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Economics of Demand-Side and Supply-Side Climate Policies

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Abstract

Should a jurisdiction seeking to cut greenhouse gas emissions use demand-side climate policies that target fossil fuel consumption? Or should it introduce supply-side policies that target extraction? My analysis points to a policy portfolio rather than an either/or choice. "Leakage" of emissions to unregulated jurisdictions can be mitigated by combining standard demand-side carbon emissions pricing with supply-side pricing of carbon extraction. Emissions pricing drives leakage by lowering fossil fuel prices abroad; extraction pricing counteracts this effect. Supply-side climate policies in practice, however, do not broadly price extraction but instead narrowly foreclose investments in fossil fuel infrastructure and are thus inefficient. To reduce carbon demand, an alternative to emissions pricing is support for clean energy. I emphasize reforms to transmission planning and utility governance as crucial for unlocking clean energy resources' potential, and I highlight the case for publicly supporting clean energy R&D, including green industrial policy, to reduce carbon emissions not just at home but also abroad. I close by discussing distributional consequences. Domestically, carbon pricing and clean energy subsidies have sharply different distributional profiles. Globally, carbon extraction pricing would harm low-income countries that are also fossil fuel importers, though there also exist low-income fossil fuel exporters that would benefit.

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1 Introduction

Governments around the globe have made starkly different choices from the climate policy menu. The EU has operated the largest and most comprehensive carbon emissions pricing program in the world, with emissions trading system (ETS) prices exceeding EUR 60 per metric ton (tonne) nearly continuously since 2022.[1] In the U.S., the Biden administration did not implement carbon pricing but instead enacted a package of clean energy subsidies via the Inflation Reduction Act, and it administratively took steps to curtail fossil fuel development on public lands and to foreclose investments in oil and gas transportation infrastructure. Many of these steps have been rolled back by the second Trump administration and its allies in Congress. There is now a prominent debate on the U.S. left between advocates of "keep it in the ground" policies and an "abundance" movement that is enthused for climate policies that promote and facilitate clean energy.[2] Another example is China, which stands out for its use of clean energy subsidies as an industrial policy to become the global leader in the manufacture of solar photovoltaics (PV), batteries, and electric vehicles (EVs).

My goal in this paper is to summarize the economic tradeoffs between these climate policy instruments. I broadly categorize climate policies into *demand-side* and *supply-side* policies. Demand-side climate policies target reductions in the consumption of fossil fuels. They include carbon emissions pricing and energy efficiency programs, as well as subsidies and other support for clean energy that induce energy demand to substitute away from fossil fuels (clean energy policies may explicitly target clean energy *supply*, but from the perspective of the climate they serve to reduce the *demand* for carbon). Supply-side climate policies, on the other hand, target reductions in fossil fuel extraction. Supply-side policies, to the best of my knowledge, have not taken the form of broad carbon extraction pricing analogous to demand-side carbon emission pricing, but rather have been exemplified by policies such as prohibitions on the construction of fossil fuel transportation infrastructure.

I do not conclude with a bottom line that demand-side policies dominate supply-side policies or vice versa. Instead, different choices from the policy menu make tradeoffs across a variety of desiderata, and the economics suggests a portfolio of policies rather than a single tool. I organize my discussion around an analysis of these tradeoffs along four dimensions:

1. **Local versus global emissions reductions (section 3).** Carbon is a global, not local, pollutant. Consequently, a jurisdiction that aspires to reduce CO_2 emissions must grapple with the question "How will policies I enact at home affect emissions

[1] Historical EU ETS price data are available at `https://tradingeconomics.com/commodity/carbon`.

[2] Friedman and Plumer (2026) discusses recent shifts in U.S. Democrats' policy stances away from supply-side policies. The book *Abundance* (Klein and Thompson, 2025) advocates for achieving climate goals through clean energy abundance.

elsewhere?" A challenge is emissions "leakage", which occurs when domestic climate policies increase emissions abroad. While leakage through trade in energy-intensive goods has received most of the attention in policy-making and the academic literature, I emphasize that leakage can also occur through trade in fossil fuels. Coupling demand-side carbon emissions pricing with supply-side pricing of carbon extraction reduces this leakage by counteracting the reduction in energy prices abroad caused by emissions pricing. I show that carbon extraction pricing is especially valuable for jurisdictions like the U.S. that are major fossil fuel producers.

2. **Climate policies in practice (section 4).** Energy markets and climate policies often depart from textbook ideals. I highlight three departures that are especially important for the efficacy of demand-side and supply-side climate policies, with emphasis on the U.S. First, supply-side policies in practice often take the form of proscriptions on investments in fossil fuel infrastructure, such as pipelines and liquefied natural gas (LNG) export terminals. Because market actors can adapt to infrastructure restrictions by using other transportation modes or other fuels, these instruments are inefficient relative to broad carbon extraction pricing and can fail to significantly reduce emissions. Second, retail electricity tariffs involve variable charges (i.e., charges per kilowatt-hour (kWh) consumed) that in many parts of the country are substantially marked up relative to the social marginal cost of generation. These markups provide an argument for clean electricity subsidies as an efficient demand-side policy. Third, I discuss barriers to the development of long-distance transmission, which pose an obstacle to clean energy development and the efficacy of CO_2 emissions pricing and clean electricity subsidies. These barriers reflect not just local and federal permitting hurdles but also balkanized transmission planning processes and misaligned economic incentives on the part of electric utilities and incumbent generators. Process and governance reforms that overcome these barriers would increase the efficiency of electricity markets and reduce the demand for fossil fuels.

3. **Decarbonizing the world (section 5).** How might domestic climate policies not just avoid emissions leakage but actually stimulate emissions reductions abroad? I emphasize the value of clean energy technologies that can be deployed in growing low- and middle-income countries. I discuss public investments in research and development, and I consider industrial policies for stimulating private-sector innovation and technology deployment, drawing especially from studies of China's clean energy boom.

4. **Local and global distributional consequences (section 6).** The sections of the paper enumerated above focus on the efficiency properties of climate instruments; this

section focuses on their distributional consequences. Domestically, the differences in the incidence of demand-side versus supply-side climate policies are important in their own right, and in addition they speak to the political challenges of enacting and implementing one policy or another. Globally, the benefits of emissions mitigation will accrue primarily to the global poor. A country's choice of demand-side versus supply-side carbon pricing can work with or against this inequality reduction depending on the cross-country relationship between incomes and fossil fuel net imports.

The majority of the paper's analysis is synthesis from existing literature. Many of the above topics have been evaluated in recent research, though the lessons learned have not previously been unified. At several points, however, I introduce new facts and modeling. In section 3, I combine data on fossil fuel trade with data on trade in embodied carbon to show that direct carbon trade exceeds embodied carbon trade for most countries and for all large traders. This observation motivates a model in which emissions leakage occurs not just through trade in carbon-intensive goods but also through trade in fossil fuels and changes in their global price. The model I construct closely follows Weisbach, Kortum, Wang and Yao (2023), but with the addition of a clean energy sector and the possibility of subsidizing clean energy production as a tool to mitigate leakage. And in section 6, I combine country-level data on fossil fuel trade with estimates of climate damages to investigate the global distributional consequences of demand-side versus supply-side carbon pricing.

Finally, there are aspects of climate policy that are out of scope for this paper, and I leave them for others to discuss. I focus on the economic consequences of emission mitigation actions that might be taken unilaterally by a single jurisdiction or a coalition. The framework thus studies policy impacts taking other countries' climate policies as given, leaving out strategic interactions and international climate negotiations by which a given jurisdiction might influence other countries' policies. A prominent example is Nordhaus's (2015) idea for "climate clubs": coalitions of countries that encourage participation from others via the imposition of tariffs on imports from non-participants. This idea has motivated, in part, the EU's carbon border adjustment mechanism (CBAM) that taxes the carbon content of imports from countries that have not imposed their own carbon pricing, and it is also related to the Open Coalition on Compliance Carbon Markets that was recently launched by Brazil, China, and the EU. See Campolmi, Fadinger, Forlati, Stillger and Wagner (2025), Clausing, Colmer, Hsiao and Wolfram (2026), and Ferguson, Staiger and Yurukoglu (2026) for recent theoretical and quantitative work on this topic. I also do not discuss domestic climate politics and coalition-building, though the distributional analysis in section 6 is an input into these considerations. Finally, the paper focuses on CO_2 emissions mitigation. I do not discuss climate adaptation policies, nor policies regarding geoengineering or carbon sequestration.

2 Basic model for demand and supply-side policies

Before presenting the open-economy model of section 3, it is useful to set a baseline via a standard "Pigouvian" model in which the economy has no pre-existing distortions other than the externality from carbon emissions. Consider an economy that exists in autarky, such that there is no scope for leakage of emissions via trade. (This model can also be applied to the case of a unified global climate policy.) As has been taught to innumerable students in environmental economics, the surplus-maximizing policy in this idealized scenario is a carbon tax that is equal to the social cost of carbon (SCC). Moreover, outcomes are equivalent whether the tax is demand-side or supply-side; i.e., whether it is levied on the use or extraction of fossil fuels, or on any combination of those taxes that sums to the SCC.

To formalize this intuition, let Q_F and Q_C denote the quantities of fossil and clean energy produced in the economy. Assume that fossil and clean energy are perfectly substitutable, so that total energy consumption can be denoted $C_e = Q_F + Q_C$.[3]

Let $c_F(Q_F)$ and $c_C(Q_C)$ denote the costs of producing the quantities Q_F and Q_C, with strictly positive and increasing marginal costs: $c'_F(Q_F) > 0$, $c'_C(Q_C) > 0$, $c''_F(Q_F) > 0$, and $c''_C(Q_C) > 0$. All energy is supplied competitively. Let $U(C_e)$ denote consumers' money-denominated value of consuming energy, with $U'(C_e) > 0$ and $U''(C_e) < 0$.[4]

Climate policy is designed by a utilitarian social planner who has an SCC denoted by ϕ. I am agnostic as to how ϕ is determined; it could reflect an estimate of damages within just the jurisdiction setting the policy, an estimate of global damages, or some value in between. The planner has the following policy instruments to choose from (individually or in combination):

- A tax on the use of fossil energy, t_u, which is paid by fossil energy consumers. (The use tax is synonymous with a carbon emissions tax.)
- A tax on the extraction of fossil energy, t_e, which is paid by fossil energy producers.
- A subsidy for the production of clean energy, s_c, which is paid to clean energy producers.[5]

[3] The assumption of perfect substitutability is strong but useful, as it allows the model to nest the models of Weisbach et al. (2023) and Kay (2025). To the extent that clean energy is not fully substitutable for fossil fuel (for instance, there may be barriers to transmission, as discussed in section 4.3), the value of the clean energy subsidy will be diminished relative to the results in section 3. Different fossil fuels may also be imperfect substitutes for one another, at least in the short run, which would attenuate the leakage mechanism discussed in section 3.1.1.

[4] See appendix A for the characterization of $U(C_e)$, by way of a more complete model, per Weisbach et al. (2023), with a fixed factor input L (labor) and a numeraire good z that requires a single unit of L to produce.

[5] I do not distinguish between a subsidy on the production versus the use of clean energy, since in the

The taxes together create a wedge between the marginal value and cost of fossil energy: $U' - c'_F = t_u + t_e$. And the clean subsidy creates a wedge for clean energy in the opposite direction: $c'_C - U' = s_c$.

Let $\mathcal{T}$ denote the set of instruments $\{t_u, t_e, s_c\}$, and let $Q_F(\mathcal{T})$ and $Q_C(\mathcal{T})$ denote the fossil and clean energy quantities supplied in the competitive equilibrium given $\mathcal{T}$. The utilitarian planner's problem is as follows:

$$\max_{t_u,t_e,s_c} U(Q_F(\mathcal{T}) + Q_C(\mathcal{T})) - c_F(Q_F(\mathcal{T})) - c_C(Q_C(\mathcal{T})) - \phi Q_F(\mathcal{T}). \tag{1}$$

As shown in appendix A, the solution to this problem is achieved when the wedge between the marginal value and marginal cost of fossil energy, $U' - c'_F$, equals the SCC ϕ, and there is no corresponding wedge for clean energy: $U' - c'_C = 0$. These conditions are satisfied by setting $t_u + t_e = \phi$ and $s_c = 0$. Thus, the model produces the Pigouvian result that a carbon tax equal to the SCC maximizes total surplus, and it does not matter if the statutory incidence of the tax is on use or extraction (or spread across both). This result is an instance of the broader fact that, in general, the economic effects and incidence of a tax do not depend on its statutory incidence.

Clean energy subsidies are zero in this idealized model because they are an inefficient means to reduce carbon, since they induce over-consumption of clean energy.[6] As summarized in Sallee (2025), clean energy subsidies typically also suffer from additional inefficiencies that are not captured in the above framework: they may not generate substitution away from the most carbon-intensive energy sources, and their financing requires tax revenues to be raised, which distorts other markets.

3 Unilateral demand and supply-side policies in an open economy

This section considers how a single jurisdiction, or a coalition such as the EU, might choose among demand-side and supply-side policies while taking seriously the fact that climate change is a global problem. I build on the simple model from section 2 by considering how carbon taxes imposed by one country or coalition — labeled "Home" in the model below

trade model below I assume that clean energy is not traded, so that the statutory incidence of the clean subsidy does not matter.

[6] For a similar reason, intensity standards that regulate emissions as a share of economic output (for instance, renewable portfolio standards) are also inefficient in this framework. As discussed in Holland, Hughes and Knittel (2009), intensity standards combine an implicit tax on carbon emissions with an implicit subsidy for emission-free output.

— might increase emissions elsewhere, a phenomenon broadly known as "leakage". Leakage occurs through trade in energy-intensive goods and trade in fossil fuel itself. In an open economy model, demand-side and supply-side carbon pricing are no longer equivalent for Home because they move global fuel prices in opposite directions. The upshot will be that combining both types of pricing mitigates leakage from trade in fuel, and that clean energy subsidies help mitigate leakage from trade in energy-intensive goods.

The model I present below is a synthesis of ideas from three literatures. First, there is a large literature on how adding an output subsidy to a carbon use tax can mitigate emissions leakage that occurs through trade in energy-intensive goods. This idea dates to Fischer (2001) and Bernard, Fischer and Fox (2007), and it follows the intuition that subsidizing Home's output, while normally inefficient, has value in the presence of leakage because it attenuates the increase in Home's net imports induced by the carbon use tax. Here, a clean energy subsidy plays a role similar to that of an output subsidy.

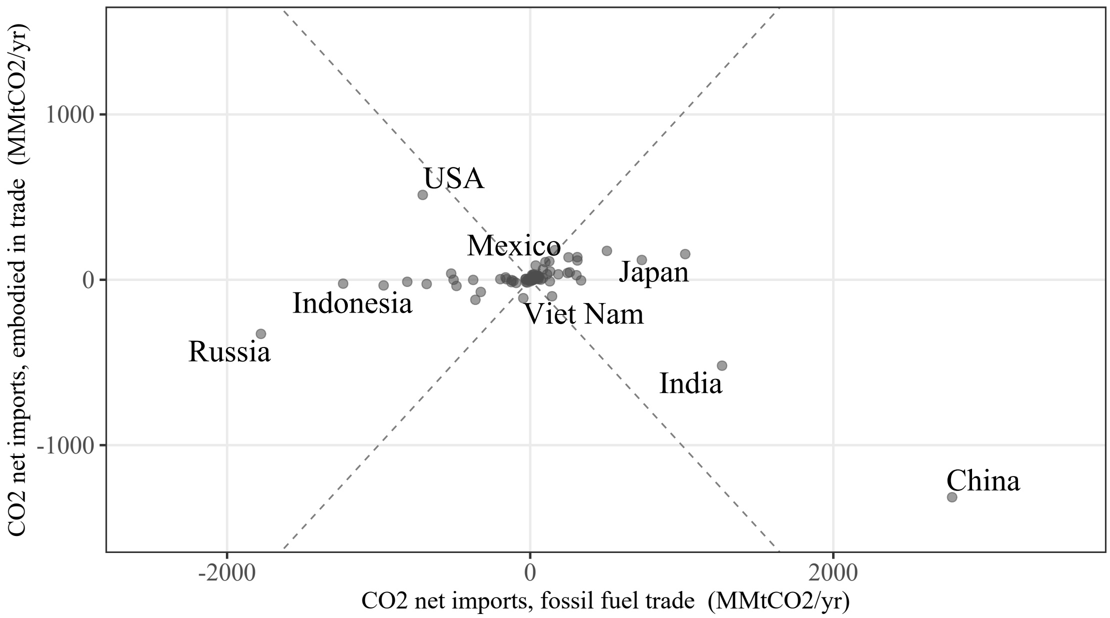
Second, I draw upon two recent papers (Kotchen and Maggi, 2024; Kay, 2025) that model the combination of a tax on fossil energy extraction with a clean energy subsidy, in an environment in which direct trade in fossil energy can lead to leakage from the tax alone.[7] In these models, the clean energy subsidy reduces leakage by attenuating the increase in energy prices induced by the extraction tax.

