Rebating revenues from a unilateral emission price

Christoph Böhringer* Carolyn Fischer† Nicholas Rivers‡

Current draft: January 2023

Abstract

We evaluate alternative options for rebating revenues from a unilateral emission price, focusing on energy-intensive and trade-exposed industry. We show that distortionary rebating policies may be welfare-improving when there is emission leakage, when there are terms-of-trade changes associated with the introduction of an emission price, or when political or other constraints prevent the emission price being set at the optimal level. We use a numerical simulation model to compare different emission price rebating options, and find that rebating emission price revenues proportionately to output reduces emission leakage and is typically superior to other rebating options when the emission price is set close to the social cost of emissions. Rebating emission revenues proportionately to emission intensity increases emission abatement, and is typically superior when the unilateral emission price is set significantly below the social cost of emissions. We show that incorrect choice of rebating option can lead to significant welfare losses.

1 Introduction

Despite significant attention to climate change worldwide, and despite the theoretical appeal of carbon pricing, only a minority of countries impose carbon prices.[1] Moreover, even where

*University of Oldenburg, e-mail: boehringer@uol.de
†World Bank Group, email: cfischer2@worldbank.org
‡University of Ottawa, email: nrivers@uottawa.ca

[1]At the time of writing, less than a quarter of global emissions are subject to a carbon price. See https://carbonpricingdashboard.worldbank.org/.

carbon prices are in place, their design often deviates from the textbook approach, in which all carbon emissions are priced at a level that reflects their social cost, and revenues from the carbon price are redistributed in a non-distortionary manner. Instead, most countries that impose carbon prices use sectoral exemptions, rebate revenues in a way that creates particular incentives, and/or impose a carbon price well below the social cost of emissions.

Deviations from the textbook approach to carbon pricing are used to address the second-best context for carbon pricing. Notably, carbon prices are applied sub-globally, leading to potential emissions leakage and competitiveness losses, as well as shifts in terms-of-trade. Moreover, political constraints and public opinion prevent carbon prices being imposed at the social cost of carbon. These issues are particularly relevant for the emissions-intensive trade-exposed (EITE) industry sector.

A number of approaches can be considered for achieving emission reductions in the EITE sector in the face of the considerations above. Partial or complete sector exemptions from carbon pricing can help reduce emissions leakage and international spillovers (Hoel, 1996), although in practice this approach does not offer large gains over undifferentiated pricing (Böhringer and Rutherford, 1997; Böhringer et al., 2014). Border carbon adjustments can be used to reduce emissions leakage associated with a carbon tax on EITE sectors, although there are difficult challenges associated with this approach in practice (Böhringer et al., 2022b). Sector-specific rebates of emission pricing revenues can also be used to address the second-best context (Fischer and Fox, 2012; Fowlie and Reguant, 2022). We focus on this latter approach in the current paper.

We build on Böhringer et al. (2022a), who examine several such rebating policies, including output-based rebating, abatement-based rebating, and intensity-based rebating in a first-best setting. In that paper, policies are formally described, and considered in terms of the incentives generated for firms. In this paper, we consider application of rebating policies in a second-best setting with incomplete global coverage of emissions, and consider how the design of these policies helps to mitigate against carbon leakage and competitiveness losses. We also consider welfare impacts of alternative revenue recycling designs when carbon prices deviate from the social cost of carbon.

We begin by using a theoretical model to consider the welfare impacts of alternative environmental policy design in a setting with sub-global emission pricing, international trade, and a carbon price that potentially departs from the social cost of carbon. We decompose welfare impacts from unilateral carbon pricing, and show that welfare impacts are determined by the net cost of the carbon price on the domestic economy, terms of trade impacts, as well as carbon leakage. We show that if carbon prices are set below the social cost of carbon, it can be optimal to rebate carbon prices in a way that promotes additional emission reductions. When carbon prices affect terms of trade or generate emissions leakage, it can be optimal to rebate carbon prices in a way that stimulates domestic output in the energy-intensive traded goods sector. 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 emission 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 emission pricing.

We supplement our theoretical analysis with analysis using a numerical general equilibrium model. We simulate unilateral economy-wide emission pricing in the EU/USA. The emission price in non-EITE sectors are rebated back to the domestic household in a non-distortionary manner. The emission price in the EITE sector is rebated back to firms in that sector. We simulate a number of alternative rebating approaches. We show the optimal rebating approach depends on the level of the carbon price relative to the social cost of carbon. If the carbon price is constrained to much below the social cost of carbon, abatement-based rebating is the optimal rebating approach. This approach generates the largest incentive to cut emissions, and helps to make up for the sub-optimal carbon price. If the domestic carbon price is set at a level approaching the social cost of carbon, it is optimal to use output-based rebates to firms in the EITE sector. This approach supports output of domestic EITE firms most effectively, and helps to limit emission leakage and reduce terms of trade losses. At intermediate levels, our analysis suggests that intensity-based rebating is most effective. 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. Markusen

(1975) is an early contributor to this literature, and shows that an optimal unilateral carbon tax combines a tax on emissions with a tariff to combat leakage and improve terms of trade. 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. Fischer and Fox (2012) and Holland (2012) compare policies to address emissions leakage, focusing on output-based rebates and border carbon adjustments. Fowlie and Reguant (2022) derive the optimal output-based rebate to accompany a unilateral carbon tax. Kortum and Weisbach (2021) and Weisbach et al. (2022) 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.

Our analysis also contributes to the literature on carbon pricing in a second-best setting. This literature focuses especially on optimal economy-wide carbon pricing in an economy with pre-existing taxes. 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 alterantive policies for reducing emissions when other taxes are present, and show that instruments that do not raise revenue (like regulations) can outperform market-based instruments in some cases. Goulder et al. (2016) take this insight to the electricity sector, and find that a clean electricity standard can outperform and emissions tax for a plausible range of parameter values in their numerical model.

Our analysis differs from these prior contributions by focusing on policy interventions in the EITE sector. Rather than just considering theoretically optimal policies, we consider EITE rebating policies that have been adopted around the world. We also consider political barriers to carbon pricing, and find that these constraints are determinative in the ranking of policy approaches.

2 Theoretical model

2.1 Model setup

There are two regions, domestic and foreign ($r \in (d, f)$). The structure of each is similar, with a representative agent consumer who supplies a factor of production L to two constant-returns-to-scale sectors, X and Y. Sector X is emissions intensive and traded, and sector Y produces no emissions and is non-traded. The regulator in the domestic region puts a price on emissions. The revenue raised using the emission price is rebated back to firms in the X sector. We consider several alternative mechanisms for this rebating of emission pricing revenues to energy intensive traded firms.

The production function for the X sector is:

$$X^r = X^r(L_X^r, Z_X^r). \tag{1}$$

We define $\mu_X^r = Z_X^r / X^r$ as the emission intensity for the sector and $l_X^r = L_X^r / X_X$ as labour intensity. Given CRTS, we can invert the production function to define labour input as a function of emission intensity and output: $L_X^r = l_X^r(\mu_X^r) q_X^r$. The price of X^r is p_X^r, there is a tax on emissions τ^r and there is a rebate of emission pricing revenues to firms. The rebate is potentially determined by firm choices, such that $R^r = R^r(\mu_X^r, X^r)$. The profit function for firm X in region r is therefore:

$$\pi_X^r = p_X^r X^r - w^r l_X^r(\mu_X^r) X^r - \tau^r \mu_X^r X^r + R^r(\mu_X^r, X^r),$$

with first order conditions:

$$\frac{\partial \pi_X^r}{\partial X^r} \longrightarrow p_X^r = w^r l_X^r(\mu_X^r) + \tau^r \mu_X^r - \frac{\partial R^r}{\partial X^r} \qquad \frac{\partial \pi_X^r}{\partial \mu_X^r} \longrightarrow -w^r (l_X^r)' = \tau^r - \frac{\partial R^r / \partial \mu_X^r}{X^r}. \tag{2}$$

The Y sector uses labour to produce output in proportion to labour input:

$$Y^r = L_Y^r, \tag{3}$$

and has associated profit function:

$$\pi_Y^r = p_Y^r Y^r - w^r L_Y^r, \tag{4}$$

such that $p_Y^r = w^r$.

Good Y is non-traded, so production of Y in region r is also consumed there. Good X is traded, and consumers have preferences for both domestic and foreign varieties. We denote domestic consumption of X in region r as $X^{r,r}$ and exports of X from region r to region s as $X^{r,s}$. All X is either consumed domestically or exported, such that:

$$X^r = X^{r,r} + X^{r,s}. \tag{5}$$

Trade is balanced, such that:

$$X^{d,f} p_X^d = X^{f,d} p_X^f. \tag{6}$$

The representative agent utility function is given by:

$$U^r = U^r(X^{r,r}, X^{s,r}, Y^r). \tag{7}$$

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

$$W^r = U^r - \delta^r Z, \tag{8}$$

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

The consumer budget constraint is given by:

$$p_X^r X^{r,r} + p_X^s X^{s,r} + p_Y^r Y^r = w^r L^r, \tag{9}$$

such that first order conditions are:

$$\frac{\partial U^r}{\partial X^{r,r}} = p_X^r \lambda^r \qquad \frac{\partial U^r}{\partial X^{s,r}} = p_X^s \lambda^r \qquad \frac{\partial U^r}{\partial Y^r} = p_Y^r \lambda^r, \tag{10}$$

where λ^r is the marginal utility of income.

