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Christoph Böhringer , Carolyn Fischer , and Nicholas Rivers

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Christoph Böhringer[*], Carolyn Fischer[†], and Nicholas Rivers[‡]

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Abstract

Carbon pricing policies worldwide are increasingly coupled with direct or indirect subsidies for emission-intensive and trade-exposed firms. We analyze the incentives created by novel forms of emissions intensity-based rebating (IBR) and contrast them with more common approaches like output-based rebating (OBR), abatement-based rebating (ABR), or lump-sum rebating (LSR). We rank the different rebate schemes in terms of output protection, emission intensity reduction, and emissions price pressure. We find that intensity-based rebating schemes typically combine elements of OBR and ABR. Given the same sectoral emissions target, revenue-neutral forms of IBR that are proportional to output or emissions lead to the same outcome as conventional output-based rebating, but with lower emissions prices. Outcomes with a simpler form of IBR that subsidizes intensity reductions directly can resemble those with OBR when reductions are less ambitious, while with deeper intensity reductions, outcomes approach those of LSR. With ABR, the emissions price fully offsets the abatement rebate and the resulting allocation is identical to LSR. We supplement partial equilibrium theoretical analysis with numerical simulations to assess the performance of different mechanisms in a multi-sector general equilibrium model which accounts for economy-wide market interactions.

[*]University of Oldenburg, e-mail: boehringer@uol.de
[†]Vrije Universiteit Amsterdam, University of Ottawa, and Resources for the Future, email: c.fischer@vu.nl
[‡]University of Ottawa, email: nrivers@uottawa.ca

1 Introduction

Economists and policymakers have for decades debated the best strategies for reducing carbon emissions. While economists have traditionally emphasized that a uniform price on all emissions is the most cost-effective policy, scholars from other disciplines have noted that carbon prices receive less public support than other approaches to reducing carbon emissions (Drews and Van den Bergh, 2016), have not yet been set at a level that generates substantial emission reductions (Green, 2021), and may not be well suited to effect a major structural transformation of the economy (Rosenbloom et al., 2020). In addition, the economic case for reliance on uniform carbon pricing alone may be weakened by second-best considerations such as initial tax distortions (Goulder et al., 2016) or technological spillovers (Fischer et al., 2017). As a consequence, various protagonists in climate policy argue in favour of specific command-and-control policies such as emission standards and bans on fossil fuels or emission-intensive technologies.

While the theoretical debate goes on about the appropriate mix of market-based and regulatory approaches to reducing emissions, in practice these approaches are converging. Carbon pricing policies worldwide are increasingly being coupled with direct or indirect subsidies for emission-intensive and trade-exposed firms. In the case of quantity-based carbon pricing systems, these subsidies take the form of free emission allocations that are updated based on firm output, which provides an incentive for firms to increase output relative to a pure carbon price (Böhringer and Lange (2005), Fischer (2001)). In the case of price-based carbon pricing systems, these subsidies take the form of output rebates, which provide identical incentives. This approach to complementing emission pricing with output-based rebates helps to alleviate concerns over incomplete global coverage leading to carbon leakage (Fischer and Fox, 2011), concerns associated with interactions of the carbon price with pre-existing taxes (Goulder et al., 2016), distributional concerns (Fischer and Pizer, 2019), concerns over interactios with pre-existing regulations (Borenstein and Bushnell, 2018), and concerns about politically sensitive impacts of a carbon price on the price of energy intensive goods (Sterner and Höglund-Isaksson, 2006).

Similarly, regulatory approaches to reducing emissions are now often designed as performance standards, which require regulated entities to achieve a mandated level of emissions per unit output. In addition, such performance standards are often made more flexible, by allowing regulated entities to trade emission allowances with one another. This approach to the design of regulatory interventions helps to alleviate concerns over poor cost-effectiveness of more prescriptive regulatory approaches. When a performance standard is paired with a system of tradable credits, which is often the case, regulated firms face the similar incentives as under the modified "market-based" approaches described above. Notably, they face an incentive to reduce emissions, represented by the cost of the tradable emissions allowance, and face an incentive to increase output relative to a pure carbon pricing system (Fischer (2001), Holland et al. (2009)).

In practice, then, much of the debate about market-based versus regulatory approaches to reducing emissions is semantic rather than reflecting concrete differences between the way that these two approaches are typically applied. There has been a recent convergence towards adopting this type of hybrid approach to reducing greenhouse gas emissions, which implicitly provides an incentive to reduce emissions but blunts the incentive to reduce output relative to a uniform carbon price (Fischer, 2019).