The model I ultimately adopt is closest to a third literature that considers carbon use and extraction taxes when there is direct trade in fossil energy, along with trade in energy-intensive goods (Weisbach et al., 2023; Garcia-Lembergman, Ramondo, Rodríguez-Clare and Shapiro, 2025; Kortum and Weisbach, 2026). The core result from these papers is that by combining both types of taxes, a jurisdiction can manipulate the price of fossil energy abroad, thereby reducing emissions leakage from unilateral climate policy. I primarily follow Weisbach et al. (2023), which itself is a simplified version of the model in Kortum and Weisbach (2026). I extend that model by including a clean energy sector and the possibility of subsidizing clean energy production as a tool to mitigate leakage, per the intuition from the other two literatures.

The essential feature of the model is its emphasis on emissions leakage via global trade in fossil energy, not just trade in energy-intensive goods. This emphasis is motivated by the large volume of global fossil fuel trade. Figure 1 presents a scatter plot of country-level direct net imports of CO_2 via fossil fuel trade, versus indirect net imports of CO_2 via embodied carbon in trade in goods. This figure shows that for most countries, and for all "large"

[7] Kay (2025) presents its model as a model of trade in goods with a tax on the use of fossil fuels in producing goods, but the nature of the model (with perfect substitutability of energy-intensive goods produced at home vs. abroad) is such that it is equivalent to direct trade in fossil energy itself, with a tax on fossil fuel extraction.

Figure 1: Country-level direct net imports of CO_2 via fossil fuel trade versus indirect net imports of CO_2 via embodied carbon in trade in goods



Note: Dashed lines denote equality between direct and indirect net imports, in absolute value. Direct net imports of CO_2 are computed as the carbon content of fossil fuel net imports, using data from U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b). Indirect net imports of CO_2 are computed as net imports of embodied carbon from an updated version of Peters, Minx, Weber and Edenhofer (2011), courtesy of the Global Carbon Budget. See section 3.2 for a discussion of the data, and see appendix B for additional details.

traders, direct trade exceeds indirect trade in magnitude. This fact suggests that changes in international movements of fossil fuels may play a prominent role in emissions leakage from unilateral climate policies, and that models and policies that focus only on trade in energy-intensive goods may be missing an important mechanism for leakage.

Subsection 3.1 presents the model and analytic results for the surplus-maximizing combination of policies. Then in subsections 3.2 and 3.3 I calibrate the model to the U.S. and EU, quantifying the policies' magnitudes and their implications for emission reduction.

3.1 Model

3.1.1 Trade in fossil energy but no trade in energy-intensive goods

The model is the same as that in Weisbach et al. (2023), but with the inclusion of a clean energy sector and the possibility of subsidizing clean energy production. I present here the setup of the model and its main results; see appendix A for a more detailed description of the model and all derivations.

There are two regions: "Home", which is implementing climate policy, and the "rest of world" (ROW), which is not. Like Weisbach et al. (2023), I build intuition by beginning with a model in which fossil energy is traded between Home and ROW, but energy-intensive goods are not. Throughout, I restrict direct trade in clean energy to zero, since such trade is small in practice (most clean energy is in the form of clean electricity, which requires long-distance transmission infrastructure to enable trade).[8]

The energy quantities and the utility and cost functions for Home are denoted as in section 2 above: $U(C_e)$, $c_F(Q_F)$, and $c_C(Q_C)$. I denote the corresponding variables and functions for ROW with a superscript R.

Let P denote the ROW price of fossil energy. Home's tax instruments now create the wedges $t_u = U' - P$, $t_e = P - c'_F$, and $s_c = c'_C - U'$ (so that $c'_C = P + s_c + t_u$). Home's marginal utility function then implies the energy demand function $D_e(P+t_u) = U'^{-1}(P+t_u)$. Similarly, its marginal cost functions imply the fossil and clean energy supply functions $S_F(P - t_e) = c'^{-1}_F(P - t_e)$ and $S_C(P + s_c + t_u) = c'^{-1}_C(P + s_c + t_u)$. ROW's corresponding demand and supply functions are denoted with a superscript R and depend on P but not on Home's policy instruments. Demand for fossil energy is energy demand net of clean energy supply; i.e., $D_e(P + t_u) - S_C(P + s_c + t_u)$ for Home and $D^R_e(P) - S^R_C(P)$ for ROW.

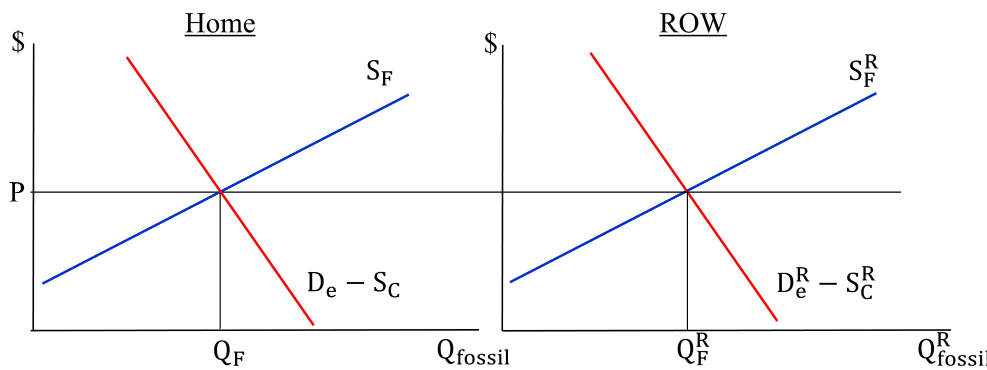
Leakage arises in this model because Home's use and extraction taxes change the world price P of fossil energy, which in turn affects ROW's fossil energy consumption and production. The use and extraction taxes have opposite effects on P, leading them to yield different allocations, unlike the case from section 2 in which the taxes were equivalent.

Figure 2 illustrates the mechanics of this leakage in a symmetric model in which Home and ROW have identical supply and demand for fossil energy, up to a scaling factor. Panel (a) illustrates the baseline situation in which there is no climate policy, and fossil supply and demand meet at the same P in both markets, so that there is no trade in equilibrium. Panel (b) illustrates the effects of a carbon use tax in Home. The tax reduces Home's consumption of fossil energy and lowers the world price P of fossil energy (if it didn't, then Home would have excess supply). This price reduction induces ROW to increase its fossil energy consumption, resulting in leakage via exports of fossil energy from Home to ROW. Panel (c) illustrates a carbon extraction tax in Home, which has the opposite effect. The extraction tax reduces Home's fossil energy quantity supplied, which raises the world price

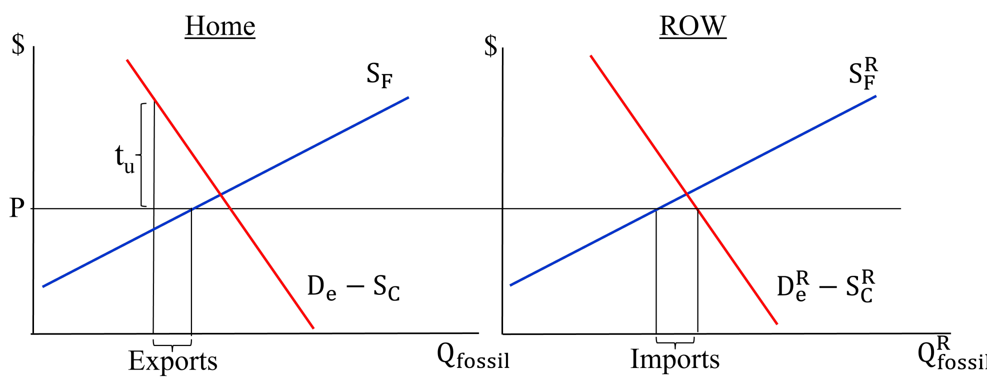
[8] Hong (2026) observes that even though clean energy itself is generally not traded, clean energy equipment, e.g., wind turbines and solar PV panels, is traded. This observation leads to the insight that subsidizing clean energy equipment manufacturing can encourage additional clean energy production abroad by lowering equipment prices globally. In contrast, subsidizing clean energy production can have the opposite effect by raising equipment prices. I abstract from this distinction in this paper's model.

Figure 2: Illustration of leakage from unilateral carbon use or extraction taxes when used in isolation

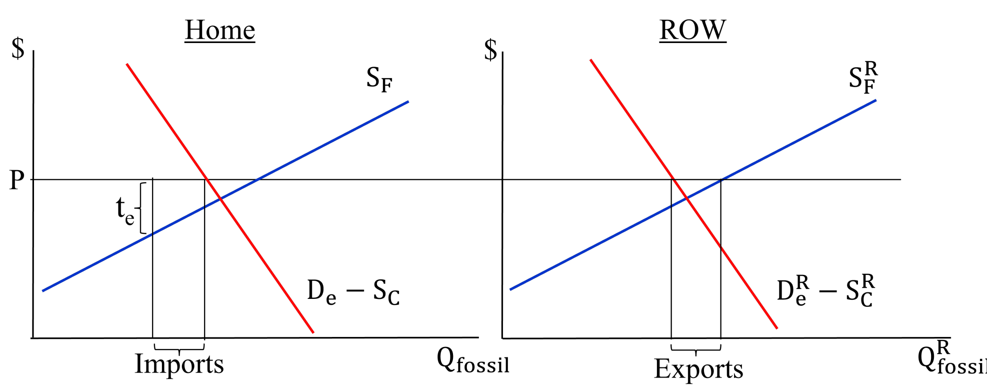
(a) No taxes



(b) Use tax only



(c) Extraction tax only



Note: Figure corresponds to a model with no trade in energy-intensive goods, and at baseline (no taxes) Home's and ROW's fossil energy demand and supply functions are identical, up to a scaling factor, so that in equilibrium trade in fossil energy is zero. A carbon use tax in Home leads to leakage via fossil energy exports to ROW, and a carbon extraction tax in Home leads to leakage via fossil energy imports from ROW.

of fossil energy. This price increase also leads to leakage, in this case by inducing ROW to increase its extraction of fossil energy and export its surplus to Home.

Because carbon is a global pollutant, Home must account for these leakage mechanisms when designing its carbon policy. Its objective function therefore includes emissions from Home and ROW, both weighted by the SCC ϕ. In modeling Home's objective, I also follow Weisbach et al. (2023) in ignoring terms-of-trade effects, which on their own would provide an incentive for Home to tax carbon extraction if it were a net fossil energy exporter, and to tax carbon use if it were a net importer. Formally, ignoring terms-of-trade effects amounts to including ROW's benefits and costs in Home's objective function.

Home's problem can then be formally expressed as the following constrained maximization problem, where again $\mathcal{T}$ denotes the set of instruments $\{t_u, t_e, s_c\}$:

$$\begin{aligned}
\max_{t_u,t_e,s_c} & U(C_e(\mathcal{T})) - c_F(Q_F(\mathcal{T})) - c_C(Q_C(\mathcal{T})) \\
& + U^R(C_e^R(\mathcal{T})) - c_F^R(Q_F^R(\mathcal{T})) - c_C^R(Q_C^R(\mathcal{T})) \\
& - \phi(Q_F(\mathcal{T}) + Q_F^R(\mathcal{T})), \\
\text{subject to } & Q_F + Q_C + Q_F^R + Q_C^R = C_e + C_e^R. \qquad (2)
\end{aligned}$$

In appendix A, I show that this problem is solved by the following combination of policies:

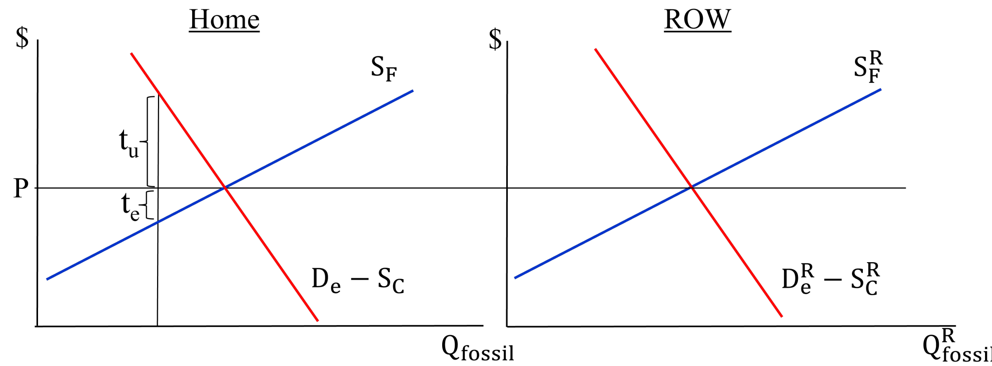
$$\begin{aligned}
t_u^* &= \phi \frac{S_F^{R'}}{S_F^{R'} + S_C^{R'} - D_e^{R'}} \\
t_e^* &= \phi \frac{S_C^{R'} - D_e^{R'}}{S_F^{R'} + S_C^{R'} - D_e^{R'}} \\
s_c^* &= 0, \qquad (3)
\end{aligned}$$

where $S_F^{R'} > 0$, $S_C^{R'} > 0$, and $D_e^{R'} < 0$ are the slopes of ROW's fossil energy supply, clean energy supply, and energy demand functions, respectively, at the equilibrium quantities.

To interpret these expressions, first observe that the optimal use and extraction taxes sum to the SCC ϕ, so that the total carbon tax is Pigouvian. Crucially, the surplus-maximizing policy uses both taxes, not just the demand-side use tax t_u or supply-side extraction tax t_e in isolation.[9] The surplus-maximizing combination of taxes is illustrated in figure 3, for the same situation from figure 2 in which fossil supply and demand in ROW are proportional to fossil supply and demand in Home. In this case, the surplus-maximizing tax combination leaves the world price P of fossil energy unchanged and results in zero leakage, even as

[9] Also, the extraction tax is not rebated at the border for fossil fuels that are exported from Home. Such a rebate would effectively transform the extraction tax into a use tax.

Figure 3: Illustration of the surplus-maximizing unilateral combination of carbon use and extraction taxes



Note: Figure corresponds to a model with no trade in energy-intensive goods, and at baseline (no taxes) Home's and ROW's fossil energy demand and supply functions are identical, up to a scaling factor, so that in equilibrium trade in fossil energy is zero. The surplus-maximizing combination of carbon use and extraction taxes leaves the world price P of fossil energy unchanged and results in zero leakage. In the figure, this combination involves a larger use tax t_u than extraction tax t_e, since ROW's fossil energy supply is more price-sensitive than its fossil energy demand.

emissions in Home are reduced. In essence, the decrease in P induced by the demand-side tax is balanced out by the increase in P induced by the supply-side tax. More generally — i.e., when Home and ROW are not symmetric such that Home is either a net exporter or importer in the pre-policy baseline — Home's optimal tax combination will typically change the world price P to effectively manipulate ROW's emissions, potentially resulting in negative leakage.[10]

The relative weights on t_u versus t_e are functions of the slope of ROW's fossil energy supply, $S_F^{R'}$, relative to the slope of ROW's demand for fossil energy, equal to $S_C^{R'} - D_e^{R'}$ in absolute value. t_u is large when $S_F^{R'}$ is large relative to $S_C^{R'} - D_e^{R'}$ (as is the case in figure 3), since in this case the decrease in P caused by t_u does not greatly increase ROW's fossil energy demanded, whereas an increase in P caused by t_e would greatly increase ROW's fossil energy supplied.

The surplus-maximizing clean energy subsidy s_c^* is zero, contrasting with results in Kotchen and Maggi (2024) and Kay (2025) that clean subsidies can efficiently mitigate emissions leakage that results from the imposition of a carbon extraction tax. The difference in results stems from this paper's inclusion of a carbon use tax t_u as a policy instrument.[11]

[10]For instance, if Home is a fossil energy exporter and $S_F^{R'}$ is small in magnitude, Home's optimal tax combination will weight toward the extraction tax t_e, raising ROW's energy price P and decreasing ROW's fossil energy consumption without substantially increasing its fossil energy extraction.

[11]If I force $t_u = 0$ and re-optimize t_e and s_c, I find expressions that match those in Kay (2025), including the feature that $t_e^* + s_c^* = \phi$. See the derivation in appendix A.3.

Both the use tax and the clean subsidy reduce the ROW energy price P, but the clean subsidy does so inefficiently, since it leads to over-consumption of clean energy in Home.

