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Rebating Revenues from Unilateral Emissions Pricing

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Rebating Revenues from Unilateral Emissions Pricing

Abstract

This paper evaluates alternative options for rebating revenues from a unilateral emissions price, focusing on energy-intensive and trade-exposed industries. A theoretical model is developed to demonstrate that conditional rebating policies—which would be distortionary in a first-best world—may be welfare-improving. For example, this could occur in a context where emissions leakage and terms-of-trade changes are associated with the introduction of an emissions price, or when political constraints prevent the emissions price from fully reflecting the social cost of the emissions. A numerical simulation model is used to quantify the differences in welfare, leakage, terms of trade, output, and emissions across carbon prices with alternative rebating options for these leakage-prone industries. The different situations of the European Union and the United States are used as examples. The findings indicate that from a domestic perspective, rebating emissions revenues proportionately to firm output is typically superior to other rebating options when the emissions price is set close to the social cost of emissions. Rebating emission revenues to reward reductions in emissions intensity is typically superior when emissions are significantly under-priced. A country that is more emissions-intensive and less exposed to leakage may prefer to rebate in proportion to total abatement when the emissions price is sufficiently low. The quantitative results indicate that there are significant welfare losses for incorrect choices of the rebating option.

JEL-Codes: D580, D620, H230, Q580.

Keywords: unilateral climate policy, carbon pricing, revenue recycling.

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1 Introduction

Despite global concern about climate change and the clear scientific case for carbon pricing as a cost-effective means for reducing emissions, only a minority of countries are putting a price on carbon.¹ In addition to being highly fragmented, carbon pricing worldwide is almost everywhere insufficiently stringent. Parry et al. (2021) report that the average emissions price imposed worldwide is only about US\$3/tCO₂, 30 to 100 times below recent estimates of the social cost of carbon (Barrage and Nordhaus, 2024; United States Environmental Protection Agency, 2022; Rennert et al., 2022; Environment and Climate Change Canada, 2022; Bilal and Känzig, 2024; Ricke et al., 2018).

One of the main reasons for the low ambition of existing carbon pricing policies is their political unpopularity (Douenne and Fabre, 2022; Dechezleprêtre et al., 2022; Baranzini and Carattini, 2017; Anderson et al., 2023). When asked about carbon pricing, survey respondents indicate that they do not believe carbon pricing will effectively reduce emissions (Douenne and Fabre, 2022), do not trust political parties that impose emissions prices (Anderson et al., 2023) or believe that carbon pricing will reduce their real incomes or increase income inequality (Douenne and Fabre, 2022). The globally fragmented nature of carbon pricing, with its drastic disparities in regional prices,² raises concerns about counterproductive emissions leakage and unfair impacts on competitiveness, particularly with respect to emissions-intensive and trade-exposed (EITE) industries.

As a consequence, policy makers in several countries with more ambitious carbon pricing policies in place have linked the emissions price to output-based allocations of emission permits for their EITE industries.³ Output-based rebating of revenues from emissions pricing acts as an implicit production subsidy (Fischer, 2001; Böhringer et al., 1998), and thus may

¹As of mid-2024, less than a quarter of global emissions are subject to an emissions price. See <https://carbonpricingdashboard.worldbank.org/>.

²As of mid-2024, the World Bank in its carbon pricing dashboard reports a price range of US\$0.46/tCO₂ to US\$167/tCO₂ for those countries that charge emissions prices.

³For example, output-based allocations of emission permits are used in Canada (<https://laws-lois.justice.gc.ca/eng/acts/g-11.55/>), California (<https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program>), China (Goulder et al., 2022), New Zealand (<https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/ets/nz-ets-market/>), and the European Union (https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/allocation-industrial-installations_en).

help to reduce emissions leakage (Fischer and Fox, 2012) and avoid excessive competitiveness losses (Böhringer et al., 2017; Rivers, 2010) relative to an emissions price stand-alone. As a consequence, output-based rebating may help loosen some political constraints to carbon pricing, but it does not help to address the inefficiently low emissions reductions from *lax* carbon pricing that remains from those constraints. Indeed, by implicitly subsidizing output, output-based rebating of carbon pricing increases emissions (Fischer, 2001; Fowlie and Reguant, 2022).

This paper considers alternative approaches to rebating revenues from an emissions price. As do existing free allocation policies in practice, we focus on EITE industries where concerns about carbon leakage and competitiveness losses are most prominent. Consistent with the empirical literature cited above and the observation that existing emissions prices are far below the social cost of carbon, we assume that political constraints prevent regulators from implementing an emissions price equal to the social cost of carbon. We are therefore interested in emissions revenue rebating schemes that can *both* help to mitigate emissions leakage as well as increase the emission reductions achieved with a given emissions price.

We build on Böhringer et al. (2023), who examine several rebating policies in a first-best setting, including output-based rebating, abatement-based rebating, and intensity-based rebating. That paper uses a partial equilibrium model to formally derive how the different approaches create different incentives for the choice of production levels and emissions intensities at the firm level, ignoring international spillover effects and political economy constraints. In this paper, we consider rebating policies in a second-best general equilibrium framework which incorporates international spillovers and political constraints on pricing emissions at the social cost of carbon.

We begin with a theoretical analysis that decomposes the welfare impacts from unilateral carbon pricing into (i) the net cost of carbon pricing for the domestic economy (i.e. the economy-wide cost of emissions abatement net of benefits from reduced domestic emissions), (ii) terms of trade changes, and (iii) carbon leakage. We show that if emissions prices are set below the social cost of carbon, the revenues should be rebated in a way that promotes additional emission reductions. When emissions prices (negatively) affect terms of trade or generate emissions leakage, rebating should be designed in a way that stimulates domestic

output in the EITE industries. We consider how alternative rebating options affect EITE firm incentives to reduce emissions as well as to increase output. We show that abatement-based rebating and intensity-based rebating may be desirable when the emissions price is constrained to a level below the social cost of carbon, and that output-based rebating and intensity-based rebating may be desirable as a result of sub-global coverage of emissions pricing.

We supplement our theoretical analysis with numerical simulations using a multi-sector multi-region computable general equilibrium model of the global economy to quantify the effects of alternative rebating schemes to EITE industries for the US and EU economies. The numerical results confirm the basic theoretical insight that the optimal rebating approach depends on the level of the emissions price relative to the social cost of carbon. If the emissions price is constrained to be much below the social cost of carbon, abatement-based rebating generates larger welfare gains relative to other rebating approaches. This approach generates the largest incentive to reduce emissions and helps to make up for the sub-optimally low emissions price. If the domestic emissions price is set at a level approaching the social cost of carbon, it is best to use output-based rebates to firms in the EITE sector. This approach supports output of domestic EITE firms most effectively, thereby limiting counterproductive emissions leakage. At intermediate levels, the numerical simulations suggest that intensity-based rebating is most effective, which can be explained by the fact that intensity-based rebating has elements of both abatement-based rebating, by stimulating additional emission reductions, and output-based rebating, by supporting EITE output.

Our analysis contributes to the large literature on sub-global carbon pricing. A wide range look at the use of complementary trade measures in an optimal tax framework. Markusen (1975) is an early contributor to this literature, showing that a unilateral emissions tax to combat a global externality should be combined with a tariff as a second-best instrument to correct for international spillovers. In recent examples, Kortum and Weisbach (2023) and Weisbach et al. (2023) develop an analytic model with extraction of fossil fuels, (traded) goods, and services. They show that the optimal unilateral policy includes both a tax on production of fossil fuels as well as on emissions and on goods that use fossil fuels as inputs. Others focus on how emissions taxes and rebates should be set in the absence of import tax

options. Hoel (1996) considers sub-global carbon pricing with heterogeneous industries and shows that it can be desirable to differentiate carbon taxes by sector to address emissions leakage; and Böhringer et al. (2014a) derive optimal emissions taxes in view of both leakage and terms-of-trade effects. Fischer and Fox (2012), Holland (2012), and Böhringer et al. (2014b) compare policies to address emissions leakage, focusing on output-based rebates and border carbon adjustments. Fowlie and Reguant (2022) and Bernard et al. (2007) derive the optimal output-based rebates to confront emissions leakage arising from incomplete coverage of carbon pricing.

Our analysis also contributes to the literature on carbon pricing in a second-best setting. Much of this literature focuses on optimal economy-wide carbon pricing in the presence of distortionary taxes. For example, Bovenberg and De Mooij (1994) show that in an economy with pre-existing taxes, the optimal carbon tax is below the social cost of carbon. Goulder et al. (1999) compare alternative policies for reducing emissions when other taxes are present, and show that instruments that do not raise revenues (like regulations) can outperform market-based instruments in some cases. Other studies consider second-best optimal responses to policy constraints, which may be motivated by political or institutional factors. Fischer et al. (2021) consider how policy portfolios should adjust to different policy constraints in a context of multiple market failures, when policy makers must confront technology spillovers as well as environmental externalities.

Our analysis differs from these previous contributions by evaluating a range of actual rebating policies to EITE sectors that have recently been implemented around the world. Our context includes trade, environmental, and domestic cost considerations. We focus on the implications of political constraints that impede optimal carbon pricing and find that the degree of underpricing of the emissions externality drives the welfare ranking of alternative rebating schemes.

The paper proceeds as follows. Section 2 describes the theoretical model that motivates the use of rebates from a unilateral emissions price. Section 3 describes the numerical model that we use for quantitative simulations. Section 4 presents results of our numerical simulations. Section 5 concludes.

2 Theoretical model

2.1 Model setup

There are two regions, domestic and foreign ($r, s \in \{D, F\}$). The structure of each is similar, with a representative agent consumer who supplies a factor of production L to two sectors ($i \in \{G, B\}$), an emission-intensive trade-exposed (EITE) sector B (for brown) and clean service sector G (for green), which is untraded, and which has a lower emissions intensity. The regulator in the domestic region puts a price on emissions. Any revenue raised from pricing emissions in the green sector is rebated to consumers in a non-distortionary manner. The revenue raised from pricing emissions in the brown sector is rebated back to firms in that sector. Our focus is on rebating of emissions pricing revenues to brown (emissions intensive trade-exposed) firms.

Emissions from sector i in region r , E_i^r , are the product of the level of production Y_i^r and the emissions intensity of that production, μ_i^r :

$$E_i^r = \mu_i^r Y_i^r. \quad (1)$$

The labor input L_r^i required to produce that level of output is the product of the level of production and the labor intensity of production, $l_i^r(\mu_i^r)$, which is assumed to be a (weakly) decreasing function of emissions intensity (μ_i^r):

$$L_i^r = l_i^r(\mu_i^r) Y_i^r. \quad (2)$$

The result is a production function that exhibits constant returns to scale: given the emissions intensity of the production process, doubling the labor input will lead to a doubling of both output and emissions. However, as emissions are a byproduct of the production process, rather than an input themselves, there is a finite emissions intensity that minimizes the labor requirement per unit of output, beyond which no further efficiency is gained by using a dirtier process. This baseline (no-policy) intensity μ_{i0}^r solves $-l_i^{r'}(\mu_i^r) = 0$.

