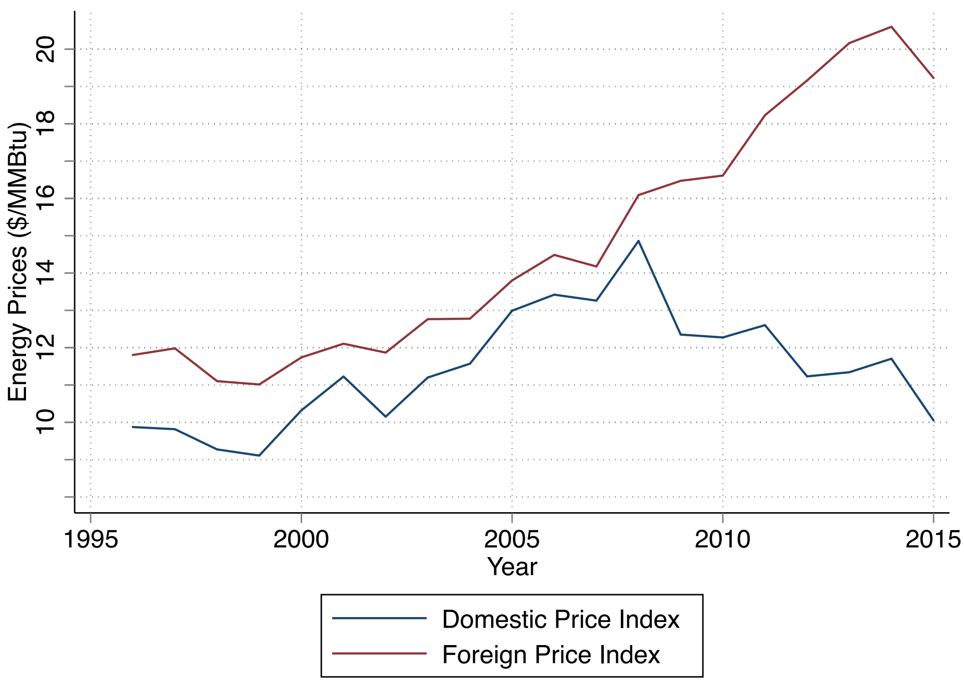


Figure E.1: Evolution of Energy Prices over time

This figure summarizes intertemporal variation in domestic energy prices, foreign natural gas prices, and foreign electricity prices over time. These energy price indices are constructed as weighted averages of the energy prices paid by industrial producers relative to their prices in some base-year. Domestic energy prices are weighted by value of shipments. Average foreign energy prices are weighted by the value of shipments from the country of origin (imports) and the value of shipments to destinations (exports). For more details, see the discussion of data set construction.