Still, clean energy plays a role in determining the surplus-maximizing t_e and t_u, since its presence increases the price sensitivity $S_C^{R'} - D_e^{R'}$ of ROW's fossil energy demand, weighting the policy more toward the extraction tax. This effect is an addition to the analysis of extraction and use taxes in Weisbach et al. (2023), which otherwise finds the same expressions as equation (3), but without the $S_C^{R'}$ terms.

3.1.2 Trade in fossil energy and energy-intensive goods

I next extend the analysis to incorporate trade in energy-intensive goods. This trade opens an additional channel for leakage: when Home imposes a carbon use tax t_u, its producers of tradeable goods must pay a higher price for energy inputs than producers in ROW, leading to a comparative disadvantage and an increase in net imports of energy-intensive goods.

In this model, C_e continues to denote Home's consumption of energy, but that energy is now used both to produce domestically consumed goods and services and to produce goods and services that are exported to ROW. Likewise, C_e^R denotes ROW's consumption of energy, including energy used to produce goods and services that are exported to Home. It is now important to distinguish how C_e and C_e^R respond to changes in the price of energy P, which I continue to denote by the demand slopes D_e' and $D_e^{R'}$, versus how they respond to changes in Home's fossil energy use tax t_u, which I denote by the derivatives $\partial C_e/\partial t_u$ and $\partial C_e^R/\partial t_u$. Holding P fixed, an increase in t_u will decrease C_e but increase C_e^R. The magnitudes of these responses depend on the substitutability of Home's and ROW's products and on tradeable goods' returns to scale in production. These factors together determine the leakage rate Λ, which describes the extent to which reductions in Home's energy consumption induced by the use tax are offset by increases in ROW's production of energy-intensive goods, holding P constant:

$$\Lambda = -\frac{\partial C_e^R/\partial t_u}{\partial C_e/\partial t_u} \in [0,1]. \tag{4}$$

The surplus-maximizing policies are now:

$$\begin{aligned} t_u^* &= \phi \frac{(1-\Lambda)S_F^{R'}}{S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda D_e'} \\ t_e^* &= \phi \frac{S_C^{R'} - D_e^{R'} - \Lambda D_e'}{S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda D_e'} \\ s_c^* &= \phi \frac{\Lambda S_F^{R'}}{S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda D_e'}. \end{aligned} \tag{5}$$

As was the case for equation (3) without trade in goods, the above expressions are the same as those in Weisbach et al. (2023) when clean energy supply is excluded from the model (so that the $S_C^{R'}$ terms disappear and there is no clean subsidy).

First, observe that the surplus-maximizing use tax is lower in equation (5) than in equation (3), since $\Lambda > 0$ and $D_e^{'} < 0$. Intuitively, since the use tax induces an increase in net imports of energy-intensive goods from ROW, the optimal use tax must fall. Second, and in contrast, the supply-side tax t_e^* is higher in equation (5) than in equation (3). This shift occurs because the extraction tax does not lead to a comparative disadvantage in energy-intensive goods production, since it increases the price of energy for all goods producers globally, not just those in Home. Finally, the surplus-maximizing clean energy subsidy s_c^* is now strictly positive, since it offsets the comparative disadvantage that results from the use tax t_u^*. The intuition is the same as that for using output subsidies to mitigate leakage from carbon use taxes, as originally developed in Fischer (2001) and Bernard et al. (2007). The magnitude of s_c^* increases with the leakage rate Λ. Altogether, the sum of the use tax, extraction tax, and clean subsidy equals the SCC ϕ.

The quantitative analysis will also consider a scenario in which Home is able to implement an ideal border tax adjustment (BTA) that taxes the carbon content of imported goods at the rate t_u and rebates the tax for carbon-intensive goods that are exported.[12] This BTA transforms the use tax from a tax on producing carbon-intensive goods to a tax on consuming carbon-intensive goods, and it reduces leakage through trade in energy-intensive goods to zero. This BTA leads to surplus-maximizing policies given by the expressions in (5), but with $\Lambda = 0$ so that they are the same as those in (3). Thus, the optimal use tax is higher, the optimal extraction tax is lower, and the optimal clean energy subsidy is zero. I describe this BTA as "ideal" because in practice BTAs face implementation challenges related to emissions measurement, the scope of goods and countries covered, and reshuffling among exporters, as discussed in Kortum and Weisbach (2017), Fowlie, Petersen and Reguant (2021), Campolmi et al. (2025), and Nehrkorn and Elkerbout (2026).

3.2 Calibration

What are the magnitudes of the surplus-maximizing taxes and subsidies implied by the model? This section numerically calibrates the model for two potential identities for the "Home" country: the U.S. and the EU. I summarize the calibration here; see appendix B for a more detailed discussion of my procedure and the data sources used.

[12]Weisbach et al. (2023) and Kortum and Weisbach (2026) point out that to maximize surplus, the carbon use tax should not be fully rebated for goods that are exported, since a reduction in Home's carbon-intensive exports will not be fully offset by an increase in ROW production of carbon-intensive goods.

I use 2023 as the base year for the calibration. I use U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b) for data on country-level primary energy production and consumption, covering all fossil and clean energy sources. The primary energy associated with thermal energy sources — all fossil energy, as well as nuclear and biomass energy — is measured in the data as the energy content of the fuel, while primary energy from geothermal, hydroelectric, solar, and wind energy is measured as the electricity generated by those sources. The conversion of thermal energy to electricity typically loses roughly two-thirds of the energy content of the fuel, so that the primary energy associated with clean energy sources is under-measured relative to that of thermal energy sources.[13] To address this issue, I convert clean energy measured as electricity output to fuel-equivalent primary energy using a conversion factor of 2.96, which is the average inverse thermal efficiency of U.S. fossil electric generators in 2023 (U.S. Energy Information Administration, 2025b).

I use a baseline global fossil fuel price of $10.75 per million British thermal units (mmBtu), based on the global consumption-weighted average of 2023 coal, oil, and natural gas prices. For 2023 country-level imports and exports of carbon embodied in trade in goods, I use data from an updated version of Peters et al. (2011), courtesy of the Global Carbon Budget.[14]

The energy production, consumption, and trade data are summarized in table 1. The U.S. extracts a much larger quantity of fossil fuels than does the EU, both in an absolute sense and relative to the quantity of energy consumed. The U.S. directly exported 9.0 quadrillion Btu (QBtu) of energy in 2023, while the EU's direct energy imports were 32.6 QBtu. Both the U.S. and EU were net importers of embodied carbon.

For the long-run elasticity of global energy demand, I use a value of -0.61, which is the average long-run estimate in Labandeira, Labeaga and López-Otero's (2017) meta-analysis. I do not know of a comparable meta-analysis for the long-run elasticity of energy supply. The energy supply literature has largely focused on crude oil and finds long-run oil supply elasticities ranging from 0.51 to 1.32 (Krupnick, Morgenstern, Balke, Brown, Herrera and Mohan, 2017; Balke and Brown, 2018; Anderson, Kellogg and Salant, 2018; Newell and Prest, 2019; Prest, 2022; Covert and Kellogg, forthcoming). For natural gas, estimates range from 0.24 to 0.81 (Hausman and Kellogg, 2015; Newell, Prest and Vissing, 2016; Prest, 2022; Abuin, 2025), and for coal, the one estimate I was able to find is 0.77 (Abuin, 2025). I adopt a value of 0.75 for the elasticity of fossil energy supply, but given the uncertainty in

[13] Waste heat from thermal energy conversion is perhaps best illustrated in a Sankey diagram that describes how primary energy sources are converted to final energy use, broken out by useful energy services versus rejected energy (waste heat). See `https://flowcharts.llnl.gov/sites/flowcharts/files/2024-12/energy-2023-united-states.png`.

[14] See `https://globalcarbonbudget.org/gcb-2025/`.

Table 1: Energy production, use, and embodied trade in 2023, in QBtu/year

	US	EU	ROW
Fossil energy production (Q_F)	86.1	5.6	434.8
Clean energy production (Q_C)	23.0	22.7	107.3
Energy use (C_e)	100.1	61.0	518.3
Net direct imports of energy ($C_e - Q_F - Q_C$)	-9.0	32.6	-23.7
Net imports of embodied fossil energy	6.8	10.9	-17.7

Notes: QBtu = quadrillion Btu. Net imports of embodied fossil energy are computed as net imports of embodied carbon from Peters et al. (2011), divided by the average carbon intensity of global fossil energy consumption, which is 0.075 gigatonnes CO_2 per QBtu in 2023.

the literature, I test 1.50 as a sensitivity.[15] I also use 0.75 for the elasticity of clean energy supply.[16]

For the leakage rate Λ, I use 0.10 for the U.S. and 0.20 for the EU.[17] These values lie roughly in the center of estimates from the literature.[18] Fowlie and Reguant (2022) and Misch and Wingender (2024) estimate how embodied energy use, imports, and exports respond to shocks to local versus global energy prices. Paroussos, Fragkos, Capros and Fragkiadakis (2015), Böhringer, Bye, Fæhn and Rosendahl (2017), Böhringer, Fischer and Rivers (2026), and Kortum and Weisbach (2026) instead compute leakage rates using a computable general equilibrium model. The higher leakage rate for the EU is a consequence of the EU's higher trade intensity; i.e., its imports plus exports relative to its domestic production (Böhringer et al., 2026).

[15]Other papers use estimates based on detailed supply models used by government agencies for forecasting purposes: Kotchen (2021) uses elasticities of 1.8 for coal and 1.6 for natural gas, based on U.S. Energy Information Administration (2023), and Prest (2022) uses elasticities of 0.4 and 0.5 for non-U.S. oil and gas production, respectively, based on International Energy Agency (2019). Finally, Kortum and Weisbach (2026) and Garcia-Lembergman et al. (2025) estimate elasticities ranging from 0.5 to 3.1 by fitting curves to assessments of resource-specific supply costs. This approach assumes that resources are extracted in order of increasing cost and that costs within a resource are constant with respect to the extraction rate, contrary to evidence (Kellogg, forthcoming).

[16]I am not aware of any papers that directly estimate the global elasticity of clean energy supply. Abuin (2025) simulates the response of natural gas prices and renewable energy generation to a large increase in U.S. LNG exports; that paper's counterfactual simulations imply a long-run clean energy supply elasticity of 1.58 for the U.S. and 0.47 for the rest of the world.

[17]I treat Λ as constant. In a richer model, Λ would be micro-founded on substitution (Armington) elasticities and firms' production functions, as in Weisbach et al. (2023), Garcia-Lembergman et al. (2025), and Kortum and Weisbach (2026). In that case, Λ would generally vary with the types and stringency of the policies adopted. The quantitative results presented in section 3.3 below can be interpreted as second-order Taylor approximations to what would be obtained from such a richer model.

[18]For various reasons, each of the papers cited here estimates an object that is greater than this paper's Λ. See the discussion in appendix B.

3.3 Quantitative results

The top row of table 2 presents the calibrated model's surplus-maximizing policies and the resulting emissions reductions. I use an SCC of $\phi = \$50$/tonne; all values in the table scale proportionally to the chosen SCC given the linearity assumptions in the model.

As required, the sum of the carbon taxes with the clean energy subsidy equals the SCC. When the U.S. is "Home", its surplus-maximizing carbon extraction and use taxes are \$29 and \$19/tonne, respectively. The extraction tax is larger than the use tax, even though the elasticity of fossil energy supply is greater than the elasticity of energy demand in magnitude, since the presence of clean energy supply and leakage through trade in goods tilts the policy mix toward the extraction tax. The optimal clean energy subsidy is \$2/tonne. This small magnitude reflects the fact that clean energy subsidies in this model are inefficient as demand-side climate policy because they induce over-consumption of energy. They increase total surplus only to the extent that they mitigate leakage from trade in energy-intensive goods, and the leakage rate Λ for the U.S. is relatively low at 0.10. Overall, the policy combination reduces global emissions by 0.88 gigatonnes of CO_2 ($GtCO_2$) per year.

The surplus-maximizing policy combination for the EU is similar to that for the U.S., tilted more toward the clean subsidy due to the EU's higher leakage rate Λ. Even though the EU has little fossil fuel extraction, the majority of the policy weight falls on the extraction tax, as was the case for the U.S., since the surplus-maximizing tax rates are primarily functions of foreign supply and demand price sensitivities, not domestic sensitivities. The EU's surplus-maximizing policies reduce global emissions by 0.24 $GtCO_2$ per year. This reduction is smaller than that achieved by the U.S. because of the EU's lower level of energy consumption and its much smaller rate of fossil energy extraction.

The next three rows of table 2 show surplus-maximizing policies and emissions reductions when only two of the three instruments are used. In each row, the remaining two instruments are re-optimized to maximize total surplus; see appendix A.3 for analytic derivations.[19] In both the U.S. and the EU, removing the clean subsidy has only a limited impact on emissions reductions, as expected given the subsidies' small magnitudes. For the U.S., removing the extraction tax has a larger impact than removing the use tax, while the opposite is true for the EU. This difference arises because the U.S. is a major fossil energy producer and exporter, while the EU has little extraction of its own.

Because the model's demand and supply functions are affine, and because the leakage rate Λ is constant, increase in total economic surplus induced by each policy combination

[19] Appendix A.4 further derives policies when only one instrument is used, for reference. In each case, the surplus-maximizing policy stringency falls short of the SCC ϕ due to leakage, and also to over-consumption in the case of the clean subsidy.

Table 2: Surplus-maximizing policy combinations and global emissions reductions

	US as "Home"				EU as "Home"			
	t_u	t_e	s_c	ΔE	t_u	t_e	s_c	ΔE
Without border tax adjustment:								
All three instruments:	\$19	\$29	\$2	-0.88Gt	\$18	\$28	\$4	-0.24Gt
No clean subsidy:	\$19	\$29		-0.88Gt	\$19	\$28		-0.23Gt
No extraction tax:	\$21		\$2	-0.35Gt	\$18		\$5	-0.21Gt
No use tax:		\$30	\$20	-0.67Gt		\$28	\$22	-0.12Gt
With border tax adjustment:								
All three instruments:	\$21	\$29	\$0	-0.93Gt	\$23	\$27	\$0	-0.31Gt
No extraction tax:	\$23		\$0	-0.41Gt	\$23		\$0	-0.28Gt

Notes: Table shows surplus-maximizing carbon use tax t_u, carbon extraction tax t_e, and clean energy subsidy s_c, in \$ per tonne of CO_2, per the model presented in section 3.1.2, treating either the U.S. or the EU as the "Home" country. ΔE shows the global change in emissions, in gigatonnes of CO_2 per year. The model's calibration is described in section 3.2 and uses an SCC of \$50/tonne.

in table 2 is proportional to the the reduction in global emissions, and the constant of proportionality is one-half the SCC.[20] Thus, the surplus-maximizing policy combination for the U.S. increases total surplus by \$22 billion per year, but the increase in surplus when the U.S. does not include the extraction tax is just \$9 billion per year.

The fifth row in table 2 presents results when the policy mix also includes an ideal border tax adjustment (BTA) that eliminates all leakage from trade in energy-intensive goods. In this case, the surplus-maximizing use and extraction taxes sum to the SCC. The surplus-maximizing clean energy subsidy is zero because it is less efficient than the BTA at addressing leakage. The BTA only modestly increases emissions reductions for the U.S., but in the EU it increases emissions reductions by 29%. This difference arises because the leakage rate Λ for the EU is twice that for the U.S., reflecting its greater trade exposure. Finally, table 2, row 6 considers a carbon use tax and a BTA, without an extraction tax. Again, removing the extraction tax substantially cuts the emissions reductions achieved by the U.S. but has only a modest effect on the EU's emissions reductions.

I have also examined a sensitivity in which I double the elasticities of fossil and clean energy supply from 0.75 to 1.50. The results are presented in appendix table C.1. With more elastic energy supply, the surplus-maximizing extraction taxes fall to \$23 and \$21/tonne for the U.S. and EU, respectively, though it remains the case that for the U.S., the extraction

[20] To see this result, observe that the emissions reductions increase surplus by the area of a Harberger triangle that has a height of ϕ and a base equal to the reduction in global emissions.

tax is a more important driver of global emissions reductions than the use tax.

Overall, these results suggest that for trade-exposed jurisdictions, efficient global emissions mitigation requires combining standard demand-side carbon use (i.e., emission) pricing with supply-side carbon extraction pricing. The importance of extraction pricing is especially pronounced for countries like the U.S. that are major fossil energy producers, and this result holds even when fossil energy supply is more than twice as elastic as energy demand. For the EU, which produces little fossil energy, the surplus-maximizing extraction tax is still large in magnitude, but its inclusion in the policy package is of secondary importance for emissions reduction. Finally, a border tax adjustment is more important for the EU than for the U.S., reflecting the EU's greater trade exposure.