We assume the carbon price is revenue neutral, so that all revenue from the carbon price on firms in sector X is used to provide rebates to firms in sector X, i.e., $\tau^r X^r \mu_X^r = R^r$.

The market clearance condition for the labour market is:

$$L^r = L_X^r + L_Y^r. \tag{11}$$

Total emissions Z are given by:

$$Z = \sum_r (Z_X^r). \tag{12}$$

2.2 Model solution

We assume that the domestic region imposes a carbon price on firms in sector X and rebates revenues raised from sector X back to that sector as described by $R^r(\mu_X^r, X^r)$ – i.e., either as a function of firm emission intensity, firm output, or both. The foreign region does not impose a tax ($\tau^f = 0$), and consequently has no rebates ($R^f = 0$). We set the foreign wage rate as the numeraire ($w^f = 1$).

We seek to understand how different rebate functions affect welfare in the domestic economy. To do this, we totally differentiate domestic welfare (equation (8)):

$$dW^d = \frac{\partial U^d}{\partial X^{d,d}} dX^{d,d} + \frac{\partial U^d}{\partial X^{f,d}} dX^{f,d} + \frac{\partial U^d}{\partial Y^d} dY^d - \delta^d dZ^d \tag{13}$$

We substitute consumer first order conditions (equation (10) to get:

$$dW^d = \lambda^d p_X^d dX^{d,d} + \lambda^d p_X^f dX^{f,d} + \lambda^d p_Y^d dY^d - \delta^d dZ^d \tag{14}$$

We substitute the emission accounting (equation (12)) and $Z^r = \mu_X^r X^r$ to get:

$$\frac{dW^d}{\lambda^d} = p_X^d dX^{d,d} + p_X^f dX^{f,d} + p_Y^d dY^d - \frac{\delta^d}{\lambda^d} \left(X^d d\mu_X^d + \mu_X^d dX^d + X^f d\mu_X^f + \mu_X^f dX^f \right) \tag{15}$$

We substitute equation (5) to get:

$$\frac{dW^d}{\lambda^d} = \left(p_X^d - \frac{\delta^d}{\lambda^d}\mu_X^d\right) dX^d - p_X^d dX^{d,f} + p_X^f dX^{f,d} + p_Y^d dY^d - \frac{\delta^d}{\lambda^d}\left(X^d d\mu_X^d + X^f d\mu_X^f + \mu_X^f dX^f\right) \tag{16}$$

Differentiate the balance of trade equation (6) to get $p_X^d dX^{d,f} + X^{d,f} dp_X^d = p_X^f dX^{f,d}$, recognizing that $dp_X^f = 0$ due to no policy in f and setting the foreign wage as the numeraire, and substitute to get:

$$\frac{dW^d}{\lambda^d} = \left(p_X^d - \frac{\delta^d}{\lambda^d}\mu_X^d\right) dX^d + X^{d,f} dp_X^d + p_Y^d dY^d - \frac{\delta^d}{\lambda^d}\left(X^d d\mu_X^d + X^f d\mu_X^f + \mu_X^f dX^f\right) \tag{17}$$

Differentiate the domestic labour market clearance equation (11) to get $dL_X^d + dL_Y^d = 0$. Substitute to get: $dY^d = -l_X^d(\mu_X^d)dX^d - (l_X^d)' X^d d\mu_X^d$. Put this in the equation above to get:

$$\frac{dW^d}{\lambda^d} = \left(p_X^d - \frac{\delta^d}{\lambda^d}\mu_X^d\right) dX^d + X^{d,f} dp_X^d - p_Y^d l_X^d(\mu_X^d) dX^d - p_Y^d (l_X^d)' X^d d\mu_X^d - \frac{\delta^d}{\lambda^d}\left(X^d d\mu_X^d + X^f d\mu_X^f + \mu_X^f dX\right. \tag{18}$$

Simplify to get:

$$\frac{dW^d}{\lambda^d} = \left(p_X^d - \frac{\delta^d}{\lambda^d}\mu_X^d - p_Y^d l_X^d(\mu_X^d)\right) dX^d - \left(p_Y^d (l_X^d)' + \frac{\delta^d}{\lambda^d}\right) X^d d\mu_X^d + X^{d,f} dp_X^d - \frac{\delta^d}{\lambda^d}\left(X^f d\mu_X^f + \mu_X^f dX^f\right) \tag{19}$$

Producer first order conditions determine the equilibrium prices and opportunity cost of labour. From above, producer first order conditions are $p_X^d = w^d l_X^d(\mu_X^d) + \tau^d \mu_X^d - \frac{\partial R^d}{\partial X^d}$, $-w^d (l_X^d)' = \tau^d - \frac{\partial R^d / \partial \mu_X^d}{X^d}$, and $p_Y^d = w^d$. In addition, because the foreign wage is the numeraire and the foreign region does not impose a policy, foreign producer first order conditions imply that $d\mu_X^f = 0$. Substituting in gives:

$$\frac{dW^d}{\lambda^d} = \left(\tau^d \mu_X^d - \frac{\delta^d}{\lambda^d}\mu_X^d - \frac{\partial R^d}{\partial X^d}\right) dX^d + \left(\tau^d - \frac{\delta^d}{\lambda^d} - \frac{\partial R^d / \partial \mu_X^d}{X^d}\right) X^d d\mu_X^d + X^{d,f} dp_X^d - \frac{\delta^d}{\lambda^d}\left(\mu_X^f dX^f\right) \tag{20}$$

alternatively:

$$\frac{dW^d}{\lambda^d} = \left(\tau^d \mu_X^d - \frac{\delta^d}{\lambda^d}\right)\left(\mu_X^d dX^d + X^d d\mu_X^d\right) - \frac{\partial R^d}{\partial X^d} dX^d - \frac{\partial R^d}{\partial \mu_X^d} d\mu_X^d + X^{d,f} dp_X^d - \frac{\delta^d}{\lambda^d}\left(\mu_X^f dX^f\right) \tag{21}$$

Define dP^d as a change in policy, consisting of a combination of an increase in the domestic emission price and a corresponding revenue-neutral increase in the domestic rebate.

Solve for the optimal output rebate:

$$\frac{\partial R^d}{\partial X^d} = \left(\tau^d - \frac{\delta^d}{\lambda^d} - \frac{\partial R^d/\partial \mu_X^d}{X^d}\right) X^d \frac{d\mu_X^d/dP^d}{dX^d/dP^d} + X^{d,f} \frac{dp_X^d/dP^d}{dX^d/dP^d} - \frac{\delta^d}{\lambda^d}\left(\mu_X^f \frac{dX^f/dP^d}{dX^d/dP^d}\right) + \left(\tau^d - \frac{\delta^d}{\lambda^d}\right)\mu_X^d \tag{22}$$

Solve for the optimal intensity rebate:

$$\frac{\partial R^d}{\partial \mu_X^d} = \left(\tau^d \mu_X^d - \frac{\delta^d}{\lambda^d}\mu_X^d - \frac{\partial R^d}{\partial X^d}\right)\frac{dX^d}{d\mu_X^d} + X^{d,f}\frac{dp_X^d}{d\mu_X^d} - \frac{\delta^d}{\lambda^d}\left(\mu_X^f \frac{dX^f}{d\mu_X^d}\right) + \left(\tau^d - \frac{\delta^d}{\lambda^d}\right) X^d \tag{23}$$

We substitute the differentiated utility function (7), differentiated first order conditions (10), differentiated balance of trade (6), differentiated production functions ((1) and (3)), and associated first order conditions ((2) and (**??**)), and labour market clearance condition ((11)), which gives:

$$\frac{1}{\lambda^d}\frac{dW^d}{d\tau^d} = \underbrace{\left(\frac{\tau^d - \frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial Z_X^d}}{1 + \frac{1}{p_X^d}\frac{\partial R^d}{\partial X^d}} - \frac{\delta^d}{\lambda^d}\right)\frac{dZ_X^d}{d\tau^d}}_{\text{EITE net cost}} + \underbrace{\left(\tau^d - \frac{\delta^d}{\lambda^d}\right)\frac{dZ_Y^d}{d\tau^d}}_{\text{non-EITE net cost}} +$$
$$\underbrace{\left(X^{d,f}\frac{dp_X^d}{d\tau^d} - X^{f,d}\frac{dp_X^f}{d\tau_d}\right)}_{\text{terms of trade}} - \underbrace{\frac{\delta^d}{\lambda^d}\frac{dZ_X^f}{d\tau^d} - \frac{\delta^d}{\lambda^d}\frac{dZ_Y^f}{d\tau^d}}_{\text{leakage}} - \underbrace{\left(\frac{\frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial L_X^d} + \frac{w^d}{p_X^d}\frac{\partial R^d}{\partial X^d}}{1 + \frac{1}{p_X^d}\frac{\partial R^d}{\partial X^d}}\right)\frac{dL_X^d}{d\tau^d}}_{\text{output rebate}}. \tag{24}$$

For a welfare optimum, this expression equals zero. The first term on the right hand side is the net cost of emission reductions in the EITE sector. This is equal to the marginal cost of emission reductions less the marginal benefit. The marginal cost of emission reductions in the EITE sector is given by τ^d as well as the rebating policy. The "effective" emission price is the actual emission price plus any additional incentive from intensity-based rebating, adjusted down for any output-based rebate. The second term on the right hand side is the net cost of emission reductions in the non-EITE sectors. The third term is the change in welfare caused by changes in terms of trade, which are a function of changes in domestic and foreign prices. The fourth term is the change in welfare caused by emission leakage, which is the change in foreign emissions multiplied by the social cost of emissions. Finally, the last term reflects the direct effect of rebates on welfare.