The price of the good is p_i^r , and there is a tax on emissions τ^r . Emissions pricing revenues

are rebated to firms according to some function of firm output and emissions intensity, such that $R_i^r = R_i^r(\mu_i^r, Y_i^r)$. Firms are price takers in product, input, and emissions markets. The profit function for firm i in region r is therefore:

$$\pi_i^r = p_i^r Y_i^r - w^r l_i^r(\mu_i^r) Y_i^r - \tau^r \mu_i^r Y_i^r + R_i^r(\mu_i^r, Y_i^r),$$

with first-order conditions:

$$\frac{\partial \pi_i^r}{\partial Y_i^r} \longrightarrow p_i^r = w^r l_i^r(\mu_i^r) + \tau^r \mu_i^r - \frac{\partial R_i^r}{\partial Y_i^r} \quad \frac{\partial \pi_i^r}{\partial \mu_i^r} \longrightarrow -w^r l_i^r(\mu_i^r) = \tau^r - \frac{\partial R_i^r / \partial \mu_i^r}{Y_i^r}. \quad (3)$$

We further assume that $\tau^D > 0$ is exogenous, $\tau^F = 0$, and rebates only apply to brown domestic goods (our emissions-intensive trade-exposed sector). Therefore,

$$\begin{aligned} p_B^D &= w^D l_B^D(\mu_B^D) + \tau^D \mu_B^D - \frac{\partial R_B^D}{\partial Y_B^D} & -w^D l_B^D(\mu_B^D) &= \left(\tau^D - \frac{\partial R_B^D / \partial \mu_B^D}{Y_B^D} \right) \\ p_G^D &= w^D l_G^D(\mu_G^D) + \tau^D \mu_G^D & -w^D l_G^D(\mu_G^D) &= \tau^D \\ p_B^F &= w^F l_B^F(\mu_B^F) & -l_B^F(\mu_B^F) &= 0 \\ p_G^F &= w^F l_G^F(\mu_G^F) & -l_G^F(\mu_G^F) &= 0 \end{aligned} \quad (4)$$

Let w^F be the numeraire. Then foreign (nominal) prices are fixed: $p_G^F = l_{G0}^F$, and $p_B^F = l_{B0}^F$, where $l_{i0}^r \equiv l_i^r(\mu_{i0}^r)$.

Good G is non-traded, so production of G in region r is also consumed there. Good B is traded, and consumers have preferences for both domestic and foreign varieties. We denote exports of good B from region r as X_B^r , and all B is either consumed domestically or exported, such that domestic consumption of the domestically-produced brown good is:

$$D_B^r = Y_B^r - X_B^r. \quad (5)$$

Trade is balanced, such that:

$$X_B^D p_B^D = X_B^F p_B^F. \quad (6)$$

The representative agent utility function is given by:

$$U^r = U^r(D_B^r, X_B^s, Y_G^r). \quad (7)$$

Welfare is given by utility less the social cost of global emissions:

$$W^r = U^r - \delta^r E, \quad (8)$$

where E is (global) emissions, and δ^r is the social cost of global emissions to region r .

The consumer budget constraint is given by:

$$p_B^r D_B^r + p_B^s X_B^s + p_G^r Y_G^r = w^r L^r + T^r, \quad (9)$$

where T^r represents the lump-sum transfer of revenues collected from the emissions price on sector G to households ($T^r = \tau^r E_G^r$). We assume the household treats the total amount of this transfer as exogenous (i.e., equivalent to the assumption that there are a large number of households), such that first-order conditions are:

$$\frac{\partial U^r}{\partial D_B^r} = p_B^r \lambda^r \quad \frac{\partial U^r}{\partial D_B^s} = p_B^s \lambda^r \quad \frac{\partial U^r}{\partial Y_G^r} = p_G^r \lambda^r. \quad (10)$$

We assume the emissions pricing policy is revenue neutral, with all emissions payments collected from sector G used to provide lump-sum rebates T^r to households (in order to retain focus on industrial carbon pricing rebates), and all emissions taxes on B used to provide rebates to firms in sector B .

The market clearing condition for the labor market is:

$$L^r = L_B^r + L_G^r. \quad (11)$$

Total emissions E are given by:

$$E = \sum_r (E_B^r + E_G^r). \quad (12)$$

2.2 Model solution

We assume that the domestic region imposes a uniform emissions price τ^D across both sectors B and G . It rebates revenues raised from sector G to the domestic household in a non-distortionary manner. It rebates revenues raised from sector B back to that sector as described by $R^D(\mu_B^D, Y_B^D)$ – i.e., either as a function of firm emissions intensity, firm output, or both. The foreign region does not impose an emissions price, and consequently has no rebates.

We seek to understand how different rebating approaches affect welfare in the domestic economy. To do this, we totally differentiate domestic welfare (equation (8)), substitute the differentiated utility function ((7)), substitute consumer first-order conditions (10), the differentiated emission accounting equation (12), the differentiated production accounting equation (5), the differentiated balance-of-trade condition (6), the domestic labor market clearance condition (11), producer first-order conditions (3) and simplify to get:

$$\frac{dW^D}{\lambda^D} = - \underbrace{\tau^D(-dE^D)}_{\text{Abatement costs}} + \underbrace{\hat{\delta}(-dE^D)}_{\text{Domestic emissions reductions}} + \underbrace{dp_B^D X_B^D}_{\text{Terms of trade}} - \underbrace{\hat{\delta}dE^F}_{\text{Leakage}}, \quad (13)$$

where $\hat{\delta} = \delta^D/\lambda^D$ is the money-metric social cost of carbon in the domestic region, and λ^D is the shadow value of the budget constraint. The change in domestic emissions is:

$$\begin{aligned} dE^D = & \left(\mu_B^D - \frac{\mu_G^D l_B^D}{l_G^D} - \partial R_B^D / \partial Y_B^D \right) dY_B^D \\ & + \left(Y_B^D + \frac{\tau^D \mu_G^D Y_B^D}{w^D l_G^D} - \partial R_B^D / \partial \mu_B^D \left(\frac{\mu_G^D}{w^D l_G^D} + 1 \right) \right) d\mu_B^D \\ & + \left(Y_G^D + \frac{\tau^D \mu_G^D Y_G^D}{w^D l_G^D} \right) d\mu_G^D, \end{aligned}$$

and as the expression shows, it can be decomposed into a component reflecting changes in the composition of domestic output (first term) and components reflecting the emissions intensity of the brown and green domestic sectors (second and third terms).

The first term in (13) is the marginal decrease in domestic welfare associated with a reduction in domestic emissions. It reflects the increase in abatement costs (on the margin

equal to the lost emissions revenue) associated with those emission reductions. The second term reflects the domestic valuation of the avoided environmental damage associated with a decrease in domestic emissions. The first two terms reflect the net cost of a marginal change in domestic emissions, ignoring international spillovers. The third term reflects changes in the terms of trade, which can have positive or negative impacts on domestic welfare, depending on the sign of the price change of the traded brown good and the domestic trade balance. Finally, the last term reflects the domestic welfare costs associated with an increase in foreign emissions (emissions leakage).

At a welfare optimum, expression (13) equals zero. If there were no leakage, and no change in the terms of trade, optimal domestic policy would set the domestic emissions price at the social cost of carbon ($\tau^D = \hat{\delta}$), and rebates would not be required to generate any additional incentives (i.e., $\partial R^D / \partial \mu_B^D = \partial R^D / \partial q_B^D = 0$). This is the standard first-best solution (Baumol and Oates, 1988).

Our theoretical model admits three potential deviations from the first-best: 1) sub-global coverage of climate policy, which creates the potential for emissions leakage; 2) international trade, which (along with sub-global climate policy) creates the potential for manipulating terms of trade; and 3) (political) constraints on carbon pricing, which restrict τ^D to fall within an “acceptable” range, such that $\tau^D < \hat{\delta}^D$. In this second-best context, the question then becomes not one of setting an optimal emissions tax but rather the appropriate design of rebates.

Rebates can be designed to reward increases or reductions in firm output, as well as reductions in firm emissions intensity. Let $R_Y^D \equiv \partial R^D / \partial Y_B^D$ represent the change in rebate as a function of output and $R_\mu^D \equiv \partial R^D / \partial \mu_B^D$ represent the change in rebate as a function of emissions intensity. We determine optimal rebates (indicted with *) by differentiating equation (13) with respect to R_Y^D and R_μ^D , setting the resultant expressions equal to zero, combining the two expressions, and using the chain rule, yielding:⁴

$$-\frac{\partial R_B^{D*}}{\partial \mu_B^D} = \frac{(\hat{\delta} - \tau^D) \left(1 + \frac{\tau^D \mu_G^D}{w^D l_G^D}\right) (Y_G^D (d\mu_G^D / d\mu_B^D) + Y_B^D)}{1 - (\hat{\delta} - \tau^D) \mu_G^D / (w^D l_G^D)}, \quad (14)$$

⁴We use the fact that $d\mu_B^D / dR_Y^D = 0$ to generate these results.

and:

$$\frac{\partial R_B^D}{\partial Y_B^D} = \underbrace{\hat{\delta} \left(-\frac{dE^F}{dY_B^D} \right)}_{\text{benefit of avoided leakage}} - \underbrace{(\hat{\delta} - \tau^D) (\mu_B^D - \mu_G^D (l_B^D / l_G^D))}_{\text{underpriced emissions cost from output shifting}} + \underbrace{X_B^D \frac{dp_B^D}{dY_B^D}}_{\text{change in terms of trade}}. \quad (15)$$

The optimal marginal rebate for intensity reductions (equation (14)) is determined by the degree that the domestic emissions price falls below the social cost of emissions. In the special case where the green sector is completely clean, so $\mu_G = 0$, the optimal marginal intensity rebate per unit of output simply reflects the level of underpricing, $\hat{\delta} - \tau^D$. In the case where the green sector has a positive but fixed emissions intensity $\mu_G > 0$, the optimal marginal intensity rebate is scaled to reflect the substitution effect with the green sector, which is emitting but not directly affected by the rebate, such that the optimal per-unit marginal intensity rebate is $-(\partial R_B^D / \partial \mu_B^D)^* / Y_B^D > \hat{\delta} - \tau^D$.

The optimal marginal rebate for output is determined by three components (equation (15)). First, the optimal output-based rebate includes a component to address emissions leakage. This term is positive, and reflects the domestic benefits of foreign emission reductions. Second, the optimal output-based rebate includes a term that reflects the welfare costs of increased domestic output when domestic emissions are underpriced. This term is negative, and reflects the welfare cost of underpriced emissions. Third, the optimal output-based rebate includes a term that reflects changes in the terms of trade associated with changes in domestic production. This sign of this term is indeterminate, depending on the equilibrium price change associated with an increase in domestic production.

2.3 Alternative rebating instruments for the EITE sector

The prior section determined optimal *marginal* rebates for the brown EITE sector. However, regulators do not set marginal rebates directly, but instead design rebating schemes that in practice can imply different marginal rebates. In this section, we consider several rebating approaches that have been applied as parts of carbon pricing schemes worldwide. We determine marginal rebates for each of the rebating approaches we consider, and discuss the rebating approaches in comparison to the optimal characteristics of rebates determined above. Our approach and derivations follow Böhringer et al. (2023), who focus on partial

equilibrium results and rank the instruments according to incentives generated for firms in the EITE sector.