As aims for carbon emission reduction become more and more ambitious to comply with the 2°C temperature target under the Paris Agreement, policymakers are increasingly searching for mechanisms that encourage deep decarbonization without unduly burdening sectors that must invest in costly abatement technologies. Indeed, if emissions caps are tightened close to zero, there are few permits remaining to allocate based on output. In other words, with dramatic decarbonization, there are few embodied carbon costs to compensate, while abatement costs loom larger. As a result, interest is growing in mechanisms that subsidize abatement rather than just output (Hagem et al., 2020).

In this paper, we consider alternative policy designs from the perspective of the economic incentives they generate for emission reduction, output performance and welfare. We compare three more innovative policy designs – as detailed below – to two more common regulatory regimes, i.e., uniform carbon pricing (with lump sum rebates, LSR) and performance standards (output-based rebating, OBR).

First, we consider an approach that prices carbon and deploys revenue raised from the carbon price to subsidize additional emissions abatement (abatement-based rebating, ABR). A form of this approach is used for example by California, which directs revenues from auctioning tradable emission allowances to a Greenhouse Gas Reduction Fund, and by Quebec, which directs similar revenues to a Green Fund. In both cases, these revenues are used to pay for additional abatement activity.

Second, we discuss approaches that use carbon revenues to incentivize reductions in firm emission intensity below some reference level (intensity-based rebating). We distinguish some simple versions, such as direct subsidies to intensity reduction (SIBR) or intensity-based rebates per unit of output (proportional intensity-based rebating, PIBR). For example, the EU allows member states to compensate electricity-intensive trade-exposed firms for indirect emissions costs, based on the electricity used in production; recent reforms now make such compensation conditional upon additional decarbonisation and energy efficiency efforts by the affected companies.[1]

Third, we analyze a particular mechanism being increasingly deployed in several jurisdictions, in which firms are eligible for a reduction in the emission price they face contingent on reducing emissions intensity (intensity-based emissions rebating, IBER). Such an approach has been used e.g. in the United Kingdom, which has made Climate Change Agreements with firms under which the carbon levy is reduced subject to the firm reducing emission intensity by a given amount.[2] British Columbia also offers a reduced emission tax to firms that successfully reduce their emission intensity through its Industrial Incentive Program.[3]

We use a simple theoretical model of a price-taking representative firm to contrast the economic incentives created by each the five policy designs. We find that, given the same emissions price, ABR and all of the intensity-based variants lead to more reductions in emissions intensity compared to LSR. ABR, for which the subsidy accentuates the opportunity cost of emissions, also leads to less output than LSR. SIBR can result in less output than LSR as well, due to increased unit costs and the lack of an output-based rebating component. By giving a rebate for intensity reductions in proportion to output, PIBR combines features

[1]https://ec.europa.eu/commission/presscorner/detail/en/ip$_2$0$_1$712($Accessed$3/3/2021)

[2]https://www.gov.uk/guidance/climate-change-agreements–2 (Accessed 3/3/2021)

[3]https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/cleanbc-industrial-incentive-program (Accessed 3/3/2021)

of SIBR and OBR. By giving firms a reduction in their emissions payments according to their intensity reductions, IBER combines aspects of PIBR and emissions-based rebating (the negative of ABR). However, if revenue neutral, both PIBR and IBER perform similarly to OBR, but with an additional incentive to reduce intensity.

Given the same sectoral emissions target, we can rank the policies in terms of output protection as a wide-spread policy objective. PIBR and IBER lead to the same outcome as conventional OBR, but with lower emissions prices. With less ambitious reductions, SIBR resembles OBR, while with deeper intensity reductions, SIBR approaches LSR. With ABR, the emissions price fully offsets the abatement rebate and the resulting allocation is identical to LSR.

In practice, however, rebating mechanisms are reserved for emission-intensive and trade-exposed sectors that are most vulnerable to emission pricing. When emissions trading covers multiple sectors, the emissions price will neither remain fixed nor fully adjust when rebating is applied to a subset of firms. Thus, in addition to comparing the policies in a partial-equilibrium analytical setting with one sector only, we will also implement each policy approach in a multi-sector computable general equilibrium (CGE) model. The CGE model will not only relax dimensionality restrictions but will allow us to account for important market interactions via economy-wide substitution and income effects.. Using the numerical model parameterized to the US context, we find imporant quantitative differences between the policy approaches.