If there is no leakage, no change in the terms of trade, and if rebates are distributed in a non-distortionary way (such that $\frac{\partial R^d}{\partial \mu_X^d} = \frac{\partial R^d}{\partial X^d} = 0$), it is optimal to set the domestic carbon price at the social cost of carbon. This is the standard first-best solution (Baumol and Oates, 1988).

Our model admits three potential deviations from the first-best: sub-global coverage of climate policy, which creates the potential for emissions leakage; international trade, which (along with sub-global emission pricing) creates the potential for manipulating terms of trade; and (political) constraints on carbon pricing, which restrict τ^d to fall within an "acceptable" range.

Consider the case where leakage is positive (i.e., $\frac{dZ^f}{d\tau^d} > 0$, which we expect), or the terms of trade term is negative (which we expect if the implementing country is an importer of energy intensive goods), but rebates remain non-distortionary. In this case, the optimal domestic carbon price is below the social cost of carbon (see Böhringer et al. (2014) for a similar result). However, if an output rebate is available, it may both directly address leakage and terms of trade impacts (i.e., through it's impacts on $\frac{dp_X}{d\tau^d}$ and $\frac{dZ^f}{d\tau^d}$) as well as offset welfare changes through these channels. The introduction of such a rebate may reduce domestic welfare loss as well as facilitate stronger domestic emission prices.

Now consider the case where there are constraints on the level of the domestic carbon price. In this case, it may be optimal to use rebates that distort the choice of emissions (i.e., rebates where $\frac{\partial R^d}{\partial \mu_X^d} < 0$ to make up for the shortfall in the domestic emission price (e.g., see Jenkins (2014), Hagem et al. (2020), or Böhringer et al. (2022a)).

The following section describes alternative approaches to rebating revenues from environmental policy. Different policies for rebating revenue generate different incentives for firms to reduce emissions as well as to increase output. As we describe above, the merits of such approaches will depend on the political and trade context for the implementing country.

2.3 Alternative rebating instruments in the energy-intensive trade exposed sector

We consider alternative approaches to rebating revenues from the emission price to firms in the EITE sector (X). Our approach and derivations follow Böhringer et al. (2022a), who focus on partial equilibrium results, and rank the instruments according to incentives generated to firms in the EITE sector.

2.3.1 Lump sum rebating

Under lump sum rebating, $\frac{\partial R^d}{\partial \mu_X^d} = \frac{\partial R^d}{\partial X^d} = 0$, so the rebating generates no additional incentives.

2.3.2 Output-based rebating

Under output-based rebating, the rebate is $R^d = \bar{\mu}_X^d \tau^d X^d$, where $\bar{\mu}_X^d$ is the benchmark emissions intensity for the domestic X sector. If the firm has an emission intensity above this benchmark, it must purchase credits, whereas if it's emission intensity is below the benchmark, it generates credits that can be sold. With eligibility for rebates determined as above, we have: $\frac{\partial R^d}{\partial X^d} = \bar{\mu}_X^d \tau^d$, and $\frac{\partial R^d}{\partial \mu_X^d} = 0$. As is well-known, output based rebating acts as a subsidy to output, without distorting the choice of emission intensity.

We consider revenue-neutral rebates, such that all rebates are financed by the carbon price on sector X. This means that $R^d = \tau^d \mu_X^d X^d$, which implies that for revenue-neutrality we have $\mu_X^d = \bar{\mu}_X^d$.

2.3.3 Abatement-based rebating

Under abatement-based rebating, the rebate is conditional on reductions in emissions. We define $\mu_X^{r0} X^{r0}$ as historical benchmark emissions in sector X in region r. The domestic rebate is then $R^d = s(\mu_X^{d0} X^{d0} - \mu_X^d X^d)$, where s is the rebate in dollars per tonne. As a result, we can derive $\frac{\partial R^d}{\partial \mu_X^d} = -sX^d$, and $\frac{\partial R^d}{\partial X^d} = -s\mu_X^d$.

We consider revenue-neutral rebates, such that all rebates are financed by the carbon price on sector X. This means that $R^d = \tau^d \mu_X^d X^d$, which implies that $s = \tau^d \frac{\mu_X^d X^d}{\mu_X^{d0} X^{d0} - \mu_X^d X^d}$.

2.3.4 Intensity-based output rebating

Under intensity-based output rebating, the rebate is conditional on both intensity and output, such that $R^d = (\bar{\mu}_X^d - \mu_X^d) z X^d$, where z is in dollars per tonne and expresses the size of the intensity- and output-conditional rebate. As a result, we can derive $\frac{\partial R^d}{\partial \mu_X^d} = -zX^d$ and $\frac{\partial R^d}{\partial X^d} = (\bar{\mu}_X^d - \mu_X^d) z$.

We consider revenue-neutral rebates, such that all rebates are financed by the carbon price on sector X. This means that $R^d = \tau^d \mu_X^d X^d$, which implies that $z = \frac{\tau^d \mu_X^d}{\bar{\mu}_X^d - \mu_X^d}$.

2.3.5 Intensity-based emission rebating

Under intensity-based emission rebating, firms are eligible for a reduction in the emission price they face conditional on meeting an intensity-performance standard. We can represent this form of rebating as $R^d = (\bar{\mu}_X^d - \mu_X^d) r \tau^d \mu_X^d X^d$, where $r > 0$ is a scalar, and where $(\bar{\mu}_X^d - \mu_X^d) r$ is the rebate per \$ of the carbon price, a fraction that is dependent on reducing emission intensity below the threshold $\bar{\mu}_X^d$. We can derive: $\frac{\partial R^d}{\partial X^d} = (\bar{\mu}_X^d - \mu_X^d) r \tau^d \mu_X^d$, and $\frac{\partial R^d}{\partial \mu_X^d} = r \tau^d X^d (\bar{\mu}_X^d - 2\mu_X^d)$.

We consider revenue-neutral rebates, such that all rebates are financed by the carbon price on sector X. This means that $R^d = \tau^d \mu_X^d X^d$, which implies that $r = \frac{1}{\bar{\mu}_X^d - \mu_X^d}$.

2.4 Comparing policy instruments

Table 1 compares the policy instruments. We compare instruments assuming the domestic carbon price is the same across all instruments. In addition, we set the same threshold $\bar{\mu}_X^d$ across all instruments where this is relevant. We also consider revenue-neutral implementation of EITE rebating policies, such that all emission pricing revenue generated from EITE emitters is rebated back to firms within the sector. Revenue-neutrality is imposed at the sector-level, not at the firm level, and we assume that individual firms take the total amount of rebates available as exogenous.

	$\frac{\partial R^d}{\partial X_d}$	$\frac{\partial R^d}{\partial \mu_X^d}$	For revenue neutrality
LS	0	0	$R^d = \tau^d Z_X^d$
O	$\bar{\mu}_X^d \tau^d$	0	$\bar{\mu}_X^d = \mu_X^d$
A	$-s\mu_X^d$	$-sX^d$	$s = \tau^d \frac{\mu_X^d X^d}{\mu_X^{d0} X^{d0} - \mu_X^d X^d}$
IO	$(\bar{\mu}_X^d - \mu_X^d)z$	$-zX^d$	$z = \frac{\tau^d \mu_X^d}{\bar{\mu}_X^d - \mu_X^d}$
IE	$(\bar{\mu}_X^d - \mu_X^d)r\tau^d\mu_X^d$	$(\bar{\mu}_X^d - 2\mu_X^d)r\tau^d X^d$	$r = \frac{1}{\bar{\mu}_X^d - \mu_X^d}$

Table 1: Comparing policy instruments

Only lump sum rebating (LS) generates no distortions on the output margin. 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. Böhringer et al. (2022a) show that, given the same emission price, the implicit subsidy under O is larger than under IE and IO, such that equilibrium output under O is highest.