For each option, we will consider revenue-neutral rebates, such that all rebates are financed from the emissions payments by the brown sector. In other words, we will assume that the policy parameters are set such that, in the general equilibrium, all revenues are fully rebated. For notational convenience, we drop the region/sector superscripts/subscripts in this section; all rebates apply to the brown domestic sector only.

2.3.1 Lump sum rebating

Under lump sum rebating (LS), $\partial R^{\text{LS}}/\partial\mu = \partial R^{\text{LS}}/\partial Y = 0$, so the rebating generates no additional incentives.

2.3.2 Output-based rebating

Under output-based rebating (O), the rebate is $R^{\text{O}} \equiv \mu_b \tau Y$, where μ_b is the benchmark emissions intensity for the domestic brown sector. If the firm has an emissions intensity above this benchmark, it must purchase credits, whereas if its emissions intensity is below the benchmark, it generates credits that can be sold. With eligibility for rebates determined as above, we have: $\partial R^{\text{O}}/\partial Y = \mu_b \tau$, and $\partial R^{\text{O}}/\partial\mu = 0$. As is well-known, output based rebating acts as a subsidy to output, without distorting the choice of emissions intensity, given an emissions price (Fischer, 2001).

For the rebating scheme to be revenue neutral, in equilibrium $R^{\text{O}} = \tau\mu Y$, which implies that the benchmark is set to equal the equilibrium average emissions intensity: $\mu_b = \mu$.

2.3.3 Abatement-based rebating

Under abatement-based rebating, the rebate is conditional on reductions in emissions. We define $\mu_0 Y_0$ as (no-policy) benchmark emissions in the domestic brown sector. The domestic rebate is then $R^{\text{A}} \equiv s(\mu_0 Y_0 - \mu Y)$, where s is the rebate in dollars per ton, which firms take as given. As a result, we can derive $\partial R^{\text{A}}/\partial\mu = -sY$, and $\partial R^{\text{A}}/\partial Y = -s\mu$. Abatement-based rebating provides incentives for firms to reduce emissions, either by reducing output or by reducing emission intensity (Böhringer et al., 2023).

The firm takes these policy parameters as given, but the policy maker sets them to achieve revenue neutrality. $R^A = \tau\mu Y$ implies that the subsidy per unit of abatement that distributes all emissions revenues in equilibrium is $s = \tau\mu Y/(\mu_0 Y_0 - \mu Y)$.

2.3.4 Intensity-based output rebating

Under intensity-based output rebating (IO), the rebate is conditional on both intensity and output, such that $R^{IO} \equiv (\bar{\mu} - \mu)zY$, where z is in dollars per ton and expresses the size of the intensity- and output-conditional rebate and $\bar{\mu}$ is the benchmark for emissions intensity below which rebates are positive. As a result, for intensities at or below this benchmark, we can derive $\partial R^{IO}/\partial\mu = -zY$ and $\partial R^{IO}/\partial Y = (\bar{\mu} - \mu)z$. Intensity-based output rebating provides firms with an implicit subsidy to output (like output-based rebating) while also acting as an implicit tax on emissions (like abatement-based rebating) (Böhringer et al., 2023).

For this rebating scheme to be revenue neutral, $R^{IO} = \tau\mu Y$ implies that in equilibrium $z = \tau\mu/(\bar{\mu} - \mu)$.

2.3.5 Intensity-based emission rebating

Under intensity-based emission rebating (IE), firms are eligible for a reduction in the emissions price they face conditional on meeting an intensity-performance standard. This form of rebating can be represented as $R^{IE} \equiv \sigma(\mu)\tau\mu Y$, where the rebated share $\sigma(\mu)$ is a function of emissions intensity performance. Consider a policy where performance is compared relative to technology-based thresholds on a sliding scale. At or above an upper threshold $\tilde{\mu}$, firms receive no rebate ($\sigma(\tilde{\mu}) = 0$). At or below a lower target threshold $\underline{\mu}$ (e.g., best available technology), emission payments are completely rebated back to firms; i.e., $\sigma(\underline{\mu}) = 1$. For intensities in between these thresholds, we assume the rebated share of emissions payments follows the formula $\sigma(\mu) = (\tilde{\mu} - \mu)/(\tilde{\mu} - \underline{\mu})$ (Böhringer et al., 2023). We can then derive: $\partial R^{IE}/\partial Y = \tau\mu(\tilde{\mu} - \mu)/(\tilde{\mu} - \underline{\mu})$, and $\partial R^{IE}/\partial\mu = \tau Y(\tilde{\mu} - 2\mu)/(\tilde{\mu} - \underline{\mu})$. Like intensity-based output rebating, intensity-based emission rebating provides incentives for firms to increase output and to reduce emissions.

For intensity-based emissions rebating to be revenue neutral in equilibrium, $\sigma(\mu) = 1$

implies that the policy must set the lower bound of the sliding scale to equal the resulting equilibrium emissions intensity: $\underline{\mu} = \mu$.

2.4 Comparing policy instruments

Table 1 compares the alternative approaches to rebating we consider. We compare rebating approaches assuming the domestic emissions price is the same across all instruments. As noted, we consider revenue-neutral implementation of EITE rebating policies, such that all emissions pricing revenue generated from EITE emitters is rebated back to firms within the sector. Recall that revenue-neutrality is imposed at the sector level, not at the firm level, and we assume that individual firms take the parameters of the rebate mechanisms as given.

Table 1 shows that only lump sum rebating (LS) does not distort the output choice. Abatement based rebating (A) provides additional incentives for firms to reduce output. In contrast, output-based rebating (O), and the two forms of intensity based rebating (IE and IO) all implicitly subsidize output, and should yield higher equilibrium output as a result.⁵ Based on (15), O, and to a lesser extent IO and IE, will be a more desirable approach when emissions leakage is higher (e.g., when the country imposing the emissions price is highly trade exposed). However, the output incentive component will be less desirable if domestic emissions are underpriced and if an increase in brown domestic output reduces export values. In these circumstances, particularly when leakage is low, (15) suggests that LS or even A better reflect optimal marginal rebates on the output margin.

Table 1 shows that neither LS nor O distort the emissions intensity margin. Based on (14), these rebating approaches are likely to be most desirable when the emissions price is set at the social cost of carbon. Abatement based rebating (A) couples the emission tax with an abatement subsidy and generates larger emission reductions than under the LS policy. Like A, IO and IE also embed an implicit tax on emissions by rewarding reductions in emissions intensity. As shown in (14), these approaches are likely to be relatively more suitable when the domestic emissions price is below the social cost of carbon.⁶

⁵Böhringer et al. (2023) show that, given the same emissions price, the implicit subsidy under O is larger than under IE and IO, such that equilibrium output under O is highest.

⁶Böhringer et al. (2023) shows that O generates the least reduction in emissions compared to IE and IO. Emission reductions under IE and IO cannot be ranked, but Böhringer et al. (2023) show that IO generates

	$\frac{\partial R}{\partial Y}$	$\frac{\partial R}{\partial \mu}$	For revenue neutrality
LS	0	0	$R = \tau\mu Y$
O	$\mu_b \tau$	0	$\mu_b = \mu$
A	$-s\mu$	$-sY$	$s = \tau \frac{\mu Y}{\mu_0 Y_0 - \mu Y}$
IO	$(\bar{\mu} - \mu)z$	$-zY$	$z = \frac{\tau\mu}{\bar{\mu} - \mu}$
IE	$\frac{\bar{\mu} - \mu}{\bar{\mu} - \underline{\mu}} \tau \mu$	$\frac{\bar{\mu} - 2\mu}{\bar{\mu} - \underline{\mu}} \tau Y$	$\underline{\mu} = \mu$

Table 1: Comparing policy instruments. As per the text τ is the emissions price, μ is equilibrium emissions intensity, Y is equilibrium output. Note that μ and Y may differ across policy alternatives. μ_b is the intensity benchmark for output-based rebating, μ_0 and Y_0 are benchmark emission intensity and output for abatement-based rebating, $\bar{\mu}$ is the benchmark for intensity-based output rebating below which rebates are positive, and $\underline{\mu}$ and $\tilde{\mu}$ are the upper and lower threshold for intensity-based emission rebating.

IE further embeds an additional emissions subsidy, since the reward for reducing emissions intensity is a lowering of the equilibrium emission tax. At deep intensity reductions ($\mu < \tilde{\mu}/2$), this marginal emissions subsidy can even completely undermine the incentive to reduce emissions intensity (i.e., leading to $\partial R^{\text{IE}}/\partial \mu > 0$). However, when comparing revenue-neutral rebating schemes, it is possible that at certain targets the incentives of 100% rebates are excessive, so this feature of attenuating the additional intensity abatement incentive may be desirable in the second best.⁷

3 Numerical model

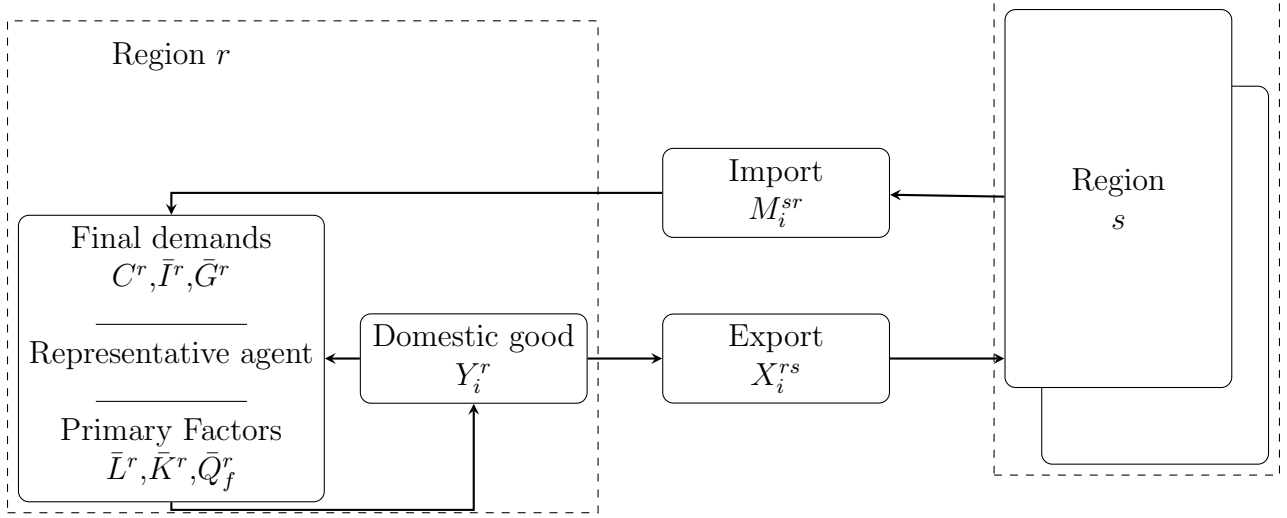
3.1 Model structure

We use a multi-sector multi-region computable general equilibrium (CGE) model of the global economy to quantify the economic and environmental impacts of alternative policy options for rebating revenues from unilateral emissions pricing. This allows us to take the qualitative insights from (14) and (15) as well as Table 1 to a realistic implementation con-

larger emission reductions in the numerical setting analyzed in that paper.