4 Demand and supply-side climate policies in practice

In the framework from section 3, the domestic energy market was assumed to operate efficiently, the only market failures stemmed from the climate externality and the lack of policy action on the part of trading partners, and the only climate policies considered were Pigouvian carbon pricing and broad subsidies for clean energy. In this section, I depart from that idealized environment and consider energy markets and climate policy in practice. I emphasize three departures that I think are especially important: (1) supply-side policies have narrowly targeted specific infrastructure and regions rather than broadly priced extraction; (2) retail electricity prices are often marked up well above social marginal cost, providing a justification for broad clean electricity subsidies as an efficient demand-side policy; and (3) significant barriers to long-distance electricity transmission investment limit the effectiveness of demand-side emission pricing or clean subsidies in stimulating renewable energy development. My discussion in this section will focus on the U.S., mostly because it is the setting I know best, though these issues are relevant in other countries as well (for instance, Joskow (2021) discusses challenges to long-distance transmission in the EU).

4.1 Inefficient supply-side policy

I am not aware of supply-side policy in practice that takes the form of that described in section 3, in which a broad tax is levied on fossil fuel extraction. Instead, a common approach is to block construction of fossil fuel transportation infrastructure, such as pipelines and export terminals, with the goal of keeping the upstream carbon in the ground. These policies have appeal because of their feasibility: infrastructure typically requires permits to be granted by multiple local and federal authorities, thus affording opponents multiple veto points. In the U.S., Covert and Kellogg (forthcoming) observes that construction of the Atlantic Coast and Keystone XL pipelines was successfully blocked, that the Dakota Access and Mountain Valley pipelines were delayed, that coal export terminals on the West Coast have faced local opposition, and that the Biden administration paused approvals of new liquefied natural gas (LNG) export terminals. Internationally, the paper also cites opposition to the East African Crude Oil, Eastern Mediterranean, and Canadian Trans Mountain pipeline projects.

Covert and Kellogg (forthcoming) examines hydrocarbon infrastructure policy in the context of crude oil pipelines, focusing on the Dakota Access Pipeline (DAPL), which was completed in 2017 and moves approximately 500,000 barrels of oil per day from North Dakota to the Gulf Coast. DAPL faced substantial opposition and was approved only after the first Trump administration took office in 2017. Covert and Kellogg (forthcoming) asks the counterfactual question: had DAPL not been completed, to what extent would the oil it now transports have been "left in the ground"?

The answer turns out to be: "not much". Covert and Kellogg (forthcoming) emphasizes that railroads exist as an alternative option to move oil out of North Dakota. Crude-by-rail is more expensive than using the pipeline — rail costs more than $10/bbl, as opposed to the DAPL tariff of $5.50–$6.25/bbl — but also affords shippers flexibility across destinations and in when they ship. The paper finds that had DAPL's construction been foreclosed, 82% of its flows would have moved to the railroads rather than stayed in the ground. Moreover, the increase in crude-by-rail would have imposed substantial local environmental costs, since diesel locomotives emit local air pollutants and travel through populated areas.

As another example, Abuin (2025) evaluates a ban on construction of U.S. LNG export terminals. It finds that foreclosing LNG exports leads to lower U.S. natural gas prices, which would increase domestic carbon emissions because cheap gas-fired generation slows down the clean energy transition. Abroad, reduced LNG imports initially lead to increased emissions because would-be importers generate electricity with coal instead, but eventually an acceleration of the clean energy transition reduces emissions. The bottom line is that blocking LNG leads to an unambiguous near-term increase in emissions — the opposite of the policy's goal — with emission reductions realized only after several decades elapse.

The U.S. has also targeted upstream extraction, but only from resources that are federally owned. In particular, the Biden administration suspended new oil and gas leases on federal mineral estates in 2021 (Prest, 2022).[21] This policy is closer in spirit to the supply-

[21] Prest (2022) evaluates how a federal leasing ban would lead to leakage through trade in fossil fuels (i.e., per a model like that of section 3.1) and finds that policies curtailing federal production would have a leakage rate of 52–72% (per section 3, this leakage could be mitigated by combining the extraction restrictions with a carbon use tax). In addition to a leasing ban, Prest (2022) and Prest and Stock (2023) also consider "royalty adders" that would effectively tax oil and gas extraction from federal estates.

side extraction tax evaluated in section 3, but still narrower in that it targets just a subset of domestic supply: only 28% of U.S. oil production is federal (U.S. Energy Information Administration, 2026d; U.S. Office of Natural Resources Revenue, 2026). This narrow targeting allows emissions leakage to occur not just via trade in fossil energy, per section 3, but also via trade in factors of production. Vreugdenhil (forthcoming) studies a hypothetical U.S. moratorium on deepwater drilling and finds that capital reallocation — movements of drilling rigs to foreign locations — would cause 36.6% of the emissions reductions to leak away.[22] Restrictions on onshore federal leasing (48% of federal oil production is onshore (U.S. Office of Natural Resources Revenue, 2026)) would also lead to leakage via factor reallocation, though in this case capital and labor would migrate to non-federal U.S. mineral estates rather than foreign locations. This leakage is likely to be pronounced because the necessary migration would not be very far. 81% of all federal onshore oil production in 2025 was in the New Mexico part of the Permian Basin, where it is surrounded by an even larger volume of Permian production from nearby private and state-owned mineral estates.[23]

The shortcoming in each of the above policies stems from substitution. This substitution is analogous to the cross-country emissions leakage considered in section 3, except here the leakage occurs across transportation modes, fuels, and domestic extraction sites. The lesson for supply-side climate policy is that in order to be an effective complement to demand-side carbon pricing, in the sense from section 3, it should be broad-based and comprehensive, rather than narrowly targeted.

4.2 Mis-pricing of retail electricity

Apart from some large industrial customers, most electricity consumers in the U.S. purchase power from electric utilities, paying bills that combine charges for the energy itself and for the delivery of that energy via the utilities' distribution lines. Borenstein and Bushnell (2022a) documents that utilities recover their distribution and overhead costs primarily through volumetric charges — i.e., charges per kilowatt-hour (kWh) of electricity consumed — rather than through fixed charges that are independent of consumption. This practice is common despite the fact that most of these costs are fixed with respect to a customer's consumption. As a consequence, retail per-kWh electricity prices are marked up well above the private marginal cost of generation, even accounting for resistive losses during transmission and distribution. Borenstein and Bushnell (2022a) finds that the average markup was about 8

[22]A broad U.S. extraction tax would also be vulnerable to this leakage mechanism, but the impact on the overall leakage rate would be minor since only a small share of U.S. extraction involves deepwater drilling.

[23]Production from New Mexico federal minerals is 1.45 million barrels per day (U.S. Office of Natural Resources Revenue, 2026), while private and state-owned mineral estates in the Permian Basin produce 4.52 million barrels per day (U.S. Energy Information Administration, 2026d).

cents per kWh during 2014–2016, relative to an average private marginal cost of just under 4 cents/kWh, with especially large markups in California and the Northeast. Borenstein and Bushnell (2022a) further shows that retail prices even exceed the full social cost of electricity, after accounting for pollution damages, in many parts of the country.[24] This over-pricing can be expected to strengthen as the grid gradually becomes cleaner.

Retail electricity price markups pose a challenge for climate policy and a clean energy transition. Deep decarbonization will require energy consumers to shift away from natural gas as a fuel for space heating and from petroleum products as a fuel for transportation. "Electrification of everything" with a clean grid is the leading candidate for achieving this transition. But consumer switching from gas and petroleum to electricity will be hindered if electricity is over-priced relative to its social costs. For instance, Borenstein, Fowlie and Sallee (2022) highlights that California's rate structure as of 2022 increases the "annual operating cost of an EV by around $600 per year on average". Borenstein and Bushnell (2022b) further observes that the magnitude by which retail electricity is over-priced is considerably greater, on average, than over-pricing of natural gas and gasoline.

The natural policy solution to this problem is rate reform that shifts the recovery of fixed distribution costs away from volumetric charges. Borenstein et al. (2022) proposes such a reform for California, wherein fixed costs would be recovered from a combination of fixed charges (indexed to households' incomes as a way to address equity concerns) and the state's general fund. The California Public Utilities Commission moved rates in this direction in a 2024 rulemaking, though the magnitude of the change was modest and insufficient to bring volumetric rates down to the level of social marginal cost (Chhabra, 2025).

In the absence of rate reform, a second-best approach to retail electricity mis-pricing is to subsidize clean electricity generation, as argued by Borenstein and Kellogg (2023). Ordinarily, clean energy subsidies are inefficient because they incentivize excess consumption of energy. But when the price of energy is marked up above its social marginal cost, subsidizing clean energy can better align retail prices — and thus consumers' incentives — with costs. Consequently, clean energy subsidies may yield a greater efficiency gain than carbon pricing, which would push retail prices higher and thus further away from social marginal cost.

Borenstein and Kellogg (2023) emphasizes that this efficiency argument for clean electricity subsidies is weakened if they do not induce reductions in generation from the most carbon-intensive generators, i.e., coal plants, in the same way that carbon pricing would. In principle, clean electricity subsidies need not do so: they induce substitution of clean energy for whichever fossil generators have the highest private costs, not the highest social costs. In

[24] Social costs include local pollution as well as climate damages. Borenstein and Bushnell (2022a) uses an SCC of $50/tonne in its main results and includes results with an SCC of $100/tonne in its appendix.

the U.S., Borenstein and Kellogg (2023) finds that fossil generators' private and social costs are highly correlated because of the low price of U.S. natural gas relative to coal, so that the efficiency argument for clean electricity subsidies is likely to hold. Borenstein and Kellogg (2023) stresses, however, that this conclusion is not likely to apply to most countries outside the U.S., where natural gas prices tend to be significantly higher.

4.3 Barriers to investment in long-distance transmission

Long-distance transmission is a complement to the development of wind and solar resources. Gonzales, Ito and Reguant (2023) documents how, in Chile, new transmission investment connected solar resources in the unpopulated north of the country to demand centers, enabling a 180% increase in solar generation, an 8% reduction in generation costs, and a 5% reduction in CO_2 emissions. In the U.S., solar and especially wind resources are also often located far from demand (Joskow, 2021; Davis, Hausman and Rose, 2023). The highest-quality wind resources run north-south in a sparsely populated belt in the center of the country, and the best solar resources are concentrated in the Southwest and, to a lesser extent, the Southeast. Most U.S. coal, oil, and natural gas reserves are also not located near population centers, but they can be transported overland for a modest cost. No such option exists for wind and solar. The value of transmission for wind and solar is further enhanced by these resources' intermittency: wires allow energy to be moved from where the sun is shining to where it isn't.

Joskow (2021) and Davis et al. (2023) point to a suite of studies documenting the significant extent to which long-distance transmission investment has not kept pace with the growth of wind and solar generation in the U.S. As a consequence of this shortfall, Davis et al. (2023) observes that renewable generation increasingly finds itself "stuck" geographically: from 2015 to 2022, curtailments of solar generation increased 18-fold in California and 37-fold in the Southwest Power Pool, and as of 2022, some wind-rich locations in the center of the U.S. "experience negative electricity prices during more than 20 percent of all hours". In line with these observations, U.S. Department of Energy, Grid Deployment Office (2024) found that inter-regional transmission would need to expand by a factor of 1.9 to 3.5 by 2050 in order to accommodate projected demand growth at lowest cost.

A lack of transmission handicaps the ability of standard demand-side policies — pricing emissions from fossil generators or subsidizing clean generation — to meaningfully reduce emissions. If clean generators cannot connect their power to load, then these policies would be essentially pushing against a wall.[25]

[25] In the context of the model from section 3, a shortfall in transmission effectively decreases the elasticity of clean electricity supply.

Why is it so hard to build transmission? Popular and political discourse has focused on the challenges of obtaining the necessary local, state, and federal authorizations. These challenges apply not just to transmission but also to the development of the wind and solar resources themselves. Jarvis (2025) and Kashner (2026) estimate local disamenities from wind development and provide evidence that these disamenities carry disproportionate weight, relative to the benefits of the energy produced, in permitting processes. And chapter two of Klein and Thompson (2025) highlights the thicket of environmental statutes, regulations, and litigation that must be overcome prior to building energy infrastructure at scale. The difficulties of permitting transmission lines are compounded by their geography: the wires necessarily cross multiple jurisdictions and are thus exposed to a series of veto points.

I want to emphasize, however, that reforms to environmental permitting and litigation processes are, on their own, not sufficient for solving the problem. Another barrier to transmission investment is posed by the transmission planning process itself, which is characterized by a lack of inter-regional coordination and by misaligned incentives.

The coordination problem arises from what Davis et al. (2023) calls an "overhang of fragmented regulated utilities". When the U.S. electricity sector began its build-out in the early 20th century, it was characterized by disconnected utilities serving urban areas. As load grew and transmission costs fell, it proved useful to develop connections between regions for short-term load balancing, but overall the balkanized nature of the industry persisted, and today the U.S. has more than 50 "balancing authorities" (BAs) that are responsible for reliability, resource planning, and transmission planning within their areas (Joskow, 2021). Some of these BAs have a large geographic footprint — e.g., the PJM independent system operator stretches from Chicago to the Eastern Seaboard — while others are utilities that serve only a single metropolitan area (Joskow, 2021).

The regulatory processes for transmission planning were built to manage investment within each BA, not across BAs. Joskow (2021) points to the lack of an "umbrella organization" with the job of identifying nation-wide opportunities for inter-regional transmission investment.[26] Joskow (2021) and DeLosa III, Pfeifenberger and Joskow (2025) further argue that existing frameworks for allocating costs of new transmission infrastructure were designed for intra- rather than inter-regional transmission, creating disputes and friction points for large projects. In addition, Macey and Mays (2024) points out that within-region,

[26] Joskow (2021) also contrasts the planning and financing for transmission lines with the processes used for natural gas pipelines, which are largely market-driven. Pipeline developers solicit bids from potential customers in an "open season", and if the open season is successful, the bids turn into binding transportation agreements that are used by the developer to secure financing and regulatory approvals. Joskow (2021) cautions that this pipeline model is likely not directly portable to electricity transmission, since pipelines are typically point-to-point whereas transmission lines exist in a more complex network, but the paper suggests a potential "hybrid" approach that combines planning with market solicitations.

"local" reliability projects offer utilities a relatively straightforward pathway for investment. Unlike regional transmission, local projects do not require competitive solicitation, and they often do not require a certificate of public convenience and necessity from the state PUC.

More fundamentally, the utilities that own and operate transmission lines have poor incentives to engage in inter-regional transmission planning or to facilitate reforms that would enable such planning. An underlying problem is the cost-of-service regulatory framework that governs utilities' incentives. As a natural monopoly, a utility is allowed to charge a tariff to customers that is sufficient to recover its costs and earn a "fair" return on its capital stock. A well-known concern that arises from this framework is the Averch–Johnson effect (Averch and Johnson, 1962): if the allowed rate of return on equity (ROE) exceeds the true cost of equity, the utility will have an incentive to over-invest in capital. Recent evidence in favor of this hypothesis is provided in Dunkle Werner and Jarvis (2026), which studies U.S. utility rate cases and finds that utilities' allowed ROE has exceeded the true cost of equity by one to five percentage points, on average, over the last decade. Much of this excess stems from asymmetry in the timing of rate cases: utilities initiate rate cases promptly when their costs rise but not when their costs are falling (evidence for this phenomenon dates to Joskow (1974)). Dunkle Werner and Jarvis (2026) also finds evidence that these excess rates lead to an increase in capital investment, consistent with Averch and Johnson (1962).

At first blush, over-investment by utilities may seem like a good thing for long-distance transmission development. Even if an excess ROE imposes costs on ratepayers, in theory it should stimulate additional transmission investment, the climate benefits of which are arguably worth it. However, there is a fault in this logic: the regulatory framework distorts not just how much utilities invest, but also the types of investments that are made.

When a utility buys power transmitted in from outside its service territory, the power purchase costs are largely passed through to ratepayers, so that it is difficult for the utility to profit. Utilities therefore have an incentive to develop local projects themselves rather than buy power generated elsewhere. This incentive misalignment is exacerbated when utilities are vertically integrated and also own fossil generation from which they earn revenue. Gold (2019) recounts the story of the energy developer Invenergy approaching the utility Oklahoma Gas and Electric (OG&E) with a proposal to build a wind farm in Oklahoma and sell the power to OG&E at a price lower than OG&E's own generation cost. Michael Polsky, Invenergy's founder and owner, recalls being told, "Why would we buy from you and make no money? We'd rather run our own plants and make money that way".[27]

The monetary stakes were recently quantified by Hausman (2025), which evaluates a hypothetical increase in transmission in the Midcontinent Independent System Operator

[27] I credit Davis et al. (2023) for reminding me of this example.