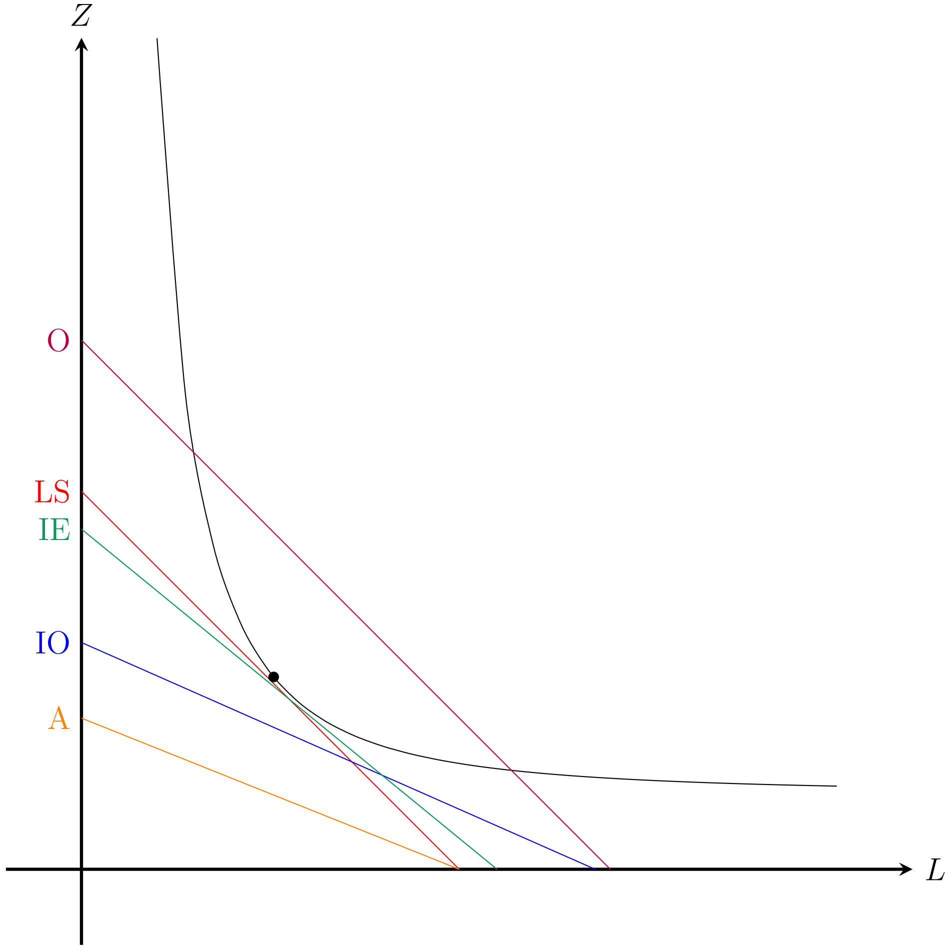
Table 1 shows that neither LS nor O distort the emission intensity margin. A couples the emission tax with an abatement subsidy, and generates larger emission reductions than under the LS policy. Like A, IO and IE also embed an implict tax on emissions by rewarding reductions in emissions intensity. IE further embeds an additional emissions subsidy, since the equilibrium emission tax is reduced contingent on achieving reductions in emission intensity. Böhringer et al. (2022a) shows that O generates the less reduction in emissions compared to IE and IO. Emission reductions under IE and IO cannot be ranked, but Böhringer et al. (2022a) shows that IO generates larger emission reductions in the numerical setting analyzed in that paper.

3 Numerical model

3.1 Model structure

We use a multi-sector multi-regional computable general equilibrium (CGE) model of the global economy to quantify the economic and environmental impacts of alternative policy

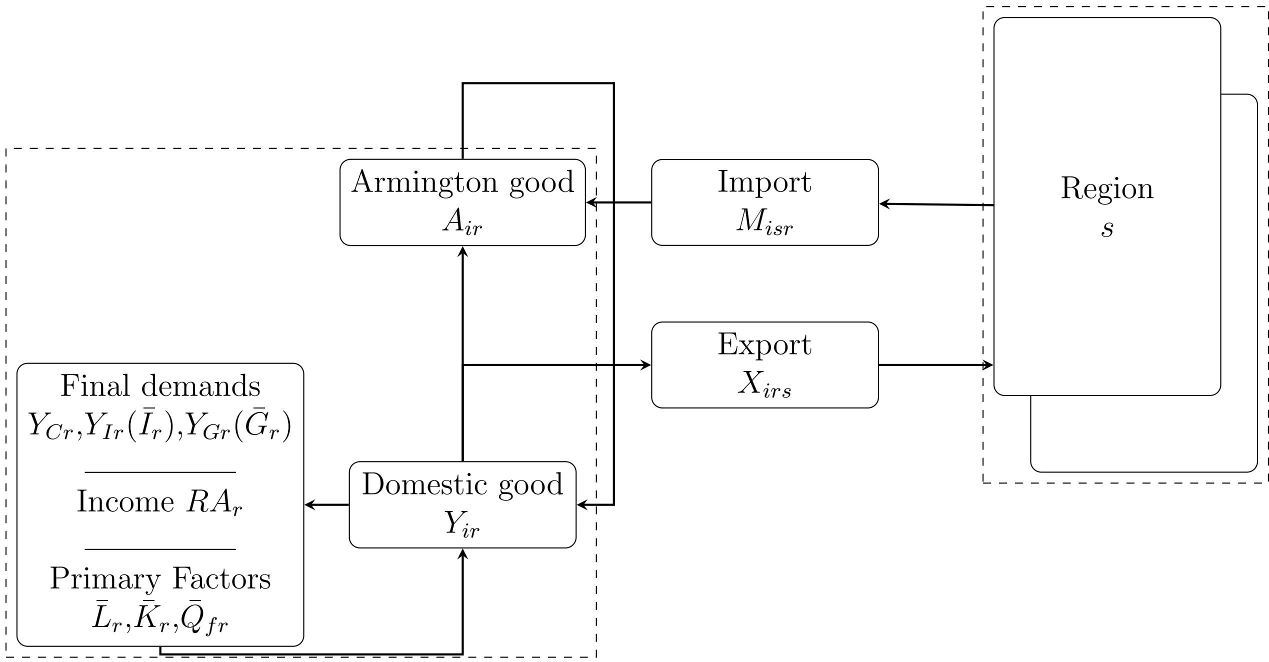
Figure 1: Impacts of alternative rebating policies with equal emissions price τ



Note: The curved black line represents the production isoquant. The downward sloping colored lines represent isocost curves. The black point indicates the equilibrium alllcation under the lump sum recycling policy. Relative positions of isocost curves are illustrative, and depend on policy parameters.

options for rebating revenues from unilateral emission pricing. 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 pref-

Figure 2: Flowchart of economic transactions in the CGE model

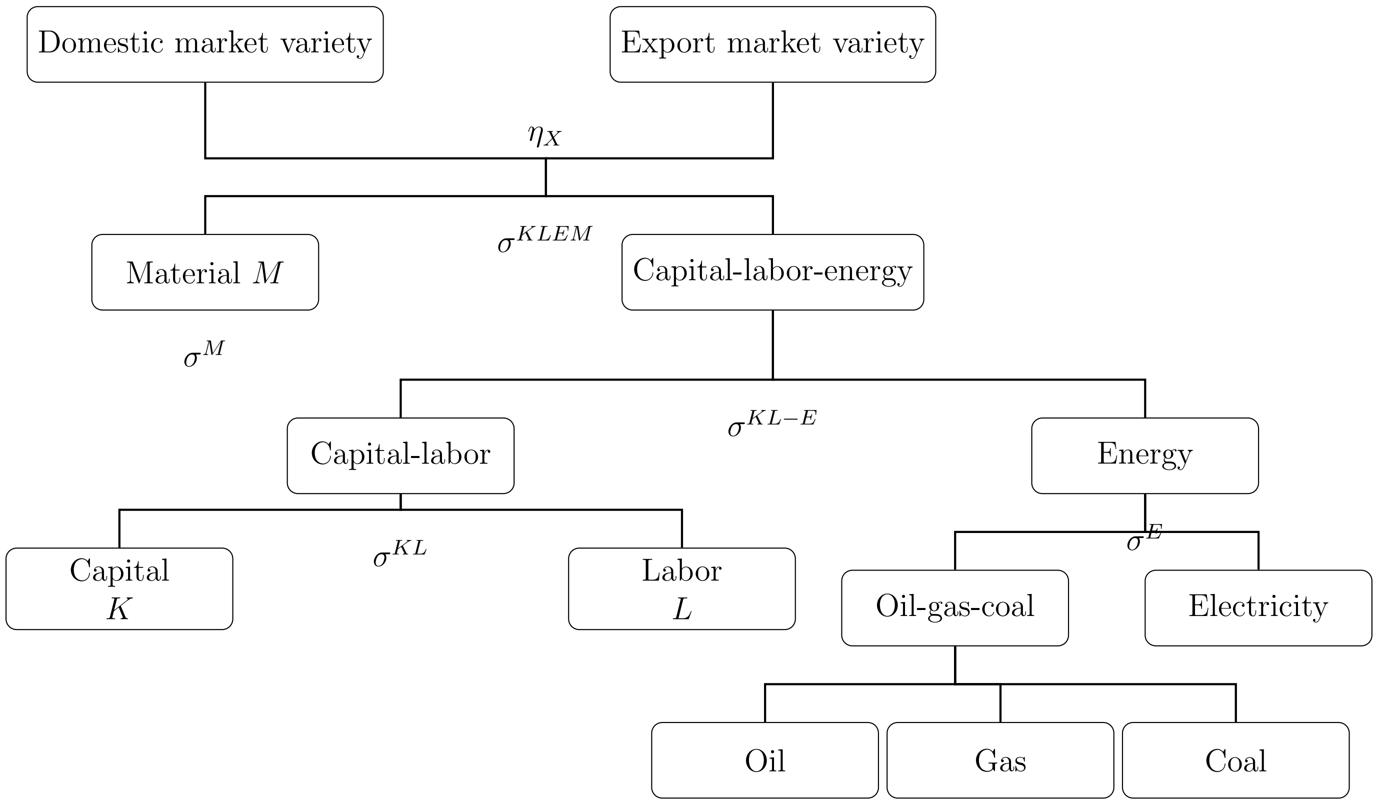


erences. Substitution and transformation possibilities in production and consumption are typically described by flexible functional forms which capture price-responsiveness based on empirical estimates of elasticities and initial cost shares derived from empirical economic accounts. The disaggregation of macroeconomic production, consumption, and trade at the sector level using regional input–output tables accommodates the of structural change induced by policy change and thereby identify 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 e.g. provided by Böhringer et al. (2015)). Figure 2 provides 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 $\bar{Q}_{fr}$ which are specific to fossil fuel production sectors f in each region. The representative agent receives income from

Figure 3: Production structure for a representative industry



factor earnings and tax revenues net of subsidies. Final demand of a consumption bundle Y_{Cr} is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment Y_{Ir} (i.e., a given demand for savings) and exogenous government provision Y_{Gr} of public goods and services. The production Y_{ir} 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 A_{ir} combine domestically produced goods and goods M_{isr} of the same variety imported from other regions s. Domestically produced goods are split into exports supply X_{irs} to other region s and domestic supply to the production of the intermediate good A_{ir}. The production Y_{ir} 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 3).