⁷Importantly, this analysis abstracts from firm heterogeneity. When firms are not identical, IE entails additional distortions, since the marginal incentive to reduce intensity per unit of output depends on firm-specific circumstances, meaning marginal abatement costs will not be equalized. We take up this issue in Fischer et al. (2024).

Figure 1: Flowchart of economic transactions in the CGE model



text. CGE models are a numerical simulation method to perform economy-wide impact assessments of policy reforms based on microeconomic theory and data (Shoven and Whalley, 1992). More specifically, CGE models are rooted in general equilibrium theory that combines assumptions regarding the optimizing behavior of economic agents with the analysis of equilibrium conditions. Producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers maximize their well-being subject to budget constraints and preferences. Substitution and transformation possibilities in production and consumption are typically described by flexible functional forms which capture price-responsiveness based on empirical estimates of elasticities and initial cost shares derived from empirical economic accounts. The disaggregation of macroeconomic production, consumption, and trade at the sector level using regional input–output tables enables the analysis of structural change triggered by policy changes and thus the identification of policy-relevant trade-offs between sector-specific incidence and macroeconomic performance.

For the sake of brevity, we confine ourselves to a brief non-technical summary of the generic model structure (a detailed algebraic exposition of the canonical multi-sector multi-region CGE model is provided by Böhringer et al. (2015)). Figure 1 shows a stylized flowchart of economic transactions.

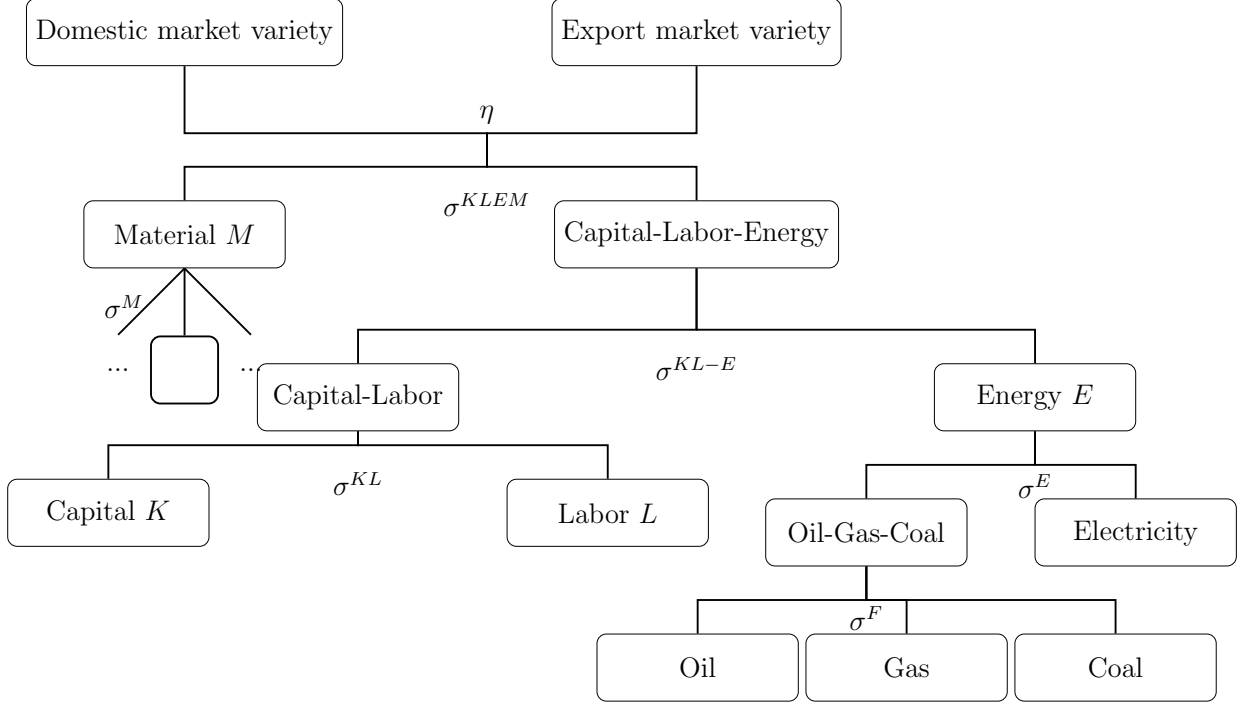
A representative agent RA^r in each region r (alias s) is endowed with three primary

factors in fixed supply: labor \bar{L}^r and capital \bar{K}^r which are both mobile across sectors with a region but immobile across regions; and fuel resources \bar{Q}_f^r which are specific to fossil fuel production sectors f in each region. The representative agent receives income from factor earnings and tax revenues net of subsidies. Final demand of a consumption bundle Y_C^r is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment Y_I^r (i.e., a given demand for savings) and exogenous government provision Y_G^r of public goods and services. The production Y_i^r of good i (including the composite consumption, investments, and public goods) in region r requires primary factor inputs as well as intermediate production inputs. Intermediate inputs combine domestically produced goods and goods Msr_i of the same variety imported from other regions s . Domestically produced goods are split into exports supply Xrs_i to other region s and domestic supply to the production of the intermediate good. The production Y_i^r of goods other than fossil fuels is represented through a four-level nested separable constant-elasticity-of-substitution (CES) functions that describe the price-dependent use of capital, labor, energy and non-energy (material) inputs (see Figure 2).

At the top level, a CES composite of intermediate (non-energy) material inputs trades off with an aggregate of energy, capital, and labor at an elasticity of substitution σ^{KLEM} . At the second level, a CES function with elasticity σ^{KL-E} describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labor and capital. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function with elasticity σ^{KL} whereas the substitution possibilities within energy composite are represented by a CES function of a fossil fuel composite and electricity with elasticity σ^E . At the fourth level, non-electric energy goods (coal, refined oil, and gas) trade off at a constant elasticity of substitution σ^F . The output in each production sector is allocated either to the domestic market or the export market according to a constant-elasticity-of-transformation (CET) function with elasticity η . In the production of primary fossil fuels (coal, gas, and crude oil), the specific resource trades off with a Leontief composite of all other inputs at a constant elasticity of substitution which is calibrated to empirical estimates for fuel supply elasticities.

Carbon emissions are linked in fixed fuel-specific proportions to the use of coal, refined

Figure 2: Production structure for a representative industry



oil, and gas. Carbon abatement induced by carbon pricing can come from fuel switching (substitution between fuels) or energy savings (either by substituting fuels with non-fuels or by reducing production and consumption activities).

Our multi-region CGE model features bilateral trade flows which implies that production and consumption decisions in a given region will affect international prices depending on initial trade shares and trade elasticities. As for the representation of international trade, which is central to the assessment of leakage and competitiveness impacts, we adopt the Armington assumption of product heterogeneity (Armington, 1969) for all traded goods. More specifically, countries are assumed to produce regionally differentiated goods under perfect competition, and these imported and domestically produced differentiated goods are combined in a constant elasticity of substitution (CES) demand system. The Armington assumption has several advantages: (i) it accommodates the empirical observation that a country imports and exports the same good (so-called cross-hauling); (ii) it avoids overspecialization implicit to trade in homogeneous goods; and (iii) it is consistent with trade in geographically differentiated products. An important implication of the Armington setting

is the allocation of market power over distinct varieties to countries (national authorities) rather than firms which behave competitively (De Melo and Robinson, 1989; Balistreri and Markusen, 2009). Product differentiation then may provide incentives at the national level to extract terms-of-trade gains through explicit trade restrictions (e.g. tariffs or import/export quotas) or other policy regulations such as unilateral emissions pricing: To the extent that trading partners cannot easily substitute away from imported good varieties, the unilaterally acting region can realize terms of trade gains. Regarding the foreign closure, each region faces a balance of payment constraint which incorporates its base-year trade deficit or surplus.

3.2 Data and parameterization

For model parameterization, we follow the standard calibration procedure in applied general equilibrium analysis: base-year input-output data together with elasticities determine the free parameters of the functional forms (cost and expenditure functions) such that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents represented in the model.

The base-year data stems from the Global Trade, Assistance and Production Project (GTAP) which includes detailed national input-output tables together with bilateral trade flows and CO₂ emission data for 141 regions and 65 sectors for the year 2014 Aguiar et al. (2019). Elasticities in international trade (Armington elasticities) as well as factor substitution elasticities are directly provided by the GTAP database. The elasticities of substitution in fossil fuel sectors are calibrated to match empirical estimates of fossil-fuel supply elasticities (Graham et al., 1999; Krichene, 2002; Ringlund et al., 2008).

We aggregate the GTAP dataset across sectors and regions focusing on the specific requirements of our research interest. As to sectors, our composite dataset explicitly features all primary and secondary energy carriers of GTAP (coal, crude oil, (natural) gas, refined oil, and electricity) which allows us to distinguish energy goods by CO₂ intensity and the degree of substitutability. We furthermore keep those GTAP sectors explicit in the aggregate dataset which are considered as emission-intensive and trade-exposed (EITE) industries (chemical products, non-metallic minerals, iron and steel, non-ferrous metals, paper-pulp-print) since these sectors are subject to competitiveness and leakage concerns making them

Region	CO ₂ intensity kg/\$	Trade index	CO ₂ (Mt)	Fossil fuel (EJ)	
				Production	Net exports
USA	0.30	0.13	5,156	122	−10
EU	0.19	0.18	2,882	43	−36
China	0.76	0.15	8,090	152	−22
India	0.94	0.19	1,912	29	−12
Other G20	0.34	0.20	4,426	138	13
Rest of World	0.39	0.21	7,554	241	68

Table 3: Base-year (2014) economic and environmental statistics (source: Aguiar et al. (2019)). The trade index is defined as (exports+imports)/(production+imports).

prime candidates for rebating policies. All remaining sectors in the GTAP database are aggregated to a composite sector (rest of industry and services). Regarding regional coverage, we alternately single out the US and the EU as those regions that undertake unilateral emissions pricing and consider alternative revenue recycling options. In addition, we split out China, India, and a composite of other G20 countries as important trading partners and geopolitical players. All other countries in the GTAP dataset are represented through a composite region (rest of world).

3.3 Base-year statistics

Table 3 shows the structural differences in the base year between the EU and the US (as the two geopolitical regions considered in our numerical analysis for unilateral climate policy action), which are important drivers for differential policy impacts. The EU has a lower CO₂ intensity of production compared to the US and is also more open to trade. From a fossil fuel standpoint, the EU produces much less and is a larger net importer of fossil fuel than the US.