(MISO) and Southwest Power Pool (SPP) regions, covering most of the Midwestern states, plus Oklahoma, Arkansas, and Louisiana. The paper finds that relieving existing inter-regional transmission congestion would have led to a $2 billion reduction in system-wide generation costs in 2022, much of it coming from unlocking wind power in the Midwest. However, this efficiency gain would be accompanied by a decrease in revenues of more than $1 billion for firms owning high-cost fossil generation, most of which are vertically integrated utilities.[28] The paper spotlights that one of these firms — Entergy, which operates in Arkansas, Louisiana, Mississippi, and Texas — would alone have lost $850 million of revenue in 2022 from grid integration with the Midwest.[29]

Hausman (2025) thus demonstrates that utilities can have incentives to impede inter-regional transmission development. Kovvali and Macey (2023) and Peskoe (2023) discuss how they can act on these incentives. One tactic is simply to build local lines that preclude the need for inter-regional transmission. Within regional transmission organizations (RTOs, such as PJM and MISO), Peskoe (2023) argues that incumbent utility transmission owners hold both formal and informal control over transmission planning processes, allowing them to steer investments toward local projects rather than regional ones. Kovvali and Macey (2023) also highlights the Entergy case, observing that it buttressed a regulatory argument against the necessity of a new $100 million inter-regional transmission line by building a $1 billion gas-fired generator within its service territory instead.

The consequence of these process and governance shortcomings is that even though utilities are investing in transmission, they are not building the long-distance projects that would unlock the best U.S. wind and solar resources. Congressional Budget Office (2026) finds that the rate of transmission investment in the U.S. more than doubled during 2012–2024, to just over $30 billion annually. However, most of this investment has been for local projects, as also documented in Macey and Mays (2024), DeLosa III et al. (2025), and Hausman (2025). For example, DeLosa III et al. (2025) reports that from 2014 to 2022, PJM invested $38.3 billion in local projects but only $6.4 billion in inter-regional transmission.

Taken together, incumbents' misaligned incentives and the balkanized nature of transmission planning pose a formidable challenge to transmission development on the scale needed to

[28]Ham, Kay and Hausman (2026) expands Hausman's (2025) analysis to the entire U.S., demonstrating that incumbent merchant generators also have strong incentives to block transmission of low-cost power into their local markets. These generators can and do lobby to block transmission, though they typically lack utilities' ability to directly participate in planning processes or build local reliability projects that preempt regional transmission.

[29]Entergy's Arkansas and Louisiana subsidiaries are regulated utilities so are not residual claimants on generation revenue. Hausman (2025) argues that they will still have incentives to protect their generation revenue for three reasons: (1) pass-through to ratepayers may be imperfect; (2) high local prices can justify additional local generation investment; and (3) high generator utilization can allow them to justify a higher rate of return on their assets.

develop the best wind and solar resources in the U.S. Overcoming these barriers will require more than just textbook carbon pricing or clean energy subsidies. Here, the necessary clean energy policy is process and governance reform. It is difficult to overstate the complexity of both the hurdles and the solutions. I have merely summarized the challenges here. Properly understanding them, much less addressing them, requires more detailed knowledge of the relevant legal and economic institutions than I can provide in this paper. I direct readers to the literature cited in this section as an excellent starting point.

5 Innovation, industrial policy, and global emissions reductions

Section 3 discussed climate policies that reduce domestic emissions while limiting leakage that would increase emissions abroad. I now turn toward policy that aims to *reduce* foreign emissions, not just hold the line. I am motivated by the challenge that significant progress on decarbonization is infeasible in the absence of emissions reductions from low- and middle income countries. Over the coming decades, projected emissions from non-OECD (Organisation for Economic Co-operation and Development) countries are expected to exceed emissions from the OECD by more than a factor of three (Greenstone, 2024). This fact leads to what Greenstone (2024) calls "the cruelty of climate arithmetic": "limiting temperature increases to the 2.0°C increase recommended by scientists requires non-OECD countries to cut their projected end-of-century CO_2 emissions by roughly 85 percent."

Inducing non-OECD countries to make such cuts is challenging for economic, political, and ethical reasons. Greenstone (2024) adopts the word "cruelty" because "these countries are most in need of higher energy consumption (and least willing to pay extra for low-carbon energy sources), account for the great majority of the world's population, and have emitted the least to date". Echoing Greenstone (2024), Borenstein and Kellogg (2023) writes, "Understandably, lower-income countries argue that it is not fair to ask them to make major sacrifices after the high-income countries have become wealthy while creating most of the GHGs that are currently in the atmosphere."

One response to this challenge is demand-side climate policy that drives down the costs of clean energy technologies, so that other nations are voluntarily willing to adopt them rather than grow their economies using fossil fuels. A risk with this approach is that clean energy adoption may lead primarily to more energy use rather than substitution away from fossil fuels, as suggested by Hassler, Krusell and Olovsson (2026). Clean technology policies thus pair well with policies, such as investment in transmission or battery storage, that increase the substitutability of clean energy for fossil energy. And reductions in the cost of clean energy will reduce the burdens imposed by carbon taxation, which may eventually reduce resistance to carbon pricing policies.

Support for clean energy research and development (R&D) is a natural policy lever. It is well known that markets for innovation suffer from the problems that creators of new knowledge cannot appropriate the full social benefit of their ideas, and that financial frictions can inhibit entrepreneurship. Economists and policy-makers have long supported government funding of R&D for this reason, and the argument is buttressed by evidence: Howell (2017) finds that U.S. federal R&D grants to energy technology startups eased their financial constraints, crowded in private venture capital investment, and ultimately increased their probability of survival. Borenstein and Kellogg (2021) highlights that the need to reduce emissions abroad strengthens the standard "innovation market failure" case for public support for R&D, while weakening the case for relying on patents and other forms of intellectual property protection that would erect barriers to global adoption of new clean technologies.

Borenstein and Kellogg (2021) also briefly argues, in a footnote, that public support for innovation should extend to new technology deployment, not just basic research and development. Deployment support intersects with industrial policy, which can have a variety of motivations beyond climate policy (for instance, national security), as discussed in Gerarden, Reguant and Xu's (2026) recent survey. Economists are normally wary of supporting new technologies all the way to the point of deployment: it is hard to avoid "picking winners", the fiscal outlays are large and can be difficult to unwind, and there are prominent examples of failure.[30] Still, innovation externalities plausibly exist at the deployment level, and evidence and theoretical arguments have recently emerged to support the case.

The evidence is primarily from China, which has become the global leader in clean manufacturing. By 2023, China accounted for 63% of the world's production of solar PV cells and 85% of the world's battery cell production capacity (Banares-Sanchez, Burgess, Laszlo, Simpson, Van Reenen and Wang, 2026; U.S. Energy Information Administration, 2025a). And in 2025 China produced 75% of the world's EVs (International Energy Agency, 2026). China now exports PV panels, batteries, and EVs throughout the world, to the benefit of energy consumers and the climate (and to the consternation of non-Chinese suppliers). The development of this green manufacturing machine has occurred alongside government support that has included R&D funding, project finance, and production and consumption subsidies. What role have these policies played in driving China's green industrial growth?

[30] Borenstein and Kellogg (2021) raises the recent nuclear power projects in South Carolina and Georgia that suffered massive delays and cost overruns (leading to cancellation in the case of South Carolina). As another example, the U.S. government has provided substantial support for cellulosic ethanol since 2005 (Yacobucci, 2011), yet the technology has not been successfully commercialized at scale.

Banares-Sanchez et al. (2026) studies how Chinese government policies helped drive a reduction in the cost of solar PV from \$5/watt in 2005 to \$0.25/watt by 2025.[31] It exploits variation in local governments' support for PV across China, and it accounts for the possibility of positive knowledge spillovers from manufacturers in one city to another, as well as negative spillovers arising from production subsidies in one city stealing business from another. The paper's bottom line is a story of success: local policy support for solar accounted for 50% of the reduction in PV prices during 2006–2020, and each dollar of subsidy on average yielded \$1.65 in social benefits (consumer and producer surplus) even before accounting for climate benefits or benefits outside China. That is, the subsidies more than paid for themselves domestically, as knowledge spillovers outweighed business stealing. When the paper compares the different forms of public support, it concludes that "production and innovation subsidies were more effective than demand-side (installation) subsidies in generating large and persistent increases in local innovation, net entry, production and exports".

A parallel paper is Barwick, Kwon, Li and Zahur (2025), which studies the vertical supply chain between Chinese battery producers and EV manufacturers. It identifies an innovation market failure: due to market power throughout the supply chain, battery producers capture less than half of the value from their cost-reducing process innovations. Instead, most of the gains go to EV producers and to end-consumers (in the form of lower EV prices). Thus, battery producers' incentive to expand output and "walk down the learning curve" is too weak. Barwick et al. (2025) argues that China's EV subsidies corrected this market failure, to the point that the resulting process innovations led the public expenditures to more than pay for themselves domestically, even without accounting for climate benefits or benefits to foreign consumers.

Finally, Aghion, Barrage, Donald, Hémous and Liu (2025) evaluates the role of coordination problems in clean energy production networks, using green hydrogen and heavy-duty trucking as its application. The underlying logic is that of a "chicken-and-egg" problem: trucking companies will be reluctant to invest in hydrogen-powered truck innovation if green hydrogen is expensive, and hydrogen producers will be reluctant to invest in green hydrogen if there is little demand from truckers. The paper shows that a "big push" of large but temporary production subsidies can help the supply chain escape the low-adoption equilibrium and transition to a stable high-adoption equilibrium.

The thread connecting the above papers is the existence of innovation market failures downstream of basic R&D, and the potential for well-targeted innovation and deployment

[31] A related paper is Gerarden (2023), which studies the PV market during 2010–2015, before China became the dominant producer of panels. It finds that subsidies for solar PV electricity production, such as Germany's feed-in tariffs, induced innovation by local producers, leading to external benefits via increased global adoption of low-cost PV.

subsidies at scale to stimulate innovation that market actors would not undertake on their own. Even as this section is primarily motivated by the goal of advancing clean technologies that can be adopted abroad, this body of work raises the possibility that domestic green industrial policy can pay off at home, even before climate benefits or benefits to foreign consumers are factored in. Central to this argument is the targeting of public support to sectors where innovation market failures are likely to be severe because of spillovers or coordination problems in supply chains. This literature is still in its early stages, and these ideas warrant additional empirical scrutiny, but there is now evidence that counters the standard arguments against industrial policy on efficiency grounds.

6 Distributional impacts of demand-side and supply-side policies

The paper's discussion thus far has evaluated climate policies based on their relative efficiency: the delivery of emissions reductions at the lowest total cost to private economic surplus. In this section, I turn to distributional impacts. Who gains from, and who bears the costs of, demand-side versus supply-side policies, both domestically and globally? Policymakers, the public, and climate economists and scientists will often care about this question for its own sake. The question also bears on climate politics and can help inform who will support and who will oppose different types of climate policies, and how concentrated or diffuse those interests might be, in the spirit of Olson (1965).

6.1 Domestic distributional impacts

In a closed economy that does not trade with the rest of the world, carbon use and extraction pricing are equivalent in terms of not only their efficiency (per section 2) but also their distributional consequences: the statutory incidence of a carbon tax does not affect its economic incidence. In aggregate, both consumers and producers of fossil fuels will bear some of the tax incidence, and the incidence will fall more heavily on the side of the market that is less elastic. The treasury will gain from the collection of carbon tax revenue, which will ultimately benefit current and future taxpayers through some combination of additional public goods provision, direct transfers, reduced taxes on income or other goods, public debt reduction, or reduced inflationary pressure.[32] And of course the public will benefit from the

[32] If carbon pricing is achieved through a cap-and-trade system in which the permits are given away for free, then the public revenue benefits will not be realized, and instead there will be a transfer of wealth from those bearing the carbon tax burden to the recipients of the free permits.

climate damages avoided by the reduction in emissions.

The equivalence between demand-side and supply-side carbon pricing changes, however, when the economy is open to trade. Both policies will still adversely impact domestic fossil fuel producers and consumers, but the burden will fall more heavily onto producers to the extent that an extraction tax is used rather than an emissions tax. An extraction tax raises the global price of fossil fuels, which harms domestic consumers, but this effect is small to the extent that the taxing jurisdiction is small relative to the global market. The bulk of the extraction tax incidence thus falls on extractors, as illustrated in panel (c) of figure 2. For the calibrated model described in section 3.2, U.S. domestic consumers bear only 7% of the total burden of a carbon extraction tax, with 93% falling on extractors. For an emissions tax these burdens are reversed: domestic consumers bear 92% of the burden, while extractors bear only 8%.[33]

Because carbon pricing is correcting an externality, it can create a Kaldor–Hicks improvement: the "winners" from the policy could in principle compensate the "losers" and still be better off. In practice, such compensation would take the form of transfers from the public treasury to fossil fuel producers or consumers. As an example, a share of revenues from California's cap-and-trade program is currently rebated to households via utility bill credits. Can such transfers transform the Kaldor–Hicks improvement from carbon pricing into a Pareto improvement by eliminating all losers? Sallee (2019) argues convincingly that the answer is no. The paper studies the incidence of a U.S. tax on gasoline, and its insight rests on the fact that the consumer-side tax burden will be heterogeneous, based on variation in households' demand for fuel. For instance, some households drive heavy-duty trucks for tens of thousands of miles per year, while others drive efficient vehicles for only short distances. Using data from the Consumer Expenditure Survey, Sallee (2019) shows that it is infeasible, using information on households' demographics and locations that the government could readily obtain, to accurately predict which households are high fuel use and which are low fuel use. For instance, a regression of gasoline tax burden on geographic indicators (state, urban vs. rural) and a variety of demographic characteristics (household size, detailed income bins) has an R^2 of just 0.36. Because achieving a Pareto improvement would require greatly compensating the high fuel use households and modestly compensating the low fuel use households, the inability to accurately target transfers implies that a Pareto improvement is infeasible. Thus, per the paper's title, Pigouvian taxation creates losers. And in the case of gasoline taxation, Sallee (2019) shows that there will be many losers: even when transfers are optimally targeted using geographic and demographic information,

[33] The extraction and emissions tax burdens are not symmetric because the emissions tax induces leakage via trade in carbon-intensive goods, while the extraction tax does not.

roughly 40% of households will still be made worse off by a gasoline tax. Naturally, such households may oppose the tax politically.

Sallee (2019) only considers the distribution of tax burden among consumers. What about the distribution of burden among producers, which would be especially meaningful for a carbon extraction tax? An instinctive take is that the prediction problem should be easier. The firms that extract coal, oil, and natural gas are relatively few in number, and their production rates are well known through regulatory filings and production reports. But a challenge arises because extraction firms are not the only agents that earn economic rents from fossil fuel development. Non-federal mineral owners, the vast majority of whom are private rather than state interests, earned approximately $69 billion in royalty income in 2025.[34] Labor is another important constituency. The reduction in conventional pollution caused by the Clean Air Act Amendments led to a 5% reduction in earnings for workers in affected industries (Walker, 2013). A broad clean energy transition would likely be even more impactful for affected workers, especially since, as argued by Greenspon and Raimi (2024), the skills of fossil fuel workers typically differ from those required in the fast-growing occupations that they could potentially transition into. Moreover, Allcott and Keniston (2018) finds that booms and busts in fossil fuel extraction spill over broadly into other sectors of the economy, especially to locally traded sectors (e.g., hospitality services) and sectors that are suppliers to the fossil fuel industry. Finally, Raimi, Davert, Neuenfeldt, Zanen and Whitlock (2024) shows that local governments in fossil fuel extraction regions are heavily reliant on the industry for their tax base, to the point that local public revenue from fossil fuel extraction exceeds the sector's wage bill in some counties.

A carbon extraction tax would thus impose a burden not just onto fossil fuel extraction firms, but also on workers, other sectors of the economy, and local governments. These impacts are difficult to predict and thus would be difficult to compensate. They would also be geographically concentrated, since fossil fuel extraction is itself geographically concentrated. For instance, the top ten oil-producing counties in the U.S. account for 37% of all U.S. production, and for 93% of all production growth from 2020 to 2024 (U.S. Energy Information Administration, 2025c). These counties represent a small share of the U.S. population but would incur significant, concentrated losses from a carbon extraction tax.