At the top level, a CES composite of intermediate (non-energy) material inputs trades off with an aggregate of energy, capital and labor. At the second level, a CES function 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 whereas the substitution possibilities within energy composite are represented by a CES function of a fossil fuel composite and electricity. At the fourth level, non-electric energy goods (coal, refined oil, and gas) trade off at a constant elasticity of substitution. 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. 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 can be calibrated to exogenous fuel supply elasticities.

Carbon emissions are linked in fixed fuels-specific proportions to the use of coal, refined oil, and gas. Carbon abatement induced by carbon pricing can take place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of 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 to the representation of international trade, which is central to our 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 paramaterization

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 exogenous 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 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 cover-

region	CO2 intensity kg/$	Trade index	CO2 (Mt)	Fossil fuel (EJ)	
				Production	Net exports
USA	0.30	0.13	5,156	122	−10
EUR	0.19	0.18	2,882	43	−36
CHN	0.76	0.15	8,090	152	−22
IND	0.94	0.19	1,912	29	−12
OG20	0.34	0.20	4,426	138	13
ROW	0.39	0.21	7,554	241	68

Table 3: Benchmark economic and environmental statistics

age, we single out the USA and the EU as those regions that undertake unilateral emission 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 are represented through a composite region (rest of the world). Table 1 summarizes the sectors (commodities) and regions included in our aggregate dataset.

3.3 Base-year statistics

Table 3 presents base-year statistics to gain insights into important drivers of economic adjustment triggered by policy interference and how structural differences between the EU and the USA as our countries considered for unilateral climate policy action may explain differential impacts. Europe has a lower CO_2 intensity of production compared to the US, and is also more open to trade. It produces much less fossil fuel, 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 conduct numerical simulations with our CGE model. In our central case scenarios, we consider either the EU or the US as candidates for unilateral emission 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 emission 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 emission pricing revenues generated in EITE sectors are reserved for rebates directed at the EITE sectors. In line with our theoretical analysis, we consider five alternative rebating schemes of emission 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).

Across all rebating variants, we assume a social cost of carbon of \$250/t, roughly in line with the new US guidance on the social cost of carbon (United States Environmental Protection Agency, 2022).

4 Results

In this section, we show results from simulations in which Europe or the USA implements a unilateral domestic emission price. We focus on alternative approaches to rebating emission pricing revenues collected from the energy intensive trade exposed sectors. We begin by illustrating impacts on important outcomes that drive differences in welfare impacts, and then show a decomposition of welfare impacts, following the approach highlighted in the prior section.

4.1 Domestic emission reductions

Figure 4 shows the change in domestic emissions associated with a unilateral emission price. Under the benchmark model calibration, a \$50/t carbon price results in roughly 30% emission reductions, and a \$250/t carbon price results in a reduction in domestic emissions of about 55%. The choice of mechanism to rebate revenues in the EITE sectors has an impact on the level of emission reductions achieved, with abatement-based rebating achieving the largest amount of emission reductions, and output-based rebating achieving the smallest amount of emission reductions, holding the emission price constant. Intensity-based output rebating

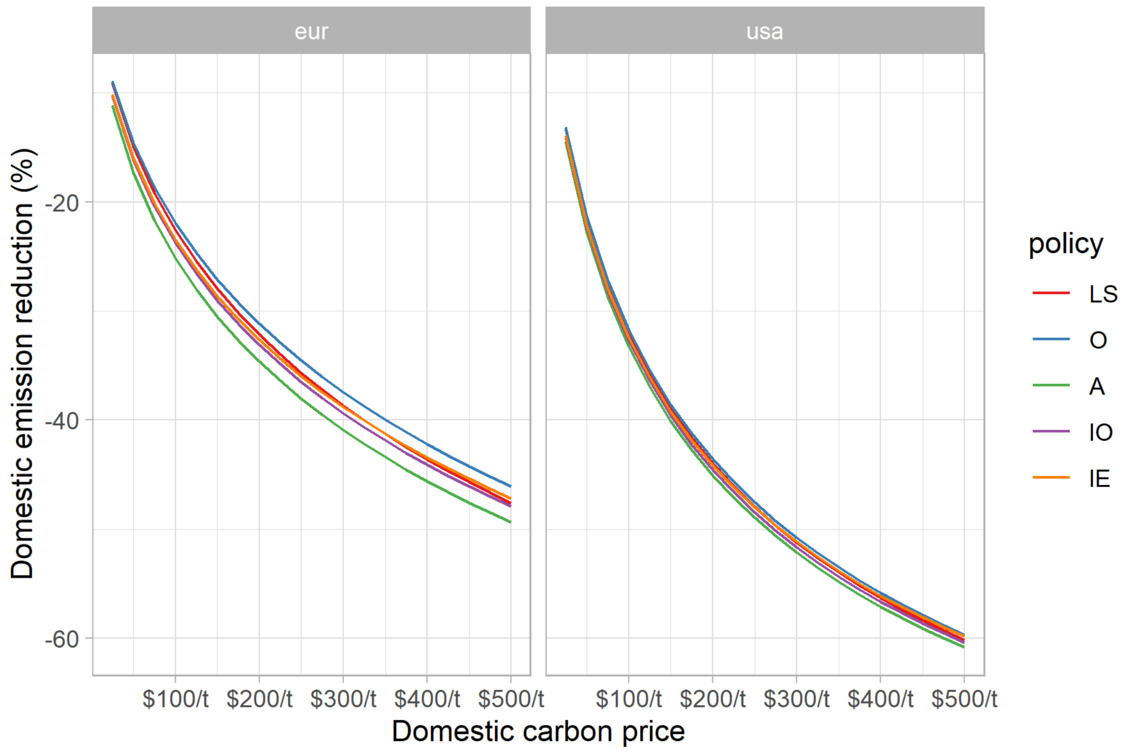


Figure 4: Domestic emission reductions

achieves almost the same degree of emission reductions as abatement-based rebating.

Figure 5 breaks emission reductions down by sector, and highlights the large effect that alternative rebating options have on EITE sector emissions. Notably, abatement-based rebating causes the largest reduction in EITE sector emissions, with emission reductions consistently 10 to 15 percentage points larger than under lump sum rebating. Output-based rebating, which stimulates EITE sector output relative to LSR, achieves less emission reductions. 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 (Figure 4) reflects the relatively small overall contribution of the EITE sector in total emissions.

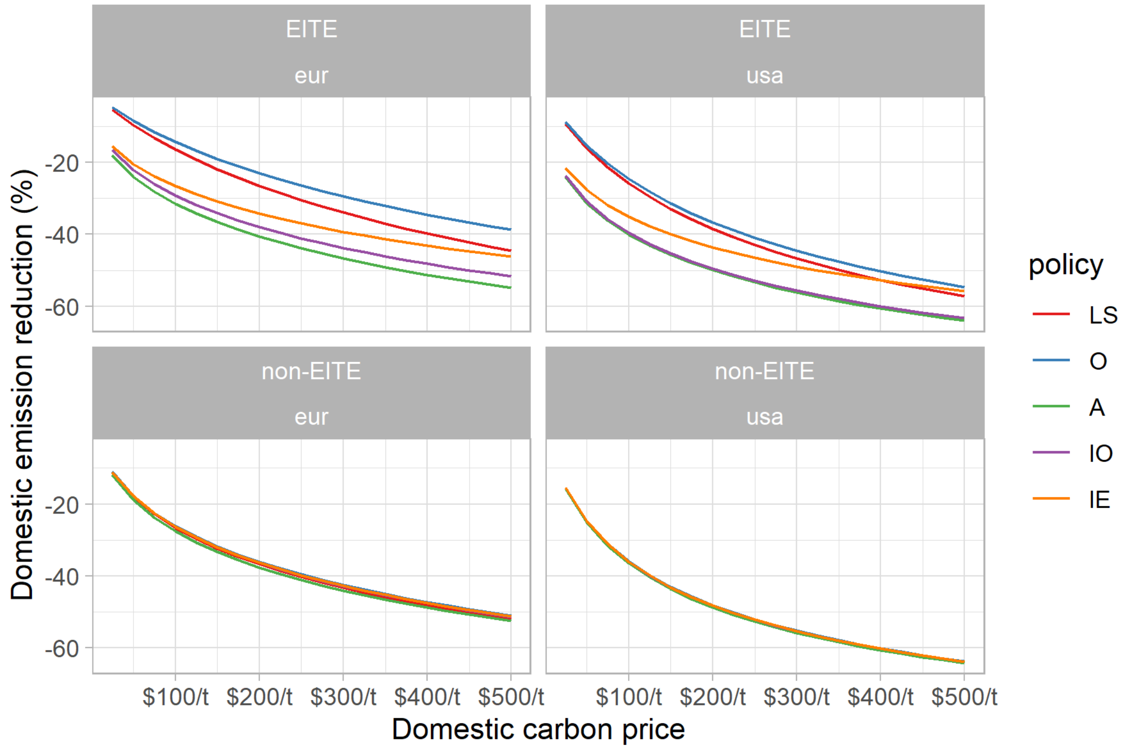


Figure 5: Domestic emission reductions by sector

4.2 Emission leakage

Figure 6 shows emission leakage associated with each policy. In general, the model suggest that emission leakage increases with a more stringent domestic emission price. Emission leakage varies from about 4% to 7% in the current model calibration and policy scenarios. The model suggests that emission leakage is consistently higher for the abatement-based rebating policy compared to other policies (recall that abatement based rebating provides additional incentives for reducing EITE emissions, and provides no output protection). Emission leakage is lowest under output-based rebating. Intensity-based emission rebating provides almost as much leakage protection as output-based rebating.