3.4 Policy scenarios

To assess the potential magnitudes of impacts associated with alternative forms of rebating, we run numerical simulations with our CGE model. In our central case scenarios, we

alternately consider either the EU or the US as candidates for unilateral emissions pricing, while other countries do not implement a climate policy but will be still affected through international spillover effects transmitted via trade. The unilaterally acting region introduces a uniform emissions price across all sectors of its domestic economy. It rebates revenues from non-EITE sectors back to the domestic representative agent (household) lump-sum, i.e. in a non-distortionary manner. The emissions pricing revenues generated in EITE sectors are reserved for rebates directed at the same EITE sectors and are fully recycled. In line with our theoretical analysis, we consider five alternative rebating schemes of emissions pricing revenues to the EITE sectors: lump-sum rebating (LS), abatement-based rebating (A), output-based rebating (O), intensity-based output rebating (IO), and intensity-based emissions rebating (IE). By requiring the policy instruments to be revenue neutral, we do not consider the *optimal* approach to rebating, which may involve rebating less than or more than 100% of the revenues.

Across all rebating variants, we assume an illustrative social cost of carbon of \$250/tCO₂, roughly in line with the new US guidance on the social cost of carbon (United States Environmental Protection Agency, 2022) as well as with recent scholarly evidence (Ricke et al., 2018; Rennert et al., 2022; Bilal and Känzig, 2024).

4 Results

We show results from simulations in which the EU or the US introduces a unilateral domestic emissions price with alternative approaches to rebating emissions pricing revenues collected from the EITE sectors. We begin by discussing the effects on domestic emissions, domestic EITE output, emissions leakage, and terms-of-trade impacts—key components that drive differences in composite welfare effects—and then show a decomposition of welfare effects according to Equation (13) in Section 2. Our focus is on evaluating changes in *domestic* welfare, rather than global welfare, although our choice of social cost of carbon reflects a valuation of global damages from climate. This perspective is the relevant one for domestic policy makers, but it also means that our analysis should not be taken as indicative of *globally* cost-effective policy designs.

4.1 Domestic emissions

Figure 3 shows the change in domestic emissions associated with a unilateral emissions price. A \$50/tCO₂ unilateral price imposed in the US results in roughly a 20% emission reduction, and a \$250/tCO₂ price results in a reduction in domestic emissions of about 48% (for the EU, which is cleaner in the baseline, the corresponding values are 17% and 37%).⁸ For a given emissions price, the choice of mechanism to rebate revenues in the EITE sectors has an impact on the level of emission reductions achieved. Abatement-based rebating achieves the largest amount of emission reductions, while output-based rebating achieves the smallest amount of emission reductions.

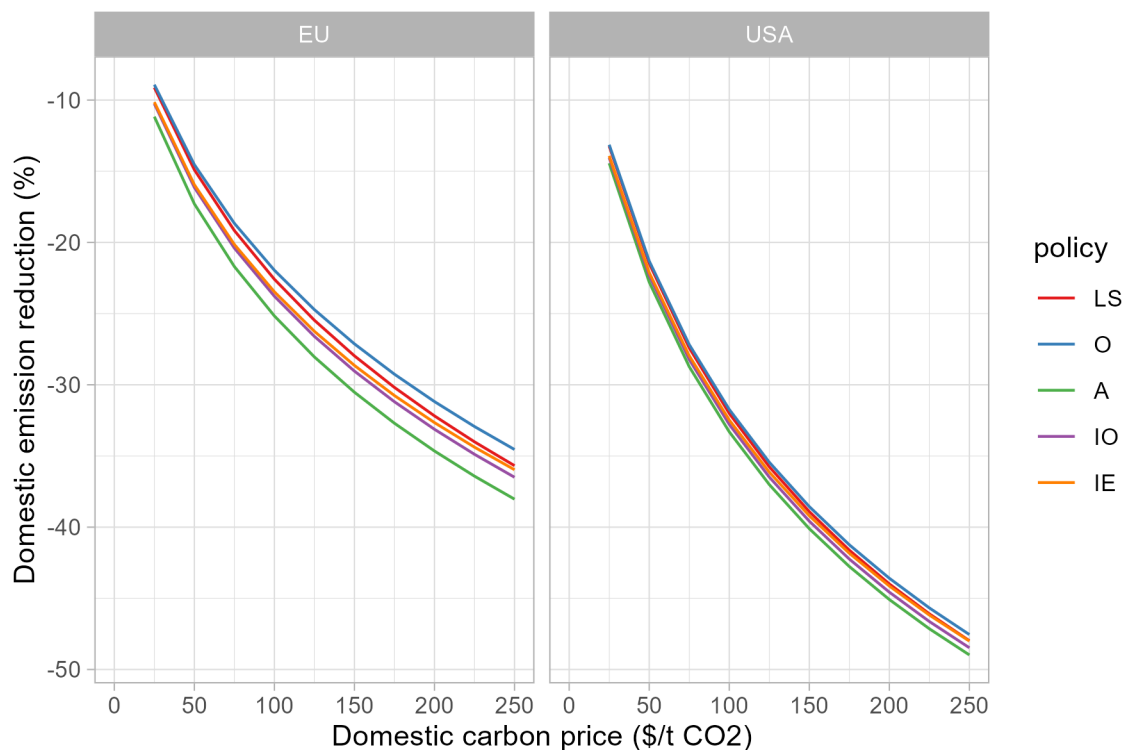


Figure 3: Domestic emissions reductions

Note: The horizontal axis shows the unilateral domestic emissions price imposed in the EU (left panel) or the US (right panel). The vertical axis corresponds to the change in domestic CO₂ emissions compared to the no-policy reference. Rebating options considered for the EITE sectors are: LS - lump-sum; O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity-based emissions, as described in the text.

Figure 4 breaks emission reductions down by EITE and non-EITE sectors, highlighting

⁸The higher emissions reductions in the US can be traced back to the higher CO₂ intensity of the US – see Table 3 – which provides relatively cheaper abatement options.

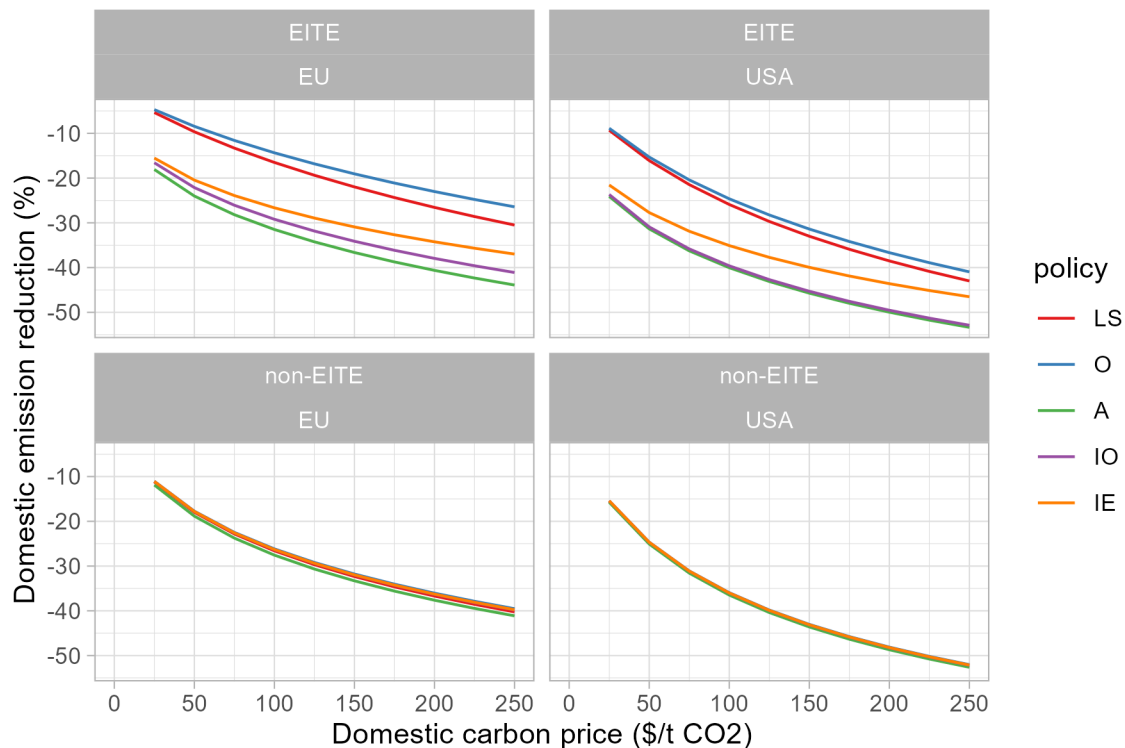


Figure 4: Domestic emissions reductions by EITE and non-EITE sectors

Note: The horizontal axis shows the unilateral domestic emissions price imposed in the EU (left panel) or the US (right panel). The vertical axis corresponds to the change in domestic CO₂ emissions compared to the no-policy reference. Top top panel shows EITE sector emissions, and the bottom panel shows non-EITE emissions. Rebating options considered for the EITE sectors are: LS - lump sum; O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity-based emissions, as described in the text.

the large effect that alternative rebating options have on EITE sector emissions. Notably, abatement-based rebating, which subsidizes emission reductions, causes the largest reduction in EITE sector emissions—consistently 10 to 15 percentage points larger than under lump-sum rebating. Output-based rebating, which stimulates EITE sector output relative to lump-sum rebating, achieves less emissions reductions—1 to 5 percentage points less than in the case of lump-sum rebating. The two intensity-based rebating options fall between the lump-sum and abatement-based alternatives. Notably, IO achieves almost the same degree of emission reductions compared to abatement based rebating. The limited difference in rebating schemes on overall emissions reductions (as seen in Figure 3) reflects the relatively small overall contribution of the EITE sector in total emissions, particularly in the US.

4.2 Domestic EITE output

Figure 5 shows output effects for the domestic EITE sectors under alternative carbon pricing rebating options. Output effects are commonly used as an indicator for “competitiveness” impacts, which play a prominent role in the debate on unilateral climate policy design (Carbone and Rivers, 2017). The figure suggests that there are important differences between the rebating mechanisms.