Clean energy subsidies have a starkly different distributional profile from that of carbon taxation. Clean energy producers are naturally the primary beneficiaries of these subsidies, and energy consumers also benefit via lower prices for energy. Fossil fuel extractors would be

[34] I compute this number using Brown, Fitzgerald and Weber's (2019) estimate that the average U.S. production-weighted royalty rate is 19%. I compute lower-48 non-federal oil and gas revenue using 2025 production and price data from U.S. Energy Information Administration (2026d) and U.S. Energy Information Administration (2026c), and federal production data from U.S. Office of Natural Resources Revenue (2026).

harmed by the decrease in energy prices, though this price decrease would be smaller than that induced by an equivalent carbon use tax (see equation (A.5) in appendix A.2). And of course, clean energy subsidies must be publicly financed, which will impose costs on current and future taxpayers — a canonical diffuse interest — via a combination of reduced public goods provision and direct transfers, increased taxes on income or other goods, increased public debt, or increased inflationary pressure.

6.2 Global distributional impacts

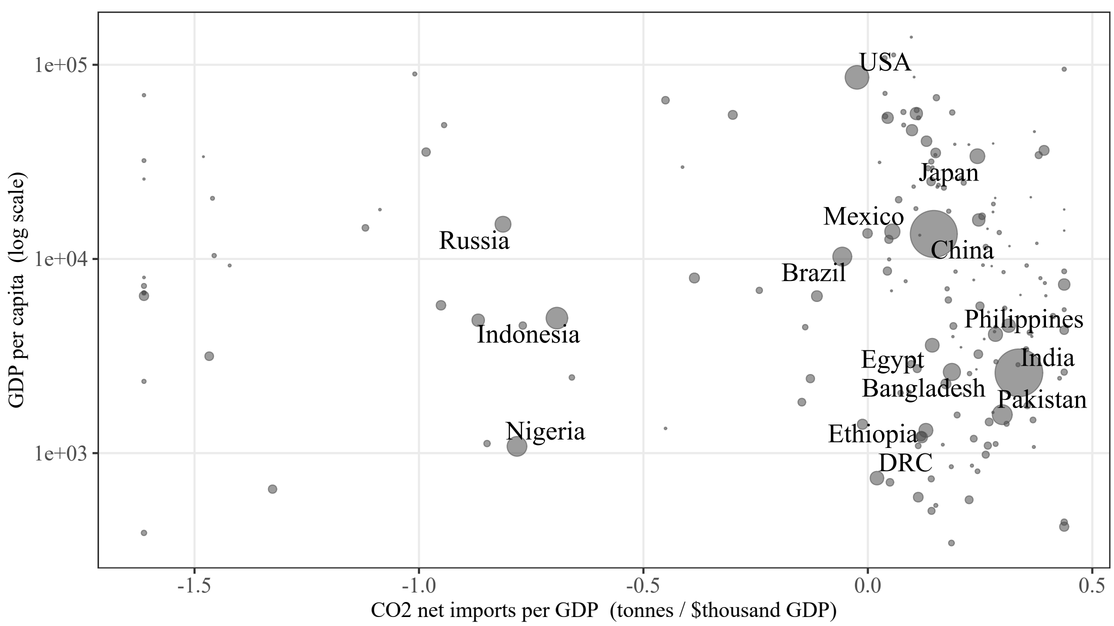
I next consider the global distributional consequences of the decision by a country or coalition to adopt demand-side or supply-side carbon pricing. Global inequality and justice factor prominently in international climate policy discussions because the majority of the damages from climate change will fall on low-income countries: they have less capacity to adapt and tend to be located in parts of the globe that already experience high temperatures (Greenstone, 2024). A corollary of this fact is that the benefits of emissions reductions will accrue disproportionately to low-income countries. Carbon emissions mitigation can thus be viewed as a mechanism for achieving both efficiency and global equity objectives. It can also be viewed as a mechanism for achieving justice, given that wealthy countries are historically responsible for the vast majority of cumulative emissions to date (Borenstein and Kellogg, 2021; Banerjee, Duflo and Greenstone, 2025).

Recalling the model and intuition from section 3.1, supply-side carbon pricing raises the global price of fossil fuel. This price increase will harm fossil fuel importers, in much the same way that the recent increase in the price of oil caused by the closure of the Strait of Hormuz has harmed oil importers (see, for instance, Krolik, Sang-Hun, Wee, Tobin and Cave (2026) for a discussion of adverse impacts in Bangladesh, India, Japan, Pakistan, the Philippines, South Korea, Taiwan, and Vietnam). Conversely, demand-side policy will lower the global price of fossil fuel, benefiting importers. Fossil fuel exporters, on the other hand, will benefit from supply-side policy and be harmed by demand-side policy.

Are net fossil fuel importers likely to be high-income or low-income countries? If the former, pricing carbon extraction will have an inequality-reducing effect, above and beyond the inequality reduction stemming from the emissions mitigation itself. But if the latter, pricing extraction will disproportionately burden low-income countries, pushing against the distributional benefits from emissions mitigation.

Figure 4 sheds light on this question by presenting a scatter plot of country-level fossil fuel net imports, as a share of GDP, versus GDP per capita. The figure exhibits no obvious positive or negative correlation, and indeed the correlation coefficient between CO_2 net

Figure 4: Country-level fossil fuel imports versus per-capita GDP



Note: The horizontal axis is winsorized at the 5th and 95th percentiles. See appendix figure C.1 for a non-winsorized version. Data on CO_2 net imports from fossil fuel trade are from U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b). Data on GDP per capita are from International Monetary Fund (2026).

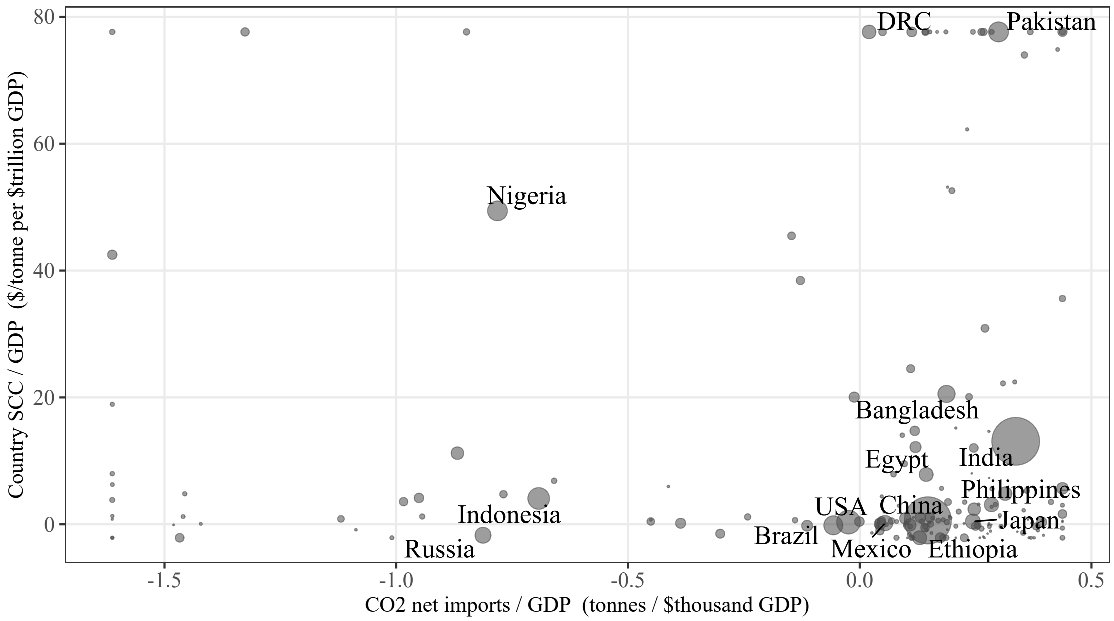
imports as a share of GDP and GDP per capita turns out to be small: -0.03.[35] Essentially, large fossil fuel importers include both wealthy (e.g., Japan) and poor (e.g., Pakistan) nations, and large fossil fuel exporters include both wealthy (e.g., the UAE) and poor (e.g., Nigeria) nations. These data therefore imply that while there is little equity tradeoff between demand-side and supply-side carbon pricing on average, there exist countries for which the economic implications are substantial.

An alternative approach to evaluating this distributional question is to evaluate the relationship between fossil net imports and the damages that countries are expected to experience from climate change. Figure 5 plots country-level fossil fuel net imports as a share of GDP versus country-level SCCs as a share of GDP, obtained from Carleton et al. (2026). These country-specific SCCs are aggregates of estimates of damages from the mortality, energy consumption, agricultural, labor disutility, and sea-level-rise impacts from climate change.[36] The correlation between CO_2 net imports as a share of GDP and the

[35]The correlation coefficients in this section are all population-weighted. The correlation between CO_2 net imports as a share of GDP and log GDP per capita (rather than its level) is -0.03. The minimal correlation parallels a finding in Clausing et al. (2026) that country-level heavy industry emission intensity is not strongly correlated with income.

[36]The SCCs are in 2025 USD per tonne of CO_2 emitted in 2019. They assume the RCP4.5 emissions

Figure 5: Country-level fossil fuel imports versus social cost of carbon (SCC) estimates



Note: The horizontal axis is winsorized at the 5th and 95th percentiles. The vertical axis is winsorized at the 10th and 90th percentiles. See appendix figure C.2 for a non-winsorized version. Data on CO_2 net imports from fossil fuel trade are from U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b). SCC estimates are from Carleton, Greenstone, Hsiang, Hultgren, Kopp, McCusker, Nath, Rising and Rode (2026). GDP data are from International Monetary Fund (2026).

SCC as a share of GDP is 0.06. This low correlation reflects the fact that the countries that will experience the largest damages from climate change, as a share of their total economic output, include both fossil fuel importers (e.g., Pakistan) and fossil fuel exporters (e.g., Nigeria).

This country-level analysis does not account for the likelihood that within countries, fossil fuel consumers and producers are concentrated in different regions and among different income groups. In the U.S., for example, workers in the oil and gas industry earn wages that significantly exceed those of the median worker in the economy (U.S. Bureau of Labor Statistics, 2026). Internationally, the resource curse literature (see Frankel (2012) for a survey) has emphasized the concentration of fossil resource ownership, and conflict stemming from that concentration, as a potential mechanism behind the poor economic performance of some resource-rich countries. Such concentration would focus the benefits of supply-side climate policies on a small group of resource owners within a fossil-fuel-exporting country, while the costs would be broadly distributed across fossil fuel consumers. A comprehensive

scenario and apply Ramsey discounting with a pure rate of time preference of 0.1% and an elasticity of marginal utility of consumption of 1.

analysis of within-country differences in incomes and wealth between fossil fuel producers and consumers is beyond the scope of this paper, but a sensible prior is that these differences likely imply that the global equity tradeoff between demand-side and supply-side carbon pricing is stronger than the cross-country analyses above suggest on their own.

7 Concluding discussion

My evaluation does not yield an unambiguous recommendation between demand-side and supply-side climate policy, or alternatively, between "abundance" and "keep it in the ground". Climate policies must instead make tradeoffs along many dimensions, and consequently the economics points toward a portfolio of policies rather than a single instrument. Even when evaluated through just the lens of efficiency, demand-side carbon pricing, supply-side carbon pricing, and support for clean energy technologies all have a place together in a climate policy package.

In order to minimize emissions leakage from unilateral climate policy, I highlight the value of combining traditional demand-side carbon pricing with supply-side carbon pricing. The leakage problem arises because carbon is a global pollutant, and because fossil fuels are traded in large volumes across borders. A carbon use tax alone, as is common in practice, depresses the global price of energy and leads to emissions leakage via increased net imports of fossil fuels by non-participating countries. Combining the use tax with a supply-side extraction tax counteracts this leakage by raising the global price of fossil fuels. This effect is especially meaningful for large fossil fuel producers, such as the U.S. In addition, extraction pricing, unlike carbon use pricing, does not lead to emissions leakage via trade in carbon-intensive goods. Instead, it raises the price of fuel for *all* global goods producers, so it confers no comparative disadvantage upon domestic producers.

In practice, however, supply-side policy has not taken the form of broad extraction pricing but rather has narrowly blocked construction of fossil fuel transportation infrastructure or restricted production from federal mineral estates. This approach is undermined by substitution of production across transportation modes, across fuels, and across reserves with different resource ownership. This substitution imposes economic costs while limiting emissions abatement. It also has the potential to worsen local air quality, as in the case of substituting railroad for pipeline transport of crude oil.

Clean energy subsidies suffer from well-known inefficiencies as a demand-side climate policy, relative to carbon pricing: they lead to excessive consumption of energy, do not directly target the externality, and must be financed with distortionary taxation. Nonetheless, failures in energy markets and markets for innovation can provide an efficiency justification for supporting clean energy with public funds. One such justification is emissions leakage: broad clean energy subsidies can be paired with carbon use taxes to address imports of energy-intensive goods from non-participating countries, though my quantitative analysis suggests that the benefits of doing so are not especially large, and vanish if border tax adjustments can be used instead. Another justification for broad clean electricity subsidies is the widespread practice among utilities and their regulators of pricing retail volumetric rates for electricity well above marginal cost. Absent retail rate reform, clean electricity subsidies can counteract this price distortion and increase efficiency, especially if the new clean generation displaces the most emissions-intensive incumbent fossil generators (i.e., coal-fired units). This outcome is likely in North America but less so in many other parts of the world in which natural gas is expensive relative to coal.

Still, the most promising clean energy policies are likely not to be broad subsidies but rather targeted policies that help unlock the potential of clean energy technologies. I present arguments for two classes of such policies, the first of which is aimed at enabling long-distance transmission of electricity. The U.S. has outstanding wind and solar resources, but they are often located far from population centers. Erecting the poles and wires to deliver these resources to consumers would deliver cost reductions and efficiency gains, and would drive down the electricity sector's demand for fossil fuels. The policy tools needed to enable a build-out of long-distance transmission are not broad subsidies but rather reforms to the planning processes and utility governance structures that have historically favored local projects over inter-regional transmission. Reform is challenging because it will erode incumbents' rents, but it is likely necessary to build the lines needed to bring the best wind and solar resources to market.

The second class of promising clean energy policies targets innovation. Private markets under-provide innovation on their own, thus supplying a strong argument for public support for research and development. For clean energy, the value of publicly investing in R&D is enhanced by the objective of reducing global, not just local, emissions. Good demand-side climate policy develops technology that will enable low- and middle-income countries to grow their economies on the back of clean energy rather than fossil fuels.

Going beyond basic R&D, evidence is emerging from China that "green industrial policy" can dramatically accelerate the production, export, and installation of clean energy equipment, especially when process innovation and learning can spill over across regions and firms, and within specialized supply chains. At the same time, economists' traditional concerns about industrial policy — picking winners, rent-seeking, and the difficulty of unwinding public support — remain valid. Even though solar PV and battery technology are success stories, there also exist failures, such as cellulosic ethanol's failure to launch despite substantial public support. The fact that public expenditure on a technology that turned out to be successful "paid for itself" ex post does not imply that the expenditure paid for itself ex ante, in expectation, when success was uncertain. The value of globally deployable clean technology innovation is large enough that I think taking big shots at green industrial policy is worth the risk, especially when it is targeted at sectors where spillovers and coordination problems within supply chains are plausibly large. But industrial policy ventures are not risk-free, and the question looms of whether public support can be withdrawn should a technology fail.

Finally, the distributional consequences of demand-side and supply-side policies differ in ways that matter for both equity and politics. Domestically, carbon pricing of either form transfers surplus from fossil energy producers and consumers to current and future taxpayers. The tax burden's split between producers and consumers depends on the instrument: in an open economy, an extraction tax falls mainly on domestic extractors — including the workers, suppliers, and local governments that depend on them — while a carbon use tax falls mainly on consumers. Because these burdens are heterogeneous and hard to predict, they cannot be fully compensated, so carbon pricing of any kind will create policy "losers" who will have reason to resist it. Clean energy subsidies have a different distributional profile, concentrating benefits on clean energy producers (and to a lesser extent energy consumers), while spreading their costs across current and future taxpayers.

Globally, reductions in CO_2 emissions advance equity objectives because the damages from climate change will be concentrated on low-income populations who are least able to adapt, many of whom already experience extreme heat. Climate policies that change the price of fossil fuels can work with or against the equity benefits of emissions mitigation, depending on whether relatively poor countries are net fossil fuel importers or exporters. I find only a modest correlation between country-level fossil fuel net imports and GDP per capita or future climate damages, implying that supply-side carbon pricing that raises global fossil fuel prices will not disproportionately harm poor countries on average. Still, within-country differences in incomes between fossil fuel producers and consumers likely present a distributional argument that favors demand-side over supply-side carbon pricing.

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Appendix to "Economics of Demand-Side and Supply-Side Climate Policies"

A Model details

A.1 Planner's problem

This subsection provides a foundation for the planner's problems given by equations (1) and (2) in the main text.