4.3 Terms of trade impacts

Figure 7 shows the impacts of policies on domestic welfare resulting from changes in terms of trade (note that other, non-policy implementing regions of the world experience symmetric

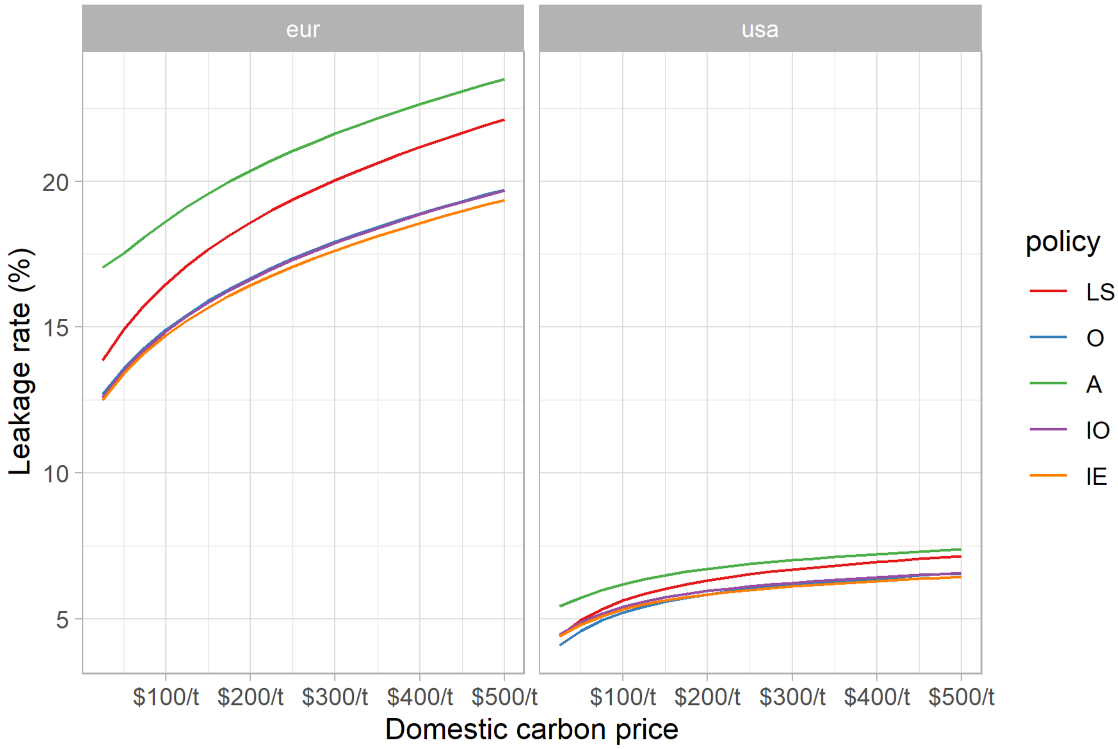


Figure 6: Emission leakage

and opposite terms of trade welfare impacts; these are zero-sum). Terms of trade impacts can be either positive or negative, depending on benchmark trade quantities as well as equilibrium changes in traded goods prices. The Figure shows that output-based rebating causes the smallest domestic welfare losses arising from terms of trade, and at high carbon prices, even results in welfare gains. The abatement-based rebating policy causes the largest terms of trade losses. Intensity-based policies are intermediate.

4.4 Welfare decomposition

Figure 8 shows total domestic welfare change associated with each policy, and with different policy stringencies. The decmoposition follows the derivation in Equation (24). The figure shows that increasing the domestic emission price to $100/t generates significant unilateral welfare gains. Even though the social cost of carbon is $250/t, domestic welfare gains begin to fall for prices higher than $100/t, reflecting the second-best nature of the model. The

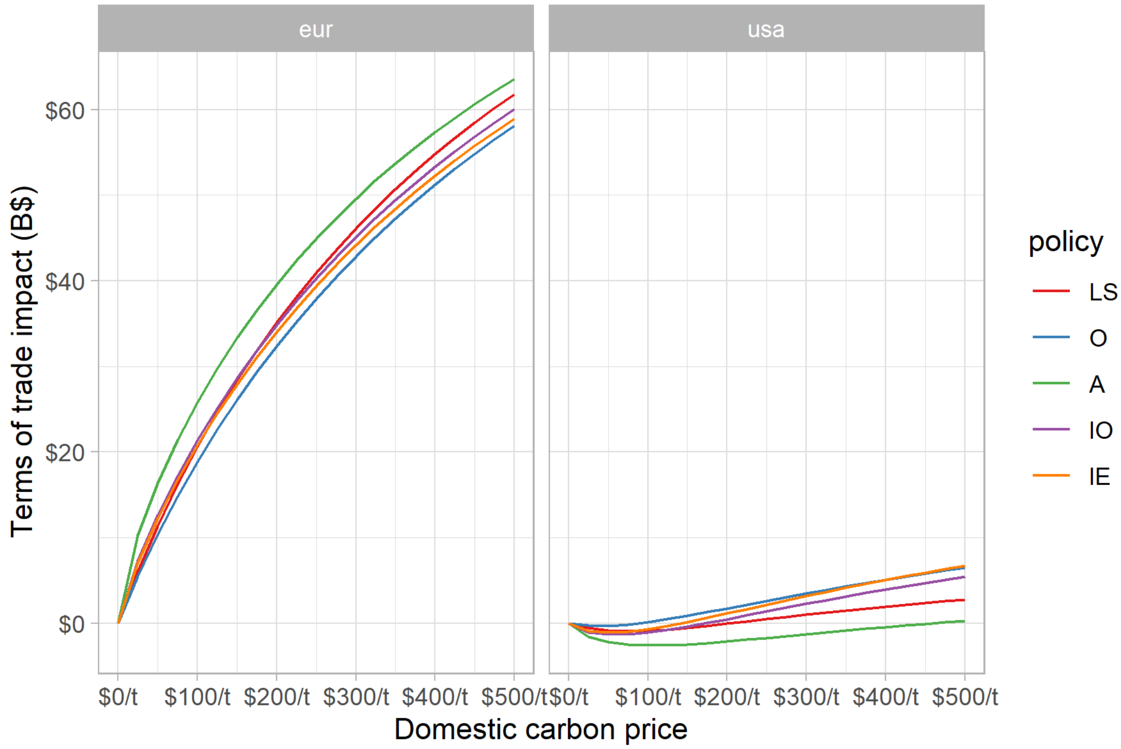


Figure 7: Terms of trade

Figure illustrates that different approaches to EITE emission rebating have different impacts on domestic welfare. At low carbon prices, abatement-based rebating – which generates additional emission reductions – is preferred to alternative forms of rebating. At higher carbon prices, output-based rebating – which reduces leakage and terms of trade impacts – is preferred.

Figure 9 decomposes welfare into the terms identified in the theoretical model. It shows sources of domestic welfare gain and loss associated with a \$25/t and \$250/t domestic carbon price, assuming the social cost of carbon is \$250/t. At a low carbon price, abatement based rebating achieves more domestic emission reductions. Although the cost of these is higher, and leakage and terms of trade impacts are larger for this policy, the net effect is a larger doestic welfare gain for this policy relative to others. This is reversed when the domestic carbon price is high. In this case, the lower domestic cost, leakage, and terms of trade effects associated with output based rebating lead that policy to dominate.