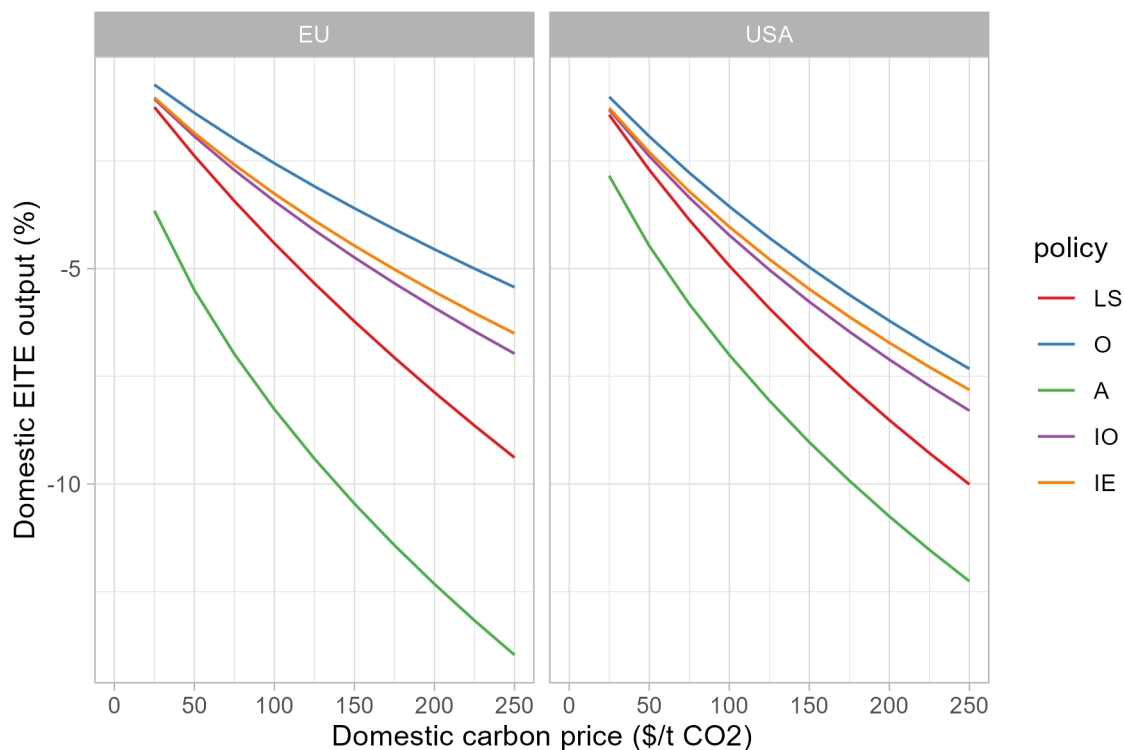


Figure 5: Domestic EITE output

Note: The horizontal axis shows the unilateral domestic emissions price imposed in the EU (left panel) or the US (right panel). The vertical axis corresponds to the change in domestic output in the emissions-intensive trade-exposed (EITE) industry sector compared to the no-policy reference. Rebating options considered for the EITE sectors are: LS - lump-sum; O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity based emissions, as described in the text.

While the prior section showed that abatement-based rebating achieves the largest emissions reductions, it also puts the most downward pressure on the domestic EITE sector output as a result of the implicit tax on output. In contrast, output-based rebating, where all revenues fund the implicit subsidy to EITE output, generates the smallest impacts on domestic EITE firm output. The intensity-based options, which each contain an implicit

subsidy to output (Böhringer et al., 2023), impose smaller reductions on EITE output than lump-sum rebating.

4.3 Emissions leakage

Figure 6 shows the economy-wide emissions leakage associated with each policy—i.e., the increase in total foreign emissions as a percentage of total domestic emissions reductions. In general, emissions leakage increases with a more stringent domestic emissions price, as well as with trade exposure and foreign-domestic emissions intensity disparities. Emissions leakage varies from about 4% to 7% in the current model parametrization and policy scenarios for the US, and from 13% to 27% for the EU.⁹

The simulation results suggest that emissions leakage is consistently higher for abatement-based rebating than for other policies. (Recall that abatement-based rebating provides additional incentives for reducing EITE emissions and provides no output protection.) Emissions leakage is lowest under either form of intensity-based rebating or output-based rebating, all of which provide incentives on the output margin, as described in Table 1.

4.4 Terms of trade

Figure 7 shows the policy effects on the portion of domestic welfare associated with changes in the terms of trade. Note that globally the terms-of-trade impacts are zero-sum. Since only one region is undertaking a policy change, the terms-of-trade impacts for that economy will equal the aggregate welfare changes across all other regions; i.e., they experience in aggregate symmetric and opposite terms-of-trade effects. Welfare changes are reported as percentage changes in Hicksian equivalent variation in income.¹⁰ Terms-of-trade impacts can be either positive or negative for individual regions, depending on the region-specific trade patterns in the base year and the trade elasticities.

Figure 7 highlights different terms-of-trade effects emerging from the imposition of climate

⁹Leakage rates in the EU are much higher than for the US as the EU is more trade open and the EU base-year emissions are much smaller than those of the US (Böhringer et al., 2014b).

¹⁰The Hicksian equivalent variation in income denotes the amount which is necessary to add to (or subtract from) the business-as-usual income of the household so that the household enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante relative prices.

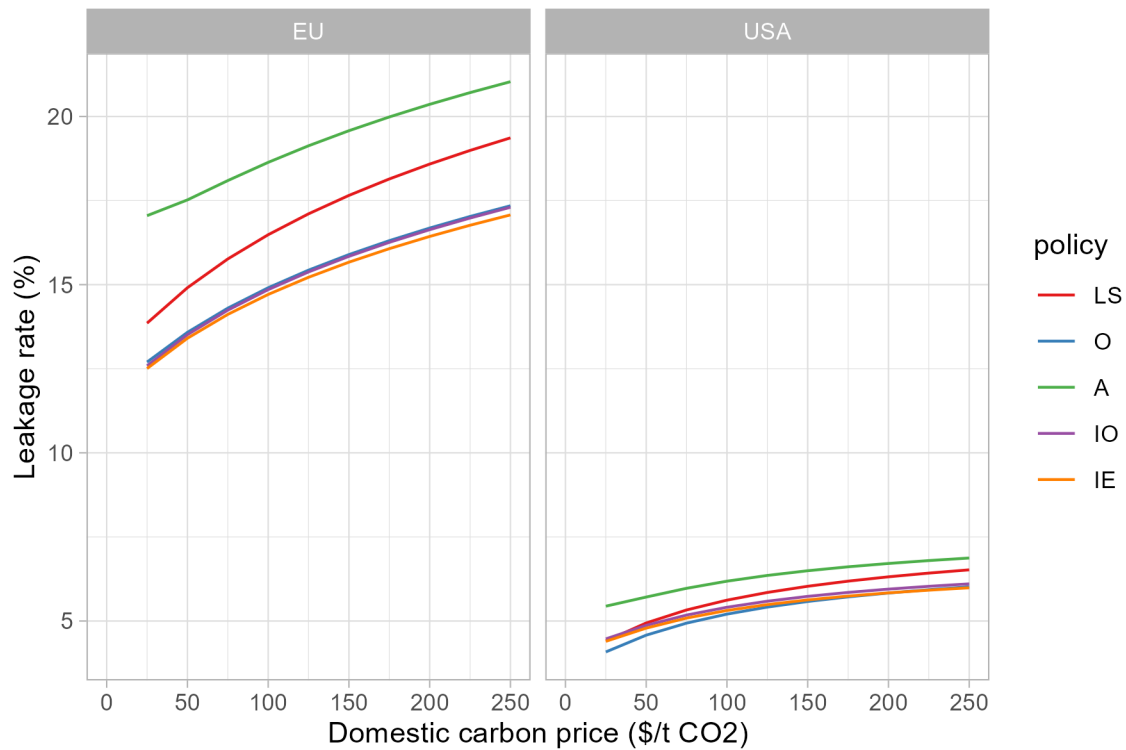


Figure 6: Emissions leakage

Note: The horizontal axis shows the unilateral domestic emissions price imposed in the EU (left panel) or the US (right panel). The vertical axis corresponds to the emissions leakage rate, defined as the change in foreign emissions divided by the change in domestic emissions. Rebating options considered for the EITE sectors are: LS - lump-sum; O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity based emissions, as described in the text.

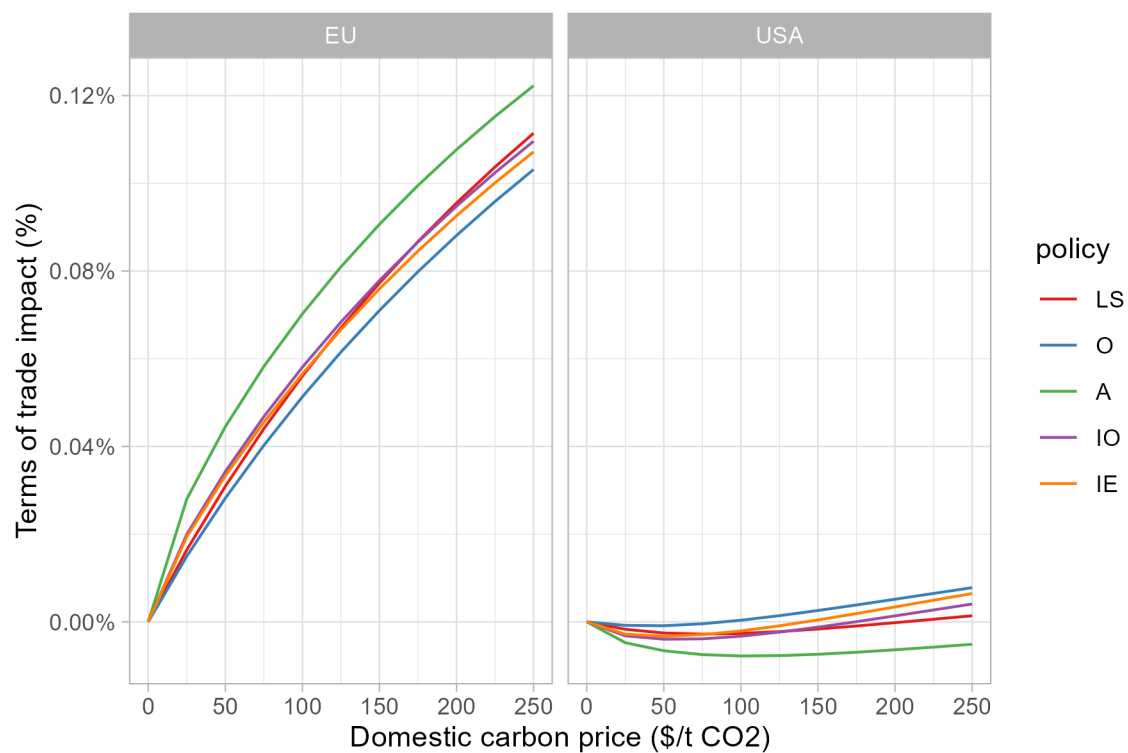


Figure 7: Terms of trade

Note: The horizontal axis shows the unilateral domestic emissions price imposed in the EU (left panel) or the US (right panel). The vertical axis corresponds to the change in domestic welfare that results from changes in terms of trade. Rebating options considered for the EITE sectors are: LS - lump-sum; O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity based emissions, as described in the text.

policies in the EU and US. We highlight two patterns that emerge from our model. First, the EU derives a terms-of-trade benefit from the imposition of domestic climate policies, because it is a net importer of fossil fuels, and the prices of some goods it exports increase with carbon pricing. In contrast, the US experiences no significant terms-of-trade effects from implementing domestic climate policy, because it is a less open economy and has more balanced trade in goods experiencing price changes from climate policies. Second, the ranking of policy variants is reversed for the two economies. Whereas the EU derives the largest terms-of-trade benefit from abatement-based rebating, this policy imposes the largest terms-of-trade cost on the US. These results illustrate how the overall terms-of-trade effects, as well as the effects of each policy variant, are determined by benchmark trade positions of the economies in question.

4.5 Welfare

Figure 8 shows the impact on overall domestic welfare for the EU and US economies of alternative conditional rebating options to EITE industries—as compared to unconditional lump-sum rebating—at different stringencies of the domestic emissions price when the social cost of carbon is $\$250\text{CO}_2$. The results highlight that different approaches to EITE emissions rebating can have very different implications for domestic welfare, and the ranking of rebating policies is particularly sensitive to the gap between the domestic emissions price and the social cost of carbon.