Begin with the case of autarky from section 2. Let L be a fixed quantity of labor available in the economy, and let z denote a non-energy-consuming numeraire good. Production of each unit of z requires one unit of labor. Let the cost functions $c_F(Q_F)$ and $c_C(Q_C)$ described in the text also be denominated in terms of units of labor required for energy production. Normalize labor to have a price of \$1 per unit, so that $U(C_e) + z$ represents consumers' money-metric utility, and $c_F(Q_F)$ and $c_C(Q_C)$ are the money-denominated costs of energy production. Then the planner's problem in autarky is:

$$\begin{aligned} \max_{t_u,t_e,s_c} W &= U(Q_F(\mathcal{T}) + Q_C(\mathcal{T})) + z(\mathcal{T}) - \phi Q_F(\mathcal{T}), \\ \text{s.t. } & c_F(Q_F(\mathcal{T})) + c_C(Q_C(\mathcal{T})) + z(\mathcal{T}) = L. \end{aligned} \tag{A.1}$$

Equation (1) in the text follows from substituting the constraint into the objective function, thereby eliminating z, and noting that labor L is a fixed constant.

In the open economy problem, let ROW also have a fixed supply of labor L^R and quasi-linear consumption utility. Elimination of terms-of-trade effects implies that Home seeks to maximize the sum of Home's and ROW's utilities net of climate damages, subject to both regions' labor availability constraints and the global energy balance constraint:

$$\begin{aligned} \max_{t_u,t_e,s_c} W = U(C_e(\mathcal{T})) + z(\mathcal{T}) - \phi Q_F(\mathcal{T}) + U^R(C_e^R(\mathcal{T})) + z^R(\mathcal{T}) - \phi Q_F^R(\mathcal{T}), \\ \text{s.t. } c_F(Q_F(\mathcal{T})) + c_C(Q_C(\mathcal{T})) + z(\mathcal{T}) = L, \\ c_F^R(Q_F^R(\mathcal{T})) + c_C^R(Q_C^R(\mathcal{T})) + z^R(\mathcal{T}) = L^R, \\ Q_F(\mathcal{T}) + Q_C(\mathcal{T}) + Q_F^R(\mathcal{T}) + Q_C^R(\mathcal{T}) = C_e(\mathcal{T}) + C_e^R(\mathcal{T}). \end{aligned} \tag{A.2}$$

The planner's problem (2) in the text follows from substituting both labor constraints into the objective function, thereby eliminating z and z^R, and noting that labor L and L^R are fixed constants.

A.2 Surplus-maximizing policies

First, without trade in fossil energy or in energy-intensive goods, the planner's problem is given by equation (1) in the main text. The first-order conditions (FOCs) for the solution are:

$$\begin{aligned}
(U' - c'_F - \phi)\frac{\partial Q_F}{\partial t_u} + (U' - c'_C)\frac{\partial Q_C}{\partial t_u} &= 0 \\
(U' - c'_F - \phi)\frac{\partial Q_F}{\partial t_e} + (U' - c'_C)\frac{\partial Q_C}{\partial t_e} &= 0 \\
(U' - c'_F - \phi)\frac{\partial Q_F}{\partial s_c} + (U' - c'_C)\frac{\partial Q_C}{\partial s_c} &= 0
\end{aligned}$$

The solution is jointly satisfied by setting $t_u + t_e = \phi$ and $s_c = 0$, as described in the main text.

I next derive the surplus-maximizing policies given by equation (5) in the main text, allowing for trade in both fossil energy and energy-intensive goods.

Per the main text, C_e denotes Home's consumption of energy both for production of domestically-consumed goods and services and for production of goods and services that are exported to ROW. C_e^R is defined similarly for ROW. In what follows it is useful to unpack these variables. Define $C_e \equiv C_{ed} + C_{ex}$, where C_{ed} is embodied energy in goods that are produced and consumed domestically, and C_{ex} is embodied energy in goods that are produced domestically and exported to ROW. Define $C_e^R \equiv C_{ed}^R + C_{ex}^R$ similarly. Imports of embodied energy in goods are given by $C_{em} \equiv C_{ex}^R$, and by $C_{em}^R \equiv C_{ex}$.

Home's money-valued consumption utility is now defined as $U(C_{ed}, C_{em})$, with partial derivatives $U_{ed} = P + t_u$ and $U_{em} = P$ in equilibrium. ROW's money-valued consumption utility is defined similarly as $U^R(C_{ed}^R, C_{em}^R)$, with partial derivatives $U_{ed}^R = P$ and $U_{em}^R = P + t_u$ in equilibrium.

The planner's problem is then:

$$\begin{aligned}
\max_{t_u, t_e, s_c} & \; U(C_{ed}(\mathcal{T}), C_{em}(\mathcal{T})) - c_F(Q_F(\mathcal{T})) - c_C(Q_C(\mathcal{T})) \\
& + U^R(C_{ed}^R(\mathcal{T}), C_{em}^R(\mathcal{T})) - c_F^R(Q_F^R(\mathcal{T})) - c_C^R(Q_C^R(\mathcal{T})) \\
& - \phi(Q_F(\mathcal{T}) + Q_F^R(\mathcal{T})), \\
\text{subject to } & \; Q_F + Q_C + Q_F^R + Q_C^R = C_e + C_e^R.
\end{aligned} \tag{A.3}$$

To derive the surplus-maximizing policies, begin by rearranging the global energy balance constraint and writing each variable as a function of the ROW energy price P and the policy variables:

$$Q_F(P - t_e) + Q_C(P + t_u + s_c) + Q_F^R(P) + Q_C^R(P) - C_e(P, t_u) - C_e^R(P, t_u) = 0. \tag{A.4}$$

Define $X' \equiv S_F' + S_C' + S_F^{R'} + S_C^{R'} - D_e' - D_e^{R'}$. The implicit function theorem implies that the ROW energy price P changes with the policy variables (t_u, t_e, s_c) in the following way:

$$\begin{aligned} \frac{dP}{dt_u} &= \frac{\partial(C_e + C_e^R)/\partial t_u - S_C'}{X'}, \\ \frac{dP}{dt_e} &= \frac{S_F'}{X'}, \\ \frac{dP}{ds_c} &= -\frac{S_C'}{X'}. \end{aligned} \tag{A.5}$$

To find the surplus-maximizing policies, set the total derivative of the planner's objective in (A.3) with respect to each instrument equal to zero. Applying the envelope theorem to firms' and consumers' optimization problems, and using the equilibrium conditions above (competitive supply, along with $U_{ed} = P + t_u$, $U_{em} = P$, $U_{ed}^R = P$, and $U_{em}^R = P + t_u$), the production and consumption changes valued at the common price P net out through the global energy balance constraint. The welfare change from a marginal policy change then reduces to

$$dW = t_u\, dC_e + t_e\, dQ_F - (t_u + s_c)\, dQ_C - \phi\, (dQ_F + dQ_F^R). \tag{A.6}$$

The three terms other than the externality reflect the wedges created by the use tax on Home's energy consumption, the extraction tax on Home's fossil production, and the net subsidy $t_u + s_c$ on Home's clean production.

We can now derive the three first-order conditions by combining the welfare change formula from (A.6) with the equilibrium responses $dQ_F = S_F'(dP - dt_e)$, $dQ_C = S_C'(dP + dt_u + ds_c)$, $dQ_F^R = S_F^{R'}\, dP$, and $dC_e = D_e'\, dP + (\partial C_e/\partial t_u)\, dt_u$, and with the price derivatives from equation (A.5). Multiplying each condition by X' yields:

$$\begin{aligned} FOC_{t_u}\colon \quad & \left(\frac{\partial(C_e + C_e^R)}{\partial t_u} - S_C'\right)\left[t_u D_e' + t_e S_F' - (t_u + s_c) S_C' - \phi(S_F' + S_F^{R'})\right] \\ & \qquad + X'\left[t_u \frac{\partial C_e}{\partial t_u} - (t_u + s_c) S_C'\right] = 0, \end{aligned} \tag{A.7}$$

$$FOC_{t_e}\colon \quad t_u D_e' + t_e(S_F' - X') - (t_u + s_c) S_C' - \phi(S_F' + S_F^{R'} - X') = 0, \tag{A.8}$$

$$FOC_{s_c}\colon \quad t_u D_e' + t_e S_F' + (t_u + s_c)(X' - S_C') - \phi(S_F' + S_F^{R'}) = 0. \tag{A.9}$$

Together, equations (A.8) and (A.9) imply that $t_u + t_e + s_c = \phi$, so that the sum of the three instruments equals the social cost of carbon. Substituting for s_c in the extraction tax condition (A.8) using this sum, the Home supply slopes S'_F and S'_C cancel, leaving

$$t_u D'_e - t_e\left(S_F^{R'} + S_C^{R'} - D'_e - D_e^{R'}\right) + \phi\left(S_C^{R'} - D'_e - D_e^{R'}\right) = 0. \tag{A.10}$$

To simplify the use tax condition (A.7), first use (A.9) to rewrite its first bracketed factor as

$$t_u D'_e + t_e S'_F - (t_u + s_c)S'_C - \phi(S'_F + S_F^{R'}) = -(t_u + s_c)(X' - S'_C) - (t_u + s_c)S'_C = -(t_u + s_c)X'.$$

Substituting this into (A.7), dividing by X', and writing $\partial(C_e + C_e^R)/\partial t_u = (1 - \Lambda)\,\partial C_e/\partial t_u$ — where $\Lambda \equiv -(\partial C_e^R/\partial t_u)/(\partial C_e/\partial t_u)$ is the leakage rate from equation (4) — gives

$$-(t_u + s_c)\left[(1 - \Lambda)\frac{\partial C_e}{\partial t_u} - S'_C\right] + t_u\frac{\partial C_e}{\partial t_u} - (t_u + s_c)S'_C = 0.$$

The $(t_u+s_c)S'_C$ terms cancel, and dividing through by $\partial C_e/\partial t_u \neq 0$ leaves $t_u = (1-\Lambda)(t_u+s_c)$. Substituting the sum $t_u + s_c = \phi - t_e$ then gives

$$t_u = (1 - \Lambda)(\phi - t_e). \tag{A.11}$$

Substituting (A.11) into (A.10) and collecting terms gives t_e^*; the sum $t_u + t_e + s_c = \phi$ and equation (A.11) then give t_u^* and s_c^*:

$$\begin{aligned} t_u^* &= \phi\frac{(1 - \Lambda)S_F^{R'}}{S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda D'_e}, \\ t_e^* &= \phi\frac{S_C^{R'} - D_e^{R'} - \Lambda D'_e}{S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda D'_e}, \\ s_c^* &= \phi\frac{\Lambda S_F^{R'}}{S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda D'_e}, \end{aligned} \tag{A.12}$$

which are the surplus-maximizing policies reported in equation (5) of the main text.

A.3 Policies with two of three instruments

This section derives the surplus-maximizing policies when only two of the three instruments are available. In each case the planner optimizes over the two available instruments, so the starting point is the pair of first-order conditions among (A.7)–(A.9) that correspond to those instruments, with the omitted instrument set to zero. Throughout I use the leakage rate Λ defined in equation (4); for the case without a clean subsidy I use the modified rate

$$\Lambda_s \equiv -\frac{\partial C_e^R/\partial t_u}{\partial C_e/\partial t_u - S_C'}, \tag{A.13}$$

which measures leakage relative to the use-tax response of fossil energy demand (energy demand net of clean supply), rather than of total energy demand. It follows from (A.13) that $\partial(C_e + C_e^R)/\partial t_u - S_C' = (1 - \Lambda_s)(\partial C_e/\partial t_u - S_C')$.

Carbon taxes only ($s_c = 0$)

The planner chooses t_u and t_e using (A.7) and (A.8). Setting $s_c = 0$ in (A.8) and rearranging,

$$t_u D_e' + t_e S_F' - t_u S_C' - \phi(S_F' + S_F^{R\prime}) = -X'(\phi - t_e),$$

which is exactly the first bracketed factor of (A.7). Substituting this expression into (A.7) with $s_c = 0$, and using $\partial(C_e+C_e^R)/\partial t_u - S_C' = (1-\Lambda_s)(\partial C_e/\partial t_u - S_C')$, the condition becomes

$$X' \left(\frac{\partial C_e}{\partial t_u} - S_C'\right) [t_u - (1 - \Lambda_s)(\phi - t_e)] = 0,$$

so that, analogous to (A.11),

$$t_u = (1 - \Lambda_s)(\phi - t_e). \tag{A.14}$$

Substituting (A.14) into (A.8) with $s_c = 0$ and collecting terms gives

$$\begin{aligned} t_u^* &= \phi \frac{(1 - \Lambda_s)S_F^{R\prime}}{S_F^{R\prime} + S_C^{R\prime} - D_e^{R\prime} - \Lambda_s(D_e' - S_C')}, \\ t_e^* &= \phi \frac{S_C^{R\prime} - D_e^{R\prime} - \Lambda_s(D_e' - S_C')}{S_F^{R\prime} + S_C^{R\prime} - D_e^{R\prime} - \Lambda_s(D_e' - S_C')}, \\ s_c^* &= 0. \end{aligned} \tag{A.15}$$

Relative to the full-instrument solution (A.12), the leakage rate Λ is replaced by Λ_s and the Home demand slope D_e' by the Home fossil-demand slope $D_e' - S_C'$. In contrast to the full-instrument case, where the three instruments sum to ϕ, the two taxes here sum to strictly less than the SCC ϕ.

Demand-side policies only ($t_e = 0$)

The planner chooses t_u and s_c using (A.7) and (A.9). As in the full derivation, setting $t_e = 0$ in (A.9) implies that the first bracketed factor of (A.7) equals $-(t_u + s_c)X'$, so (A.7) again reduces to the split $t_u = (1-\Lambda)(t_u + s_c)$. Substituting this split into (A.9) with $t_e = 0$,

$$(t_u + s_c)\left[(1-\Lambda)D_e' + X' - S_C'\right] = \phi(S_F' + S_F^{R\prime}),$$

and since $(1-\Lambda)D_e' + X' - S_C' = S_F' + S_F^{R\prime} + S_C^{R\prime} - D_e^{R\prime} - \Lambda D_e'$, the split then delivers

$$\begin{aligned} t_u^* &= \phi \frac{(1-\Lambda)(S_F' + S_F^{R\prime})}{S_F' + S_F^{R\prime} + S_C^{R\prime} - D_e^{R\prime} - \Lambda D_e'}, \\ t_e^* &= 0, \\ s_c^* &= \phi \frac{\Lambda(S_F' + S_F^{R\prime})}{S_F' + S_F^{R\prime} + S_C^{R\prime} - D_e^{R\prime} - \Lambda D_e'}. \end{aligned} \tag{A.16}$$

Again, in contrast to the full-instrument case, the two instruments here sum to strictly less than the SCC ϕ.

No carbon use tax ($t_u = 0$)

The planner chooses t_e and s_c using (A.8) and (A.9). These are the two conditions that yielded the Pigouvian sum, so with $t_u = 0$ they still imply $t_e + s_c = \phi$. Substituting $s_c = \phi - t_e$ into (A.8) with $t_u = 0$, the Home supply slopes S_F' and S_C' cancel as before, leaving $t_e(S_F^{R\prime} + S_C^{R\prime} - D_e' - D_e^{R\prime}) = \phi(S_C^{R\prime} - D_e' - D_e^{R\prime})$, so that

$$\begin{aligned} t_u^* &= 0, \\ t_e^* &= \phi \frac{S_C^{R\prime} - D_e' - D_e^{R\prime}}{S_F^{R\prime} + S_C^{R\prime} - D_e' - D_e^{R\prime}}, \\ s_c^* &= \phi \frac{S_F^{R\prime}}{S_F^{R\prime} + S_C^{R\prime} - D_e' - D_e^{R\prime}}. \end{aligned} \tag{A.17}$$

Here the extraction tax and clean subsidy sum to the SCC. Because there is no use tax, there is no use-tax leakage channel, and the leakage rate Λ drops out. These expressions match the surplus-maximizing extraction tax and clean subsidy given by equations (11) and (12) in Kay (2025), which does not include a use tax in its model.

A.4 Policies with a single instrument

This section derives the surplus-maximizing policy when only one of the three instruments is available. Because the planner now optimizes over a single instrument, only one of the first-order conditions (A.7)–(A.9) applies in each case, evaluated with the other two instruments set to zero.