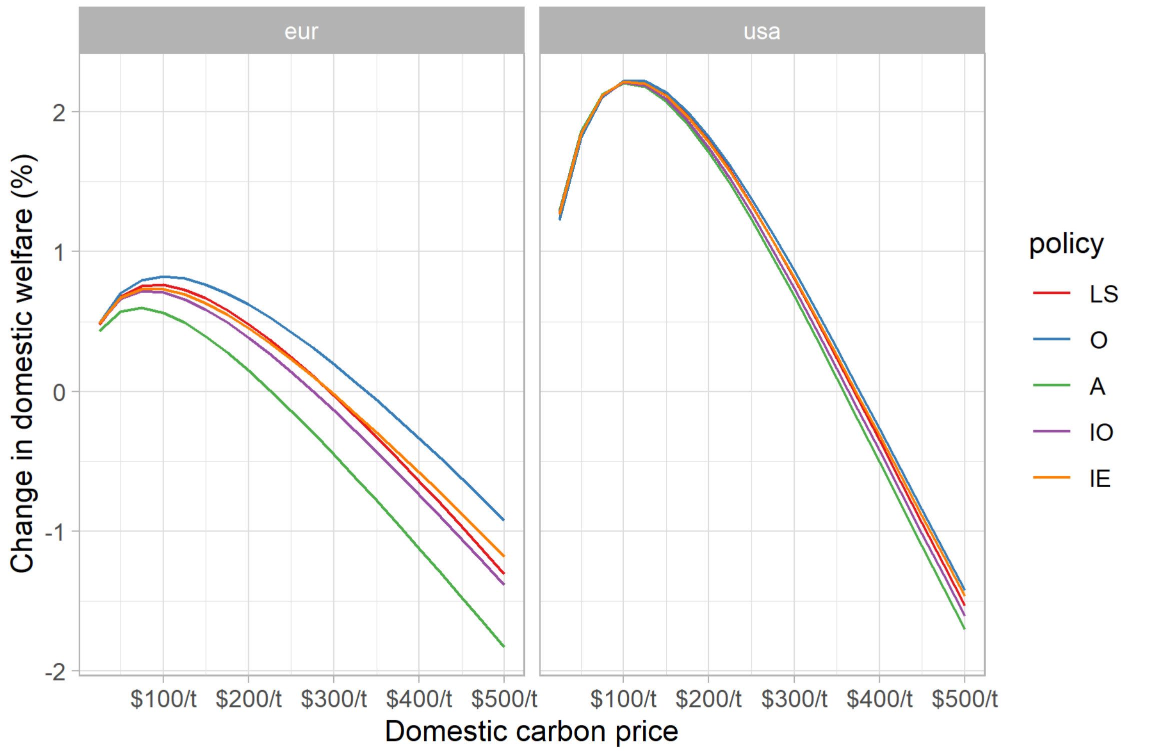


Figure 8: Caption

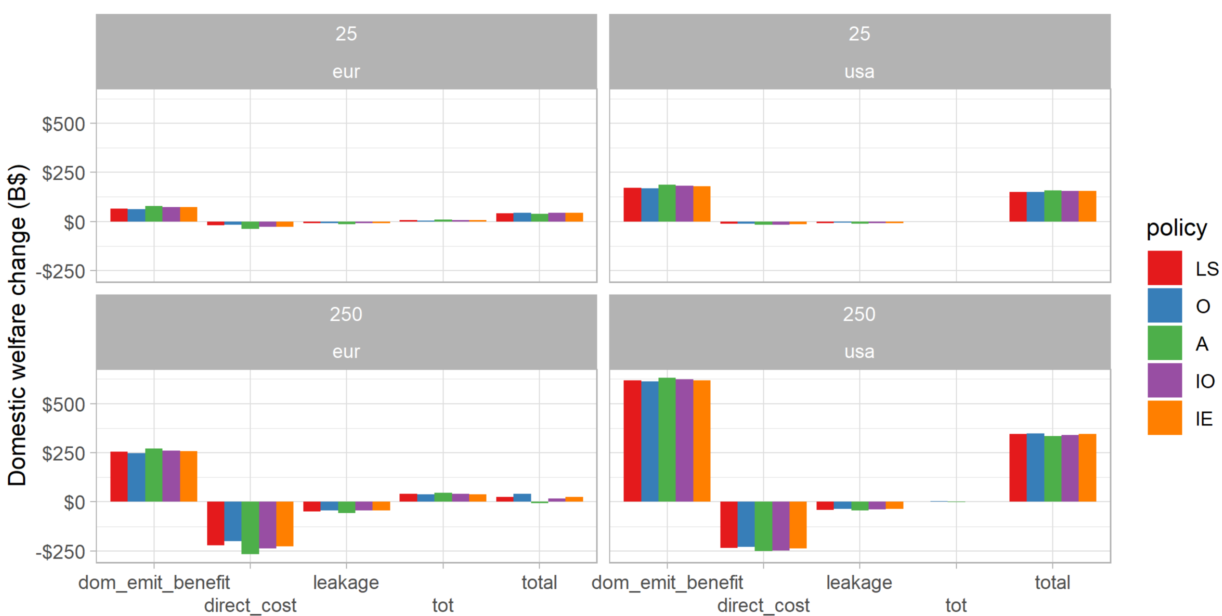


Figure 9: Welfare decomposition

4.5 Policy comparison

Figure 8 and 9 show that welfare impacts of rebating policies depend on context. In Figure 10, we show the optimal rebating policy choice, as a function of both the social cost of carbon, as well as the domestic carbon price. In each case, the welfare ranking includes the second-best elements that are highlighted in the discussion above. The figure shows that when the domestic carbon price is at or near the social cost of carbon, output-based rebates dominate as the policy choice. However, if the domestic carbon price is constrained to below the social cost of carbon, other policy options, which provide more incentives to reduce emissions, are optimal. When the domestic carbon price is around one-half to one-third the social cost of carbon, the model suggests that intensity-based policies are optimal. These policies provide incentives to reduce emissions intensity as well as increase output, and help address carbon leakage and terms of trade impacts from carbon policies while promoting additional emission reductions. When the domestic carbon price is constrained to levels well below the social cost of carbon, abatement based rebating, which stimulates the largest emission reductions, may be optimal.

The prior analysis highlighted that output-based rebates and abatement-based rebates bookend the choices available to policy-makers, with abatement based rebating preferred when the domestic carbon price is significantly below the social cost of carbon, and output-based rebating preferred when the domestic carbon price approaches the social cost of carbon. Figure 11 directly compares OBR and ABR with varying carbon prices as well as varying social cost of carbon. It shows that if the domestic carbon price is below half the social cost of carbon, it is generally preferable to use abatement based rebating, whereas if it is higher, it becomes preferable to use output based rebating. Intensity based and lump sum rebating fall between these two bookends. The figure shows that there can be significant differences in welfare outcomes under these policies. For example, at a high social cost of carbon and a high domestic carbon price, using abatement based rebating instead of output based rebating can impose costs as high as 0.5% of domestic output. In contrast, at a high social cost of carbon and a low domestic carbon price, using output based rebating instead of abatement based rebating can impose costs of up to 0.25% of domestic output.

Figure 10: Optimal policy choice

5 Conclusion

A Proofs

A.1 Steps to model solution

Start by totally differentiating domestic welfare with respect to the domestic carbon price:

$$\frac{dW^d}{d\tau^d} = \frac{dU^d}{d\tau^d} - \delta^d \frac{dZ}{d\tau^d}. \tag{25}$$

We can get an expression for $\frac{dU^d}{d\tau^d}$ by totally differentiating utility and substituting in first order conditions:

$$\frac{1}{\lambda^d}\frac{dU^d}{d\tau^d} = p_X^d \frac{dX^{d,d}}{d\tau^d} + p_X^f \frac{dX^{f,d}}{d\tau^d} + p_Y^d \frac{dY^d}{d\tau^d}. \tag{26}$$

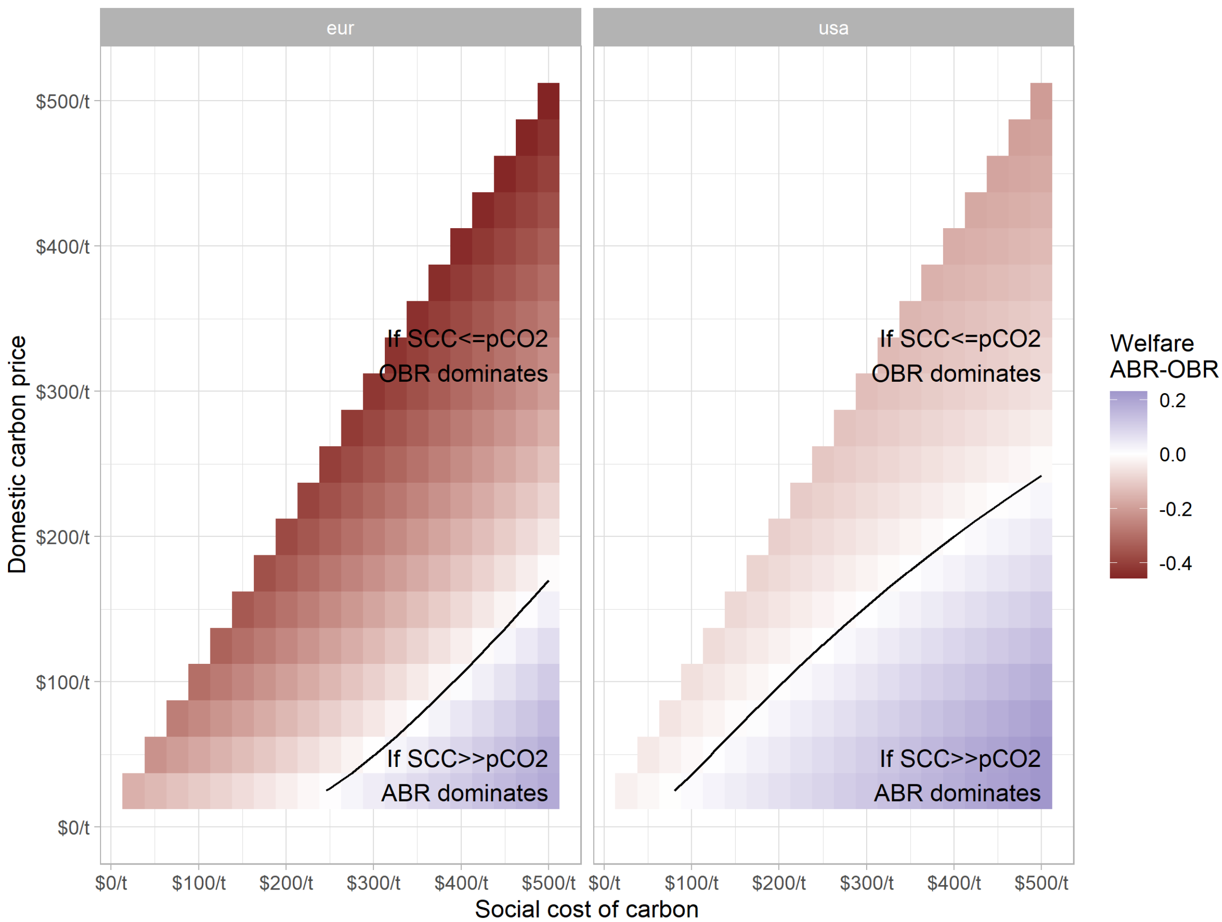


Figure 11: Comparison of OBR vs ABR

Substituting in, we now have:

$$\frac{1}{\lambda^d}\frac{dW^d}{d\tau^d} = p_X^d\frac{dX^{d,d}}{d\tau^d} + p_X^f\frac{dX^{f,d}}{d\tau^d} + p_Y^d\frac{dY^d}{d\tau^d} - \frac{\delta^d}{\lambda^d}\frac{dZ}{d\tau^d}. \tag{27}$$