When the domestic emissions price is relatively low compared to the social cost of carbon, rebating mechanisms that promote additional abatement can be preferred. When domestic abatement is sufficiently responsive and leakage pressures not too strong, as is the case in the US, significant underpricing of emissions can call for abatement-based rebating, which is the most powerful at generating additional emission reductions. At higher emissions prices, where the gap to the social cost of carbon is less pronounced, output-based rebating—which reduces the negative welfare effects of leakage and cuts domestic abatement costs—is preferred. Intensity-based rebating options are normally ranked between output-based and abatement-based rebating; however, in certain circumstances they can even dominate other choices.

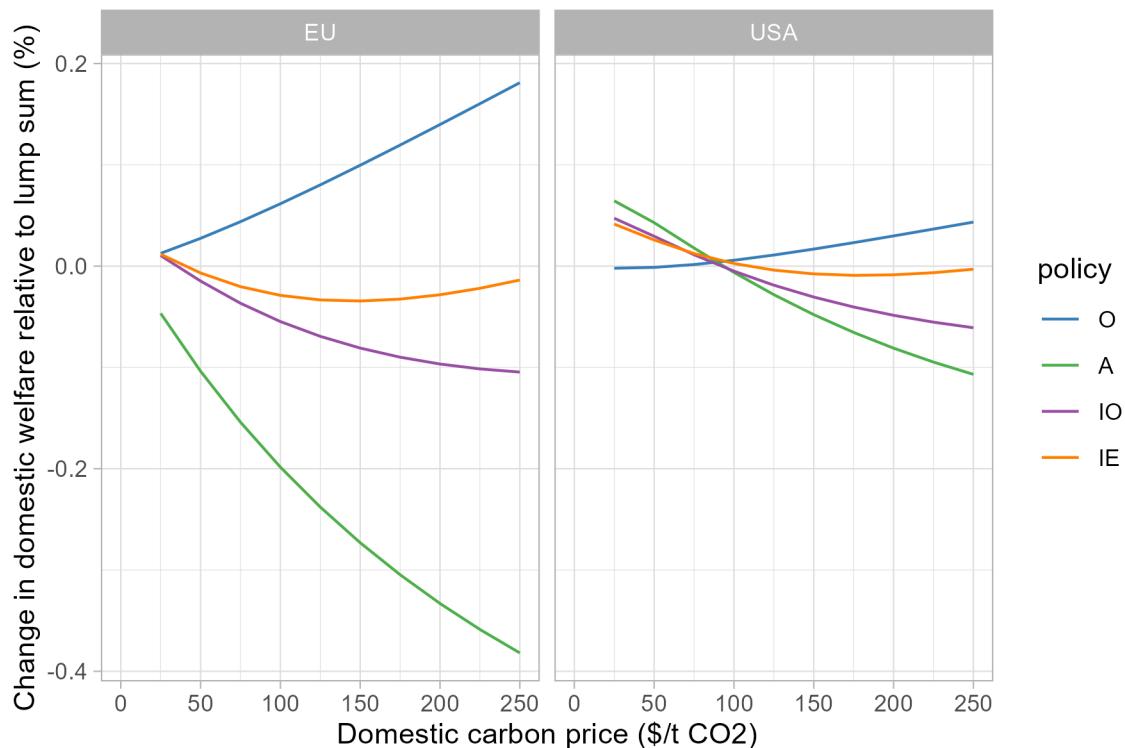


Figure 8: Welfare change relative to lump-sum recycling

Note: The horizontal axis shows the unilateral domestic emissions price imposed in the EU (left panel) or the US (right panel). The vertical axis indicates the percentage change in Hicksian equivalent variation in income relative to the welfare change imposed from implementing lump-sum rebating, at an assumed social cost of carbon of \$250/tCO₂. Rebating options considered for the EITE sectors are: O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity-based emissions, as described in the text.

To gain insight into the factors leading to policy rankings, Figure 9 decomposes welfare into the terms identified in equation (13). It shows sources of domestic welfare gain and loss for different EITE rebating options associated with a \$25/tCO₂ and \$250/tCO₂ domestic price, assuming the social cost of carbon is \$250/tCO₂, relative to the lump-sum rebating case.

Abatement-based rebating achieves more domestic emissions reductions as compared to lump-sum rebating, which generates greater benefits from domestic emissions reduction but also higher domestic abatement costs. Abatement-based rebating also increases leakage. In the US, this policy achieves the largest improvement in welfare at a low emissions price, while in the EU, where the negative leakage effect and the increase in domestic abatement

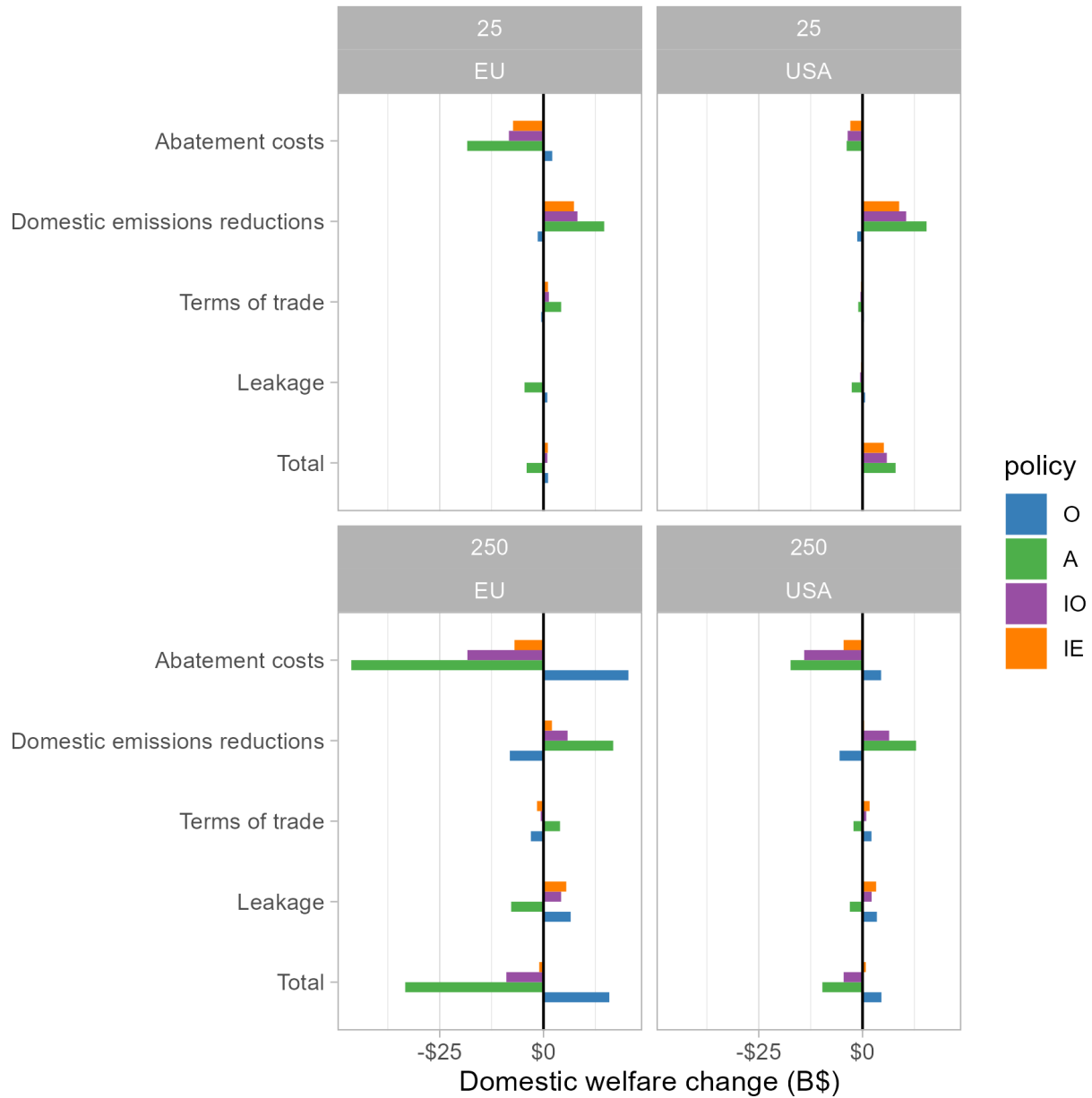


Figure 9: Welfare decomposition

Note: The figure decomposes welfare changes (in B\$) associated with different rebating policies. Welfare is compared to the lump-sum (LS) policy option. The top two panels illustrate the imposition of a unilateral domestic emissions price of \$25/tCO₂ in the EU (left) and the US (right). The bottom two panels illustrate the imposition of a unilateral \$250/tCO₂ price. In each case, the social cost of carbon is \$250/tCO₂. Rebating options considered for the EITE sectors are: O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity-based emissions, as described in the text.

costs dominate, this policy ranks last. When the domestic emissions price is high (equal to the social cost of carbon), the additional emissions reductions induced by abatement-based rebating come at a high cost (both in terms of increased leakage but much more in terms of excessive domestic abatement), and this policy is not preferred. Instead, output-based rebating, which supports output the most strongly of all rebating options, is preferred, because it mitigates leakage most effectively and reduces direct abatement costs. Intensity-based options typically fall between abatement-based rebating and output-based rebating in terms of welfare impacts, since they combine incentives for both output increases and emission mitigation (Böhringer et al., 2023). However, the composition of effects can differ; they behave more like abatement-based rebating in terms of abatement costs and reductions and more like output-based rebating in terms of leakage. Due to these different effects, the next section reveals there can be emissions prices at which these intermediate incentive mechanisms are preferred.

4.6 Ranking of rebating policies

So far, the welfare effects of different rebating options have been analyzed over a range of domestic emissions prices at a specific social cost of carbon of \$250/tCO₂. In Figure 10, we see how the ranking changes as a function of the social cost of carbon. In this figure, the social cost of carbon is portrayed on the horizontal axis and the domestic carbon price on the vertical axis. Each grid cell is colored according to which rebating variant maximizes domestic welfare.

The figure reveals the robustness of the result that when the domestic emissions price is at or near the social cost of carbon, output-based rebating dominates the other options as the domestically preferred policy choice. Under no circumstance does the acting region prefer lump-sum rebating. However, if the domestic emissions price is constrained to a level below the social cost of carbon, other rebating options that provide more incentives to reduce emissions can be preferred.