Carbon use tax only ($t_e = s_c = 0$)

Setting $t_e = s_c = 0$ in (A.7), the condition becomes

$$\left(\frac{\partial(C_e + C_e^R)}{\partial t_u} - S_C'\right)\left[t_u(D_e' - S_C') - \phi(S_F' + S_F^{R'})\right] + X'\, t_u \left(\frac{\partial C_e}{\partial t_u} - S_C'\right) = 0.$$

Using $\partial(C_e + C_e^R)/\partial t_u - S_C' = (1 - \Lambda_s)(\partial C_e/\partial t_u - S_C')$ from (A.13) and dividing through by $\partial C_e/\partial t_u - S_C' \neq 0$ gives

$$t_u\left[(1 - \Lambda_s)(D_e' - S_C') + X'\right] = \phi(1 - \Lambda_s)(S_F' + S_F^{R'}).$$

The solution is then

$$t_u^* = \phi \frac{(1 - \Lambda_s)(S_F' + S_F^{R'})}{S_F' + S_F^{R'} + S_C^{R'} - D_e^{R'} - \Lambda_s(D_e' - S_C')}. \tag{A.18}$$

Carbon extraction tax only ($t_u = s_c = 0$)

Setting $t_u = s_c = 0$ in (A.8) leaves $t_e(S_F' - X') = \phi(S_F' + S_F^{R'} - X')$. Hence,

$$t_e^* = \phi \frac{S_C' + S_C^{R'} - D_e' - D_e^{R'}}{S_C' + S_F^{R'} + S_C^{R'} - D_e' - D_e^{R'}}. \tag{A.19}$$

Clean energy subsidy only ($t_u = t_e = 0$)

Setting $t_u = t_e = 0$ in (A.9) leaves $s_c(X' - S_C') = \phi(S_F' + S_F^{R'})$. Hence,

$$s_c^* = \phi \frac{S_F' + S_F^{R'}}{S_F' + S_F^{R'} + S_C^{R'} - D_e' - D_e^{R'}}. \tag{A.20}$$

B Calibration details

In the country-level energy production and consumption data from U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b), 2023 total global energy production exceeds consumption by 10.2 QBtu, due to measurement error and changes in energy stocks. I increase ROW energy consumption by this amount to ensure that global energy production and consumption are balanced in the analysis dataset.

To convert primary energy from non-thermal clean sources to thermal equivalents, I compute the average heat rate for fossil sources, weighted by net generation from each fossil source. I obtain heat rates for coal, petroleum, and natural gas generators from table 8.1 of U.S. Energy Information Administration (2025), and net generation from each fuel from table 3.1.A of the same publication.

To compute the baseline average fossil fuel price, I use 2023 prices of \$14.23/mmBtu for oil, \$12.30/mmBtu for natural gas, and \$5.44/mmBtu for coal. The oil price is the Brent price from U.S. Energy Information Administration (2024), the natural gas price is the UK National Balancing Point price from Energy Institute (2024), and the coal price is the Northwest Europe price from Energy Institute (2024).

For the elasticity of global energy demand, the average long-run estimate of -0.61 in Labandeira, Labeaga and López-Otero's (2017) meta-analysis is similar to the long-run elasticity of -0.5 that I used for oil demand in prior work (Kellogg, 2024), based on Krupnick, Morgenstern, Balke, Brown, Herrera and Mohan (2017) and Balke and Brown (2018).

For global oil supply, Krupnick et al. (2017) and Balke and Brown (2018) estimate long-run elasticities of 0.51 and 0.55, respectively, using a DSGE model and data on oil production, prices, and demand shocks. Because oil production is extremely inelastic in the short run (Anderson, Kellogg and Salant, 2018), some recent work has focused on the elasticity of drilling investments rather than production, focusing on the U.S. where high-quality data are available. Anderson et al. (2018) estimates an investment elasticity of 0.732 for conventional Texas oil wells, Newell and Prest (2019) finds an elasticity of 1.2 for U.S. shale wells (after correcting for productivity reductions when the oil price is high), and Covert and Kellogg (forthcoming) estimates an elasticity of 1.32 for the Bakken.

Less is known regarding the supply elasticities of natural gas and coal. Hausman and Kellogg (2015) estimates an elasticity of 0.81 for drilling of U.S. natural gas wells, and Newell, Prest and Vissing (2016) estimates a drilling elasticity of 0.7. Abuin (2025) estimates production elasticities of 0.239 for global gas production and 0.769 for global coal production, using annual data.

For clean energy supply, Abuin (2025) reports that increased LNG exports would increase

U.S. natural gas prices by 5.4%, decrease ROW natural gas prices by 2.5%, increase U.S. renewable generation by 150 TWh, and decrease ROW renewable generation by 150 TWh. These values, combined with total U.S. and ROW clean energy generation, yield the long-run clean energy supply elasticities of 1.58 for the U.S. and 0.47 for ROW reported in footnote 16 in the paper.

For the leakage rate Λ, I use values of 0.10 for the U.S. and 0.20 for the EU, roughly in the center of estimates from recent papers that either estimate leakage directly or evaluate leakage through calibrated models. In the former category, Fowlie and Reguant (2022) and Misch and Wingender (2024) use variation in local energy prices, relative to global prices, to estimate how embodied energy use, imports, and exports respond to local energy price shocks. Fowlie and Reguant (2022) focuses on U.S. manufacturing and finds a median (mean) leakage rate of 0.37 (0.46) across sectors. Those values are over-estimates of Λ in this paper's model because Λ is an economy-wide leakage rate that includes changes in direct consumption of energy (e.g., personal transportation and space heating) in its denominator. Misch and Wingender (2024) estimates economy-wide leakage rates for a long list of countries and coalitions; its estimated U.S. leakage rate is 0.07, and that for the EU is 0.15. The estimates from both papers are noisy, and the implied leakage rates are upper bounds because they assume that the increase in non-participating countries' net exports of embodied carbon does not decrease their consumption of embodied carbon from their domestically-produced goods.

Böhringer, Fischer and Rivers (2026) computes leakage rates for the U.S. and EU using a computable general equilibrium model. For an emissions price of \$100/tonne (charged to domestic carbon users, not extractors), it estimates a U.S. leakage rate of 0.06 and an EU leakage rate of 0.17. Earlier papers with similar methods (Paroussos, Fragkos, Capros and Fragkiadakis, 2015; Böhringer, Bye, Fæhn and Rosendahl, 2017) find somewhat larger leakage rates for the EU, ranging from 0.20 to 0.28, though the emissions price scenarios differ. Each of these leakage estimates includes leakage driven by a decrease in the global price of fossil fuels, so that they are over-estimates of the leakage rate Λ in this paper's model, which only includes leakage driven by changes in embodied carbon from trade in goods.

B.1 Calibration of Λ_s for the model with no clean energy subsidy

If the clean energy subsidy is not used, the leakage rate Λ in the optimal tax formulas changes to Λ_s, per equation (A.13):

$$\Lambda_s = -\frac{\partial C_e^R / \partial t_u}{\partial C_e / \partial t_u - S_C'} \tag{B.21}$$

Given values for $\partial C_e/\partial t_u$ and S_C', I can evaluate Λ_s as $\Lambda_s = \Lambda \cdot \frac{\partial C_e/\partial t_u}{\partial C_e/\partial t_u - S_C'}$. S_C' is readily computed using the clean energy supply elasticity of $\eta_C = 0.75$ from the main text. $\partial C_e/\partial t_u = \eta_{t_u}^d C_{ed} + \eta_{t_u}^x C_{ex}$, where $\eta_{t_u}^d$ and $\eta_{t_u}^x$ are the elasticities of domestic energy use and energy embodied in exports with respect to the local energy price, and C_{ed} and C_{ex} denote energy used for domestic consumption and exports, respectively. Fowlie and Reguant (2022) provides estimates of these elasticities in its figure 1. Roughly averaging across the specifications suggests elasticities of -0.079 for domestic consumption ($\eta_{t_u}^d$), -0.126 for exports ($\eta_{t_u}^x$), and 0.063 for imports ($\eta_{t_u}^m$).[1] However, the Fowlie and Reguant (2022) elasticities are short-run elasticities, and thus understate the true long-run elasticities that are comparable to η_C, the elasticity of clean energy supply.

Define $r^m \equiv \eta_{t_u}^m/\eta_{t_u}^d$ and $r^x \equiv \eta_{t_u}^x/\eta_{t_u}^d$. I assume that the long-run elasticities are proportional to the short-run elasticities. To obtain a long-run estimate of $\eta_{t_u}^d$ in levels, I assume that an increase in net imports completely crowds out domestic energy use. Thus, $\partial C_e/\partial t_u = \eta_E C_e - \eta_{t_u}^m C_{em} + \eta_{t_u}^x C_{ex}$, where η_E is the elasticity of global energy demand. This assumption implies that $\eta_{t_u}^d C_{ed} = \eta_E C_e - \eta_{t_u}^m C_{em}$, so that $\eta_{t_u}^d = \frac{\eta_E C_e}{C_{ed} + r^m C_{em}}$. Given a value for the elasticity of global energy demand η_E, I can then evaluate $\eta_{t_u}^d$ and subsequently $\partial C_e/\partial t_u$ and Λ_s. I obtain $\Lambda_s = 0.08$ for the U.S. and 0.17 for the EU.

[1] These values multiply the raw estimates in Fowlie and Reguant's (2022) figure 1 by the paper's reported average manufacturing energy intensity of 3.14 mmBtu per thousand USD, since the estimating equation divides by energy intensity.

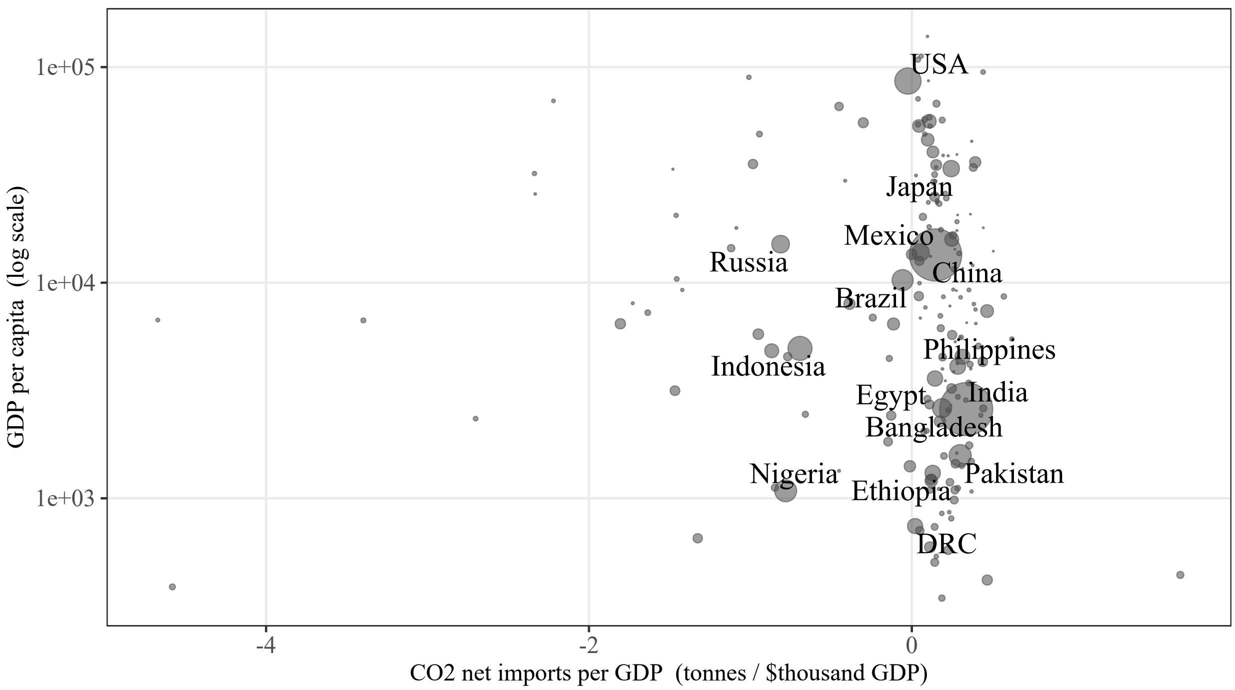
C Additional results

Table C.1: Surplus-maximizing policy combinations and global emissions reductions, with high energy supply elasticities

	US as "Home"				EU as "Home"			
	t_u	t_e	s_c	ΔE	t_u	t_e	s_c	ΔE
Without border tax adjustment:								
All three instruments:	\$24	\$23	\$3	-1.36Gt	\$23	\$21	\$6	-0.52Gt
No clean subsidy:	\$25	\$23		-1.35Gt	\$24	\$21		-0.49Gt
No extraction tax:	\$26		\$3	-0.71Gt	\$23		\$6	-0.48Gt
No use tax:		\$24	\$26	-0.99Gt		\$22	\$28	-0.32Gt
With border tax adjustment:								
All three instruments:	\$27	\$23	\$0	-1.45Gt	\$29	\$21	\$0	-0.64Gt
No extraction tax:	\$30		\$0	-0.82Gt	\$29		\$0	-0.60Gt

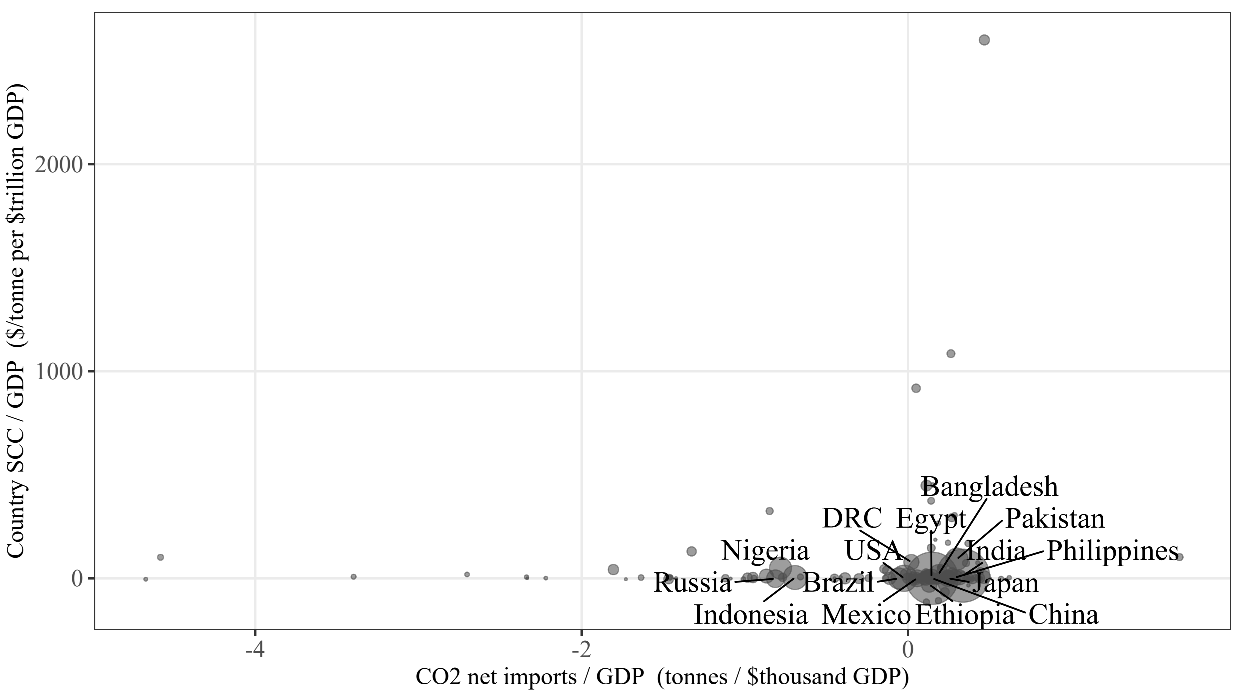
Notes: Table corresponds to table 2 from the main text, but using an elasticity of 1.50 for fossil and clean energy supply, rather than the elasticity of 0.75 used in the results presented in the main text. Table shows surplus-maximizing carbon use tax t_u, carbon extraction tax t_e, and clean energy subsidy s_c, in \$ per tonne of CO_2, per the model presented in section 3.1.2, treating either the U.S. or the EU as the "Home" country. ΔE shows the global change in emissions, in gigatonnes of CO_2 per year. The model's calibration is described in section 3.2 and uses an SCC of \$50/tonne.

Figure C.1: Country-level fossil fuel imports versus per-capita GDP



Note: This is the non-winsorized version of figure 4 from the main text. Data on CO_2 net imports from fossil fuel trade are from U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b). Data on GDP per capita are from International Monetary Fund (2026).

Figure C.2: Country-level fossil fuel imports versus social cost of carbon (SCC) estimates



Note: This is the non-winsorized version of figure 5 from the main text. Data on CO_2 net imports from fossil fuel trade are from U.S. Energy Information Administration (2026a) and U.S. Energy Information Administration (2026b). SCC estimates are from Carleton, Greenstone, Hsiang, Hultgren, Kopp, McCusker, Nath, Rising and Rode (2026). GDP data are from International Monetary Fund (2026).

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