We can substitute $dX^{d,d} = dX^d - dX^{d,f}$ and substitute the totally differentiated balance of trade condition to get:

$$\frac{1}{\lambda^d}\frac{dW^d}{d\tau^d} = p_X^d\frac{dX^d}{d\tau^d} + p_Y^d\frac{dY^d}{d\tau^d} + \left(X^{d,f}\frac{dp_X^d}{d\tau^d} - X^{f,d}\frac{dp_x^f}{d\tau_d}\right) - \frac{\delta^d}{\lambda^d}\frac{dZ}{d\tau^d}. \tag{28}$$

We can substitute the differentiated production functions and associated first order conditions to get:

$$\frac{1}{\lambda^d}\frac{dW^d}{d\tau^d} = p_X^d\left(\frac{w^d - \frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial L_X^d}}{p_X^d + \frac{\partial R^d}{\partial X^d}}\right)\frac{dL_X^d}{d\tau^d} + p_X^d\left(\frac{\tau^d - \frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial Z_X^d}}{p_X^d + \frac{\partial R^d}{\partial X^d}}\right)\frac{dZ_X^d}{d\tau^d} + w^d\frac{dL_Y^d}{d\tau^d} + \tau^d\frac{dZ_Y^d}{d\tau^d} + \left(X^{d,f}\frac{dq_X^d}{d\tau^d} - X^{f,d}\frac{dq_x^f}{d\tau_d}\right) - \frac{\delta^d}{\lambda^d}\frac{dZ}{d\tau^d}. \tag{29}$$

From labour market clearing we have:

$$-\frac{dL_X^r}{d\tau^r} = \frac{dL_Y^r}{d\tau^r} \tag{30}$$

Therefore, we end up with:

$$\frac{1}{\lambda^d}\frac{dW^d}{d\tau^d} = -\left(\frac{\frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial L_X^d} + \frac{w^d}{p_X^d}\frac{\partial R^d}{\partial X^d}}{1 + \frac{1}{p_X^d}\frac{\partial R^d}{\partial X^d}}\right)\frac{dL_X^d}{d\tau^d} + \left(\frac{\tau^d - \frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial Z_X^d}}{1 + \frac{1}{p_X^d}\frac{\partial R^d}{\partial X^d}}\right)\frac{dZ_X^d}{d\tau^d} + \tau^d\frac{dZ_Y^d}{d\tau^d} + \left(X^{d,f}\frac{dq_X^d}{d\tau^d} - X^{f,d}\frac{dq_x^f}{d\tau_d}\right) - \frac{\delta^d}{\lambda^d}\frac{dZ}{d\tau^d}. \tag{31}$$

Finally, rearraging emissions gives:

$$\frac{1}{\lambda^d}\frac{dW^d}{d\tau^d} = -\left(\frac{\frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial L_X^d} + \frac{w^d}{p_X^d}\frac{\partial R^d}{\partial X^d}}{1+\frac{1}{p_X^d}\frac{\partial R^d}{\partial X^d}}\right)\frac{dL_X^d}{d\tau^d} + \left(\frac{\tau^d - \frac{\partial R^d}{\partial \mu_X^d}\frac{\partial \mu_X^d}{\partial Z_X^d}}{1+\frac{1}{p_X^d}\frac{\partial R^d}{\partial X^d}} - \frac{\delta^d}{\lambda^d}\right)\frac{dZ_X^d}{d\tau^d} + \left(\tau^d - \frac{\delta^d}{\lambda^d}\right)\frac{dZ_Y^d}{d\tau^d} + \left(X^{d,f}\frac{dq_X^d}{d\tau^d} - X^{f,d}\frac{dq_x^f}{d\tau_d}\right) - \frac{\delta^d}{\lambda^d}\frac{dZ}{d\tau^d}. \tag{32}$$

References

Aguiar, Angel, Maksym Chepeliev, Erwin L Corong, Robert McDougall, and Dominique Van Der Mensbrugghe, "The GTAP data base: version 10," *Journal of Global Economic Analysis*, 2019, *4* (1), 1–27.

Armington, Paul S, "A theory of demand for products distinguished by place of production," *Staff Papers*, 1969, *16* (1), 159–178.

Balistreri, Edward J and James R Markusen, "Sub-national differentiation and the role of the firm in optimal international pricing," *Economic Modelling*, 2009, *26* (1), 47–62.

Baumol, William J and Wallace E Oates, *The theory of environmental policy*, Cambridge university press, 1988.

Böhringer, Christoph and Thomas F Rutherford, "Carbon taxes with exemptions in an open economy: a general equilibrium analysis of the German tax initiative," *Journal of Environmental Economics and Management*, 1997, *32* (2), 189–203.

_ , André Müller, and Jan Schneider, "Carbon tariffs revisited," *Journal of the Association of Environmental and Resource Economists*, 2015, *2* (4), 629–672.

_ , Andreas Lange, and Thomas F Rutherford, "Optimal emission pricing in the presence of international spillovers: Decomposing leakage and terms-of-trade motives," *Journal of Public Economics*, 2014, *110*, 101–111.

_ , Carolyn Fischer, and Nicholas Rivers, "Intensity-based rebating of emission pricing revenues," Technical Report, Oldenburg Discussion Papers in Economics 2022.

__ , __ , **Knut Einar Rosendahl, and Thomas Fox Rutherford**, "Potential impacts and challenges of border carbon adjustments," *Nature Climate Change*, 2022, *12* (1), 22–29.

Bovenberg, A Lans and Ruud A De Mooij, "Environmental levies and distortionary taxation," *The American Economic Review*, 1994, *84* (4), 1085–1089.

Fischer, Carolyn and Alan K Fox, "Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates," *Journal of Environmental Economics and management*, 2012, *64* (2), 199–216.

Fowlie, Meredith L and Mar Reguant, "Mitigating emissions leakage in incomplete carbon markets," *Journal of the Association of Environmental and Resource Economists*, 2022, *9* (2), 307–343.

Goulder, Lawrence H, Ian WH Parry, Roberton C Williams Iii, and Dallas Burtraw, "The cost-effectiveness of alternative instruments for environmental protection in a second-best setting," *Journal of public Economics*, 1999, *72* (3), 329–360.

__ , **Marc AC Hafstead, and Roberton C Williams III**, "General equilibrium impacts of a federal clean energy standard," *American Economic Journal: Economic Policy*, 2016, *8* (2), 186–218.

Graham, Paul, Sally Thorpe, and Lindsay Hogan, "Non-competitive market behaviour in the international coking coal market," *Energy Economics*, 1999, *21* (3), 195–212.

Hagem, Cathrine, Michael Hoel, and Thomas Sterner, "Refunding emission payments: Output-based versus expenditure-based refunding," *Environmental and Resource Economics*, 2020, *77* (3), 641–667.

Hoel, Michael, "Should a carbon tax be differentiated across sectors?," *Journal of public economics*, 1996, *59* (1), 17–32.

Holland, Stephen P, "Emissions taxes versus intensity standards: Second-best environmental policies with incomplete regulation," *Journal of Environmental Economics and management*, 2012, *63* (3), 375–387.

Jenkins, Jesse D, "Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design?," *Energy Policy*, 2014, *69*, 467–477.

Kortum, Samuel S and David A Weisbach, "Optimal unilateral carbon policy," 2021.

Krichene, Noureddine, "World crude oil and natural gas: a demand and supply model," *Energy economics*, 2002, *24* (6), 557–576.

Markusen, James R, "International externalities and optimal tax structures," *Journal of international economics*, 1975, *5* (1), 15–29.

Melo, Jaime De and Sherman Robinson, "Product differentiation and the treatment of foreign trade in computable general equilibrium models of small economies," *Journal of international economics*, 1989, *27* (1-2), 47–67.

Ringlund, Guro Børnes, Knut Einar Rosendahl, and Terje Skjerpen, "Does oilrig activity react to oil price changes? An empirical investigation," *Energy Economics*, 2008, *30* (2), 371–396.

Shoven, John B and John Whalley, *Applying general equilibrium*, Cambridge university press, 1992.

United States Environmental Protection Agency, "Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review"," Technical Report Docket ID No. EPA-HQ-OAR-2021-0317 2022.

Weisbach, David, Samuel S Kortum, Michael Wang, and Yujia Yao, "Trade, Leakage, and the Design of a Carbon Tax," Technical Report, National Bureau of Economic Research 2022.