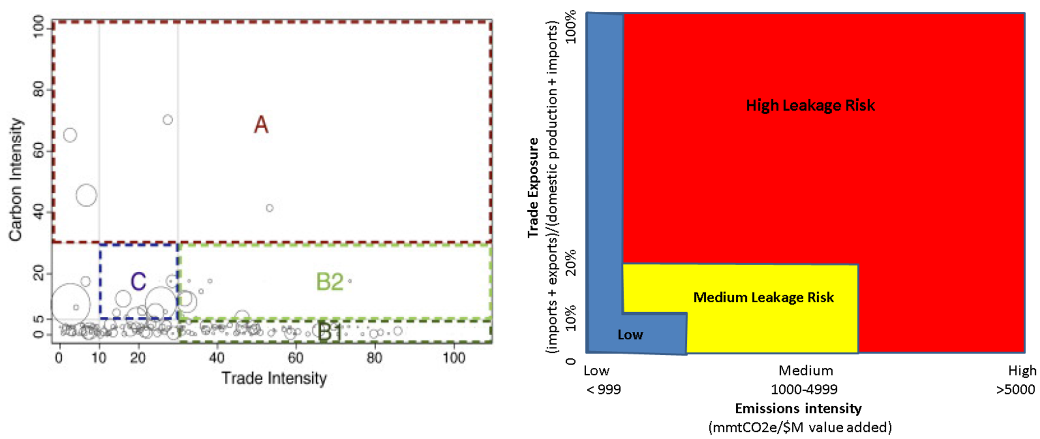


Figure E.2: Criteria used to assess industrial leakage risk

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

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

Figure E.3: Comparison of Direct and Embodied Emissions Intensities

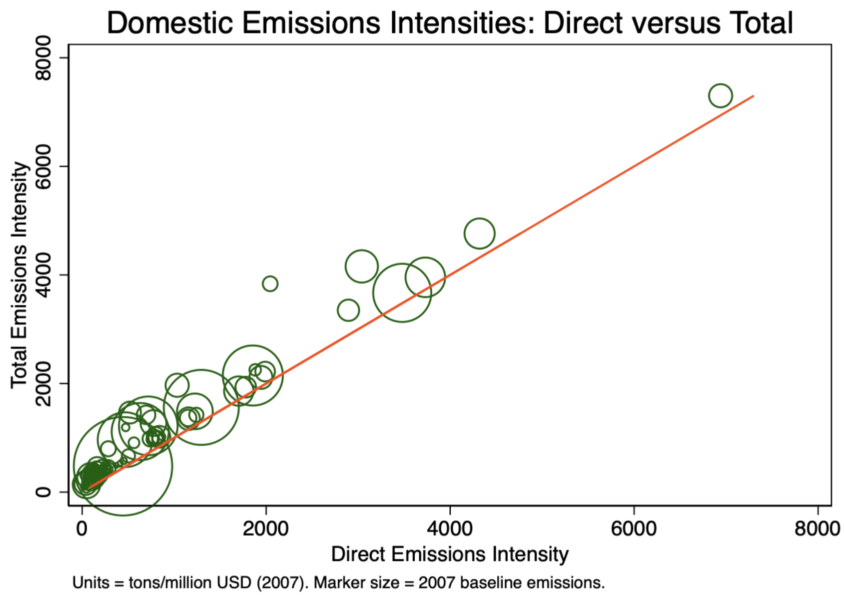
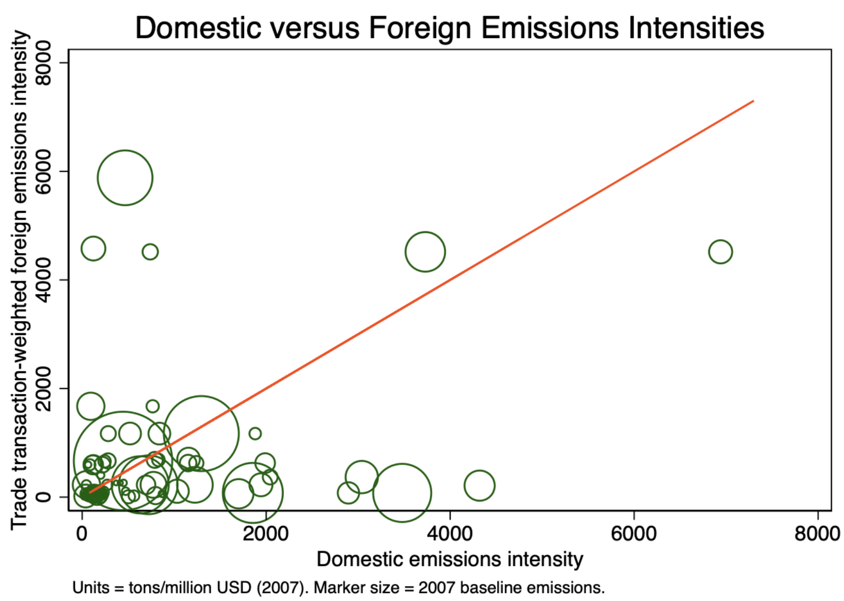


Figure E.4: Comparison of Domestic and Foreign Emissions Intensities



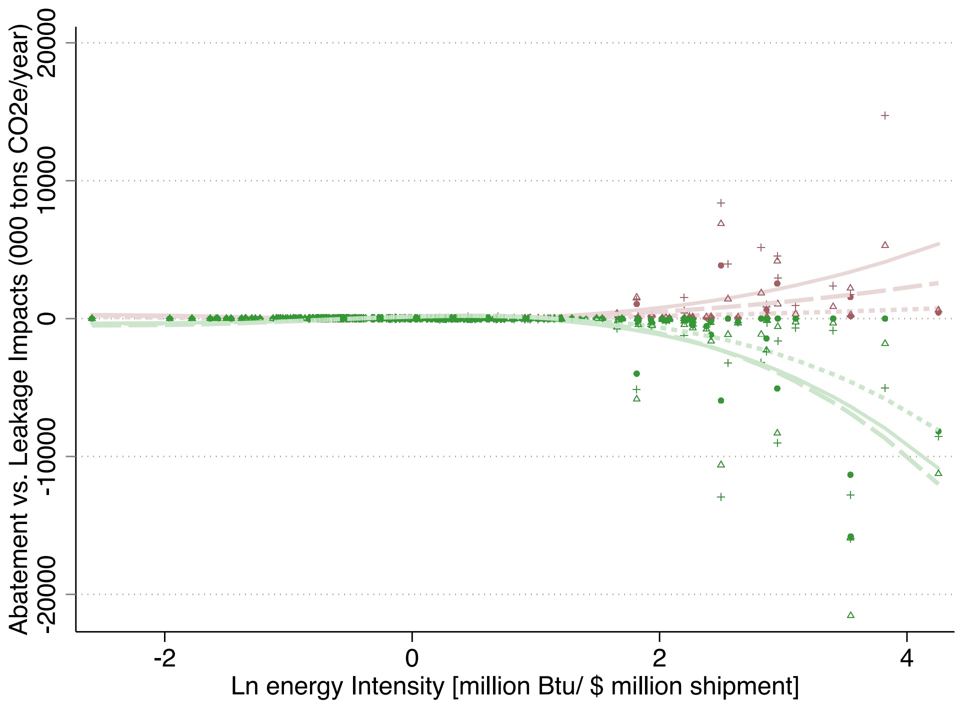


Figure E.5: Simulated Domestic Emissions Abatement and Emissions Leakage

This figure displays the simulated impacts of alternative CO_2 carbon pricing regimes on emissions reductions (green) and associated emissions leakage (red). Each marker corresponds to a NAICS6 industry/policy regime pair. The tax regime (assuming a tax of $25/ton) is associated with '+' markers and the solid lines. The tax regime combined with industry-specific leakage mitigating subsidies is associated with 'o' markers and the short-dashed lines. The cap-and-trade regime combined with the targeted subsidies is associated with 'Δ' markers and the long-dashed lines.