At \$250/tCO₂, the choice was essentially reduced to output-based or abatement based rebating, the former of which was always better for the EU and latter of which emerged as a good option for the US when carbon pricing was sufficiently constrained. Recall that the

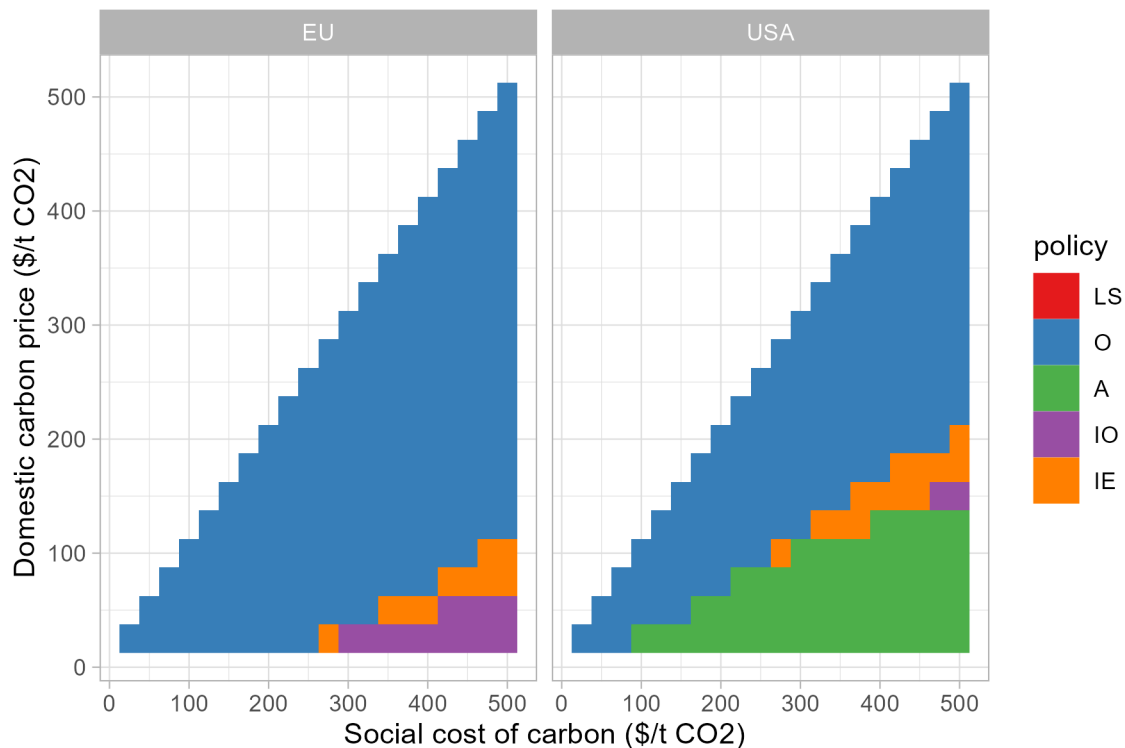


Figure 10: Dominant rebating choice

***Note:** This figure shows the rebating option associated with the highest level of domestic welfare out of the five considered. The dominant rebating option is considered for different social cost of carbon (horizontal axis) and domestic emissions prices (vertical axis). Rebating options considered for the EITE sectors are: LS - lump-sum; O - output-based; A - abatement-based; IO - intensity-based output; IE - intensity based emissions, as described in the text.*

leakage problem is more pronounced for the EU (Figure 6) and marginal abatement costs are higher (Figure 9) as compared to the US. We see in Figure 10, some of this pattern continues across a broad range of social costs of carbon, where the US would prefer to respond to strong emissions pricing constraints with abatement-based rebating to prioritize stimulating additional emission reductions.

However, as social costs of carbon rise above \$250/tCO₂, we observe that intensity-based policies can emerge as preferred policies. The reason is that they can compensate for emissions underpricing with additional abatement incentives while also addressing mounting leakage pressures with output support, which abatement-based rebating cannot. In a certain range, when the domestic emissions price is below but getting closer to the social cost of

carbon, emissions-based intensity rebating is preferred to intensity-based output rebating. In this case, the implicit subsidy to emissions avoids over-incentivizing emissions reduction from the revenue-neutral rebate as the domestic carbon price internalizes more of the social cost of carbon, while maintaining some additional incentive for intensity reduction and output protection. The simulations indicate that the more leakage-prone EU has a larger range where the combination of a high social cost of carbon and low domestic price would imply a preference for intensity-based output rebating.

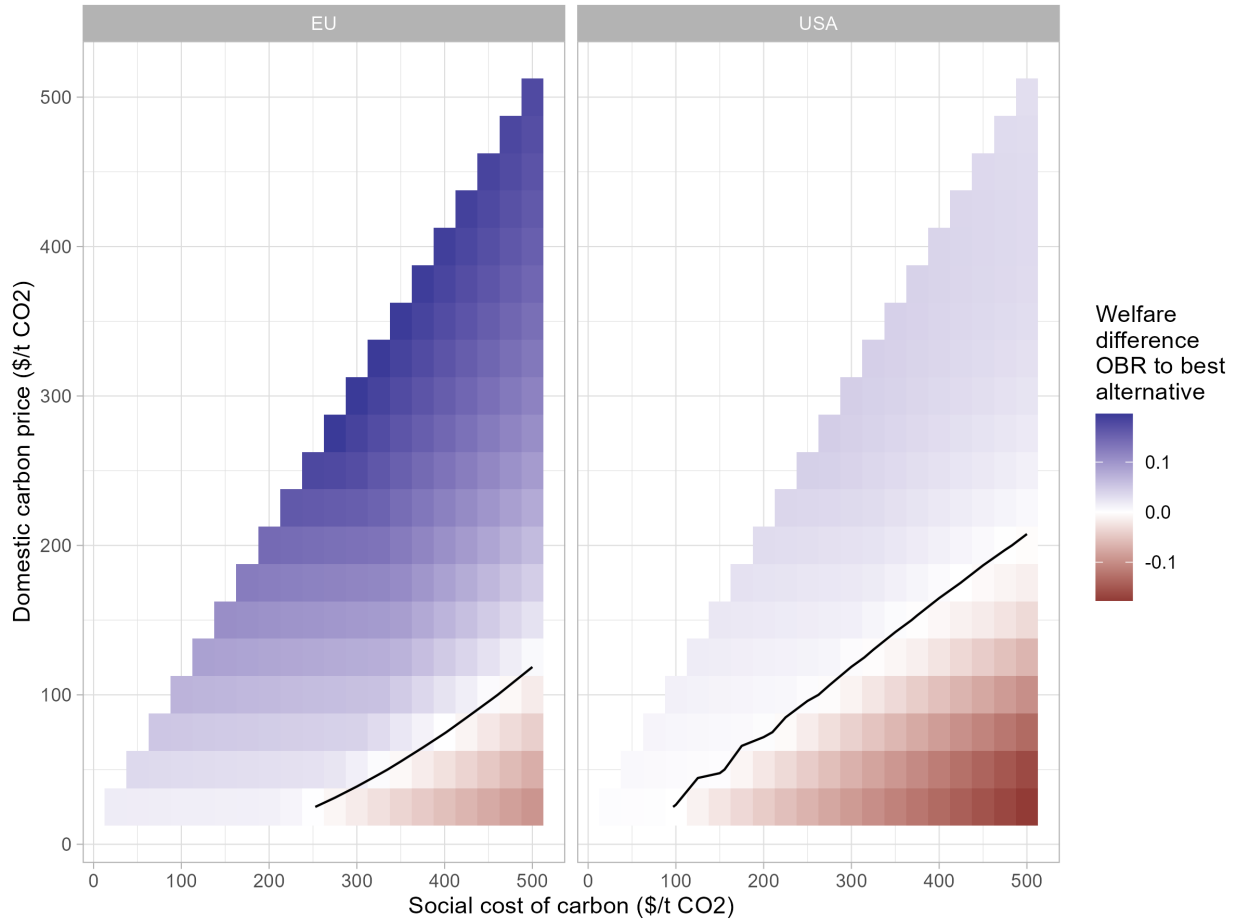


Figure 11: Comparison of OBR vs alternative rebating policies

***Note:** This figure shows the total domestic welfare under output based rebating compared to total domestic welfare under the best alternative rebating option. Values represent the difference in Hicksian equivalent variation in income under output-based rebating compared to the best alternative. The horizontal axis indicates the social cost of carbon and the vertical axis indicates the domestic emissions price. The solid black line illustrates the combination of domestic emissions price and social cost of carbon where welfare under the two rebating options is exactly equal.*

Figure 11 shows the intensity of the welfare implications of choosing output-based re-

bating compared to the next best alternative rebating policy. We compare other policies against output-based rebating, because this mechanism has emerged as the default policy approach for many countries that impose carbon pricing on industrial emissions (Böhringer et al., 2023). The figure shows that, for the EU, output-based rebating is more strongly preferred to other policies as compared to the US. If the domestic emissions price is set close to the social cost of carbon, output-based rebating generates a welfare gain of up to 0.2% of domestic income compared to alternative rebating schemes. However, even in the EU, if there is a large disparity between the social cost of carbon and the domestic emissions price, choosing output-based rebating is less beneficial compared to alternative rebating options, and can cost the domestic economy up to 0.1% of domestic income.

In the US, output-based rebating is less strongly and less often preferred, because leakage and abatement costs are lower. When a low domestic carbon price is imposed but the social cost of carbon is large (arguably the current context) output-based rebating is an inferior option, and choosing it is associated with a loss of domestic welfare greater than 0.1% of domestic income. For both regions, at a sufficiently high social cost of carbon and a low domestic emissions price, using rebating to enhance abatement incentives is more important than concerns about leakage and international spillovers.

5 Conclusions

Most jurisdictions that price carbon to reduce emissions adopt some form of rebating or free allocation system for emissions-intensive and trade-exposed (EITE) industries. Commonly, output-based rebating is deployed to address competitiveness and leakage concerns associated with unilateral carbon pricing, such as is done explicitly in California, China, Canada, and New Zealand, and effectively in the EU. A large literature has analyzed the implications of output-based rebating on carbon leakage, the performance of EITE industries, and the welfare implications of unilateral emissions pricing. In this paper, we consider a broader range of revenue-neutral rebating options, inspired by emerging mechanisms.

We focus in particular on situations in which the domestic emissions price is not optimally set, but rather is constrained to be below the social cost of carbon, reflecting real-world

practice. We show that in such cases, the optimal approach to rebating should include a component that incentivizes additional emissions reductions, to make up for the under-internalization of emissions, in addition to an output-based component that mitigates emissions leakage. Of course, optimal rebating would require tailoring separate components for each under-internalized externality or spillover on an ongoing basis and would rarely coincide with revenue neutrality in a carbon pricing program. Such customizing is difficult and may be impractical for regulators. As such, it is useful to consider rules of thumb in the form of self-adjusting earmarking mechanisms.

We find that, depending on the circumstances—including the extent of underpricing, the exposure to leakage, and domestic abatement opportunities—different rebating strategies can be preferred. When domestic emissions underpricing is severe and leakage less of a concern, abatement-based rebating is most desirable, since the primary goal is getting more abatement. As more of the social costs of carbon become internalized, addressing leakage with some output support becomes more important. Intensity-based rebating options, which are able to do both, can form a useful bridge option, although there appears to be a smaller range of circumstances under which they dominate. Once emissions prices reflect a sufficient share of the social costs, output-based rebating seems sufficient to address domestic concerns about international spillovers.

Further work could consider alternative rules of thumb for setting rebate rates that do not bind them to the emissions revenues. One could also consider the relative merit of border carbon adjustments instead of (or even in conjunction with) rebating mechanisms, as they are commanding more attention.

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