Our paper builds on a large literature that uses theoretical and numerical approaches to contrast alternative designs for greenhouse gas policies. Important antecedents to the paper are in particular Helfand (1991) and Fischer (2001), who compare tradable performance standards and output-allocated permits to a uniform carbon price with lump sum rebates using a simple theoretical model. Fischer and Fox (2007) use a numerical computable general equilibrium model to simulate the impact of adopting these policy variants on output and emissions in the United States. Bernard et al. (2007) derive rules for optimal output-based rebating when regulatory coverage is incomplete. Böhringer et al. (2017a) show theoretically that the combination of output-based rebates and a consumption tax can be equivalent with border carbon adjustments as a second-best policy to combate carbon leakage; they use a large-scale CGE model to quantify the welfare gains for the EU of imposing such a complementary consumption tax on top of its existing emissions trading system with output-based rebates to sectors at risk of carbon leakage (Böhringer et al. (2021, forthcoming)). Holland (2012) compares performance standards with a uniform carbon price in an environment where policy coverage is incomplete. Hagem et al. (2020) introduce a rebating scheme focused on abatement expenditures, and conduct an analysis using a stylized theoretical model. Several preceding papers also consider specific types of performance standards. For example, Holland et al. (2009) compare a low carbon fuel standard to uniform carbon prices, and Goulder et al. (2016) evaluate the impacts of a clean energy standard compared to a uniform carbon price in the presence of distortionary taxation. In an empirical application for the U.S. economy, Böhringer et al. (2017b) show that intensity standards may rather increase tha decrease counterproductive carbon leakage and lead to considerable welfare losses as compared to emission taxation or an emissions trading system. Overall, the prior literature suggests that the output-based rebates implicit in performance standards can result in meaningfully different outcomes compared to a carbon tax with lump sum recycling. Most importantly, performance standards are inefficient in the first best because they distort the market for output, causing higher output and lower emission intensity than the first best. However, in a market with incomplete coverage or pre-existing taxes, performance standards can become superior in efficiency terms to uniform taxes with lump-sum rebates (if pre-existing distortions are sufficiently severe).

Relative to the existing literature, our paper stands out for a broader consideration of alternative rebating options. While output-based rebating and performance standards have received substantial scrutiny, we are not aware of similar attention given to the other rebating schemes that we introduce. In addition, this paper combines both a theoretical analysis of these alternative policies with a policy-relevant numerical simulations for the U.S. economy. This two-part analysis facilitates understanding the incentives generated by each policy as well as an understanding of the quantitative importance of these incentives in a real-world setting.

2 Theoretical analysis

We consider a representative firm that is a price taker on factor, product, and emission markets. The firm has a unit cost function given by $C(q, \mu)$, where q is output and μ is the emission intensity of the firm (i.e., emissions per unit of output), implying emissions from the firm are $E = \mu q$. Production costs are increasing and convex in output and decreasing and convex in emission intensity, reflecting the costly nature of emission abatement ($C_q > 0$, $C_{qq} > 0$, $C_\mu \leq 0$, $C_{\mu\mu} > 0$).

To simplify the discourse, we will later assume that unit costs of production are constant and a function of emissions intensity $C(q, \mu) = c(\mu)q$: For example, emissions intensity can be determined by the factor mix and otherwise we have constant returns to scale.

We consider a regulator that puts a price τ on emissions. We consider several different possibilities for the use of the revenue from emissions pricing. We first compare the rebate mechanism effects given the same emissions price, and then given the same emissions target for the sector.

2.1 General

Profits for the representative firm are

$$\pi = Pq - C(q, \mu) - \tau \mu q + R(q, \mu)$$

The firm chooses emissions intensity and output to maximize profits, leading to the first order conditions

$$\begin{aligned} \frac{\partial \pi}{\partial q} &= P - C_q(q, \mu) - \tau \mu + R_q(q, \mu) = 0 \\ \frac{\partial \pi}{\partial \mu} &= -C_\mu(q, \mu) - \tau q + R_\mu(q, \mu) = 0 \end{aligned}$$

Restated, the firm equalizes the marginal costs of abating intensity per unit of output with the emissions price, net of any marginal intensity-based rebate, per unit of output:

$$-C_\mu(q,\mu)/q = \tau - R_\mu(q,\mu)/q$$

Here we see that, given a level of output, a rebate that increases with abatement ($-R_\mu > 0$) will encourage a reduction in emissions intensity. From the FOC for output, we see the firm will produce until the market price is equalized with the marginal costs of production plus the embodied emissions tax costs, net of the marginal output-based rebate:

$$P = C_q(q,\mu) + \tau\mu - R_q(q,\mu)$$

In equilibrium, markets clear and $P = P^D(q)$. Thus, given an emissions price and intensity, a positive marginal rebate for output will encourage more output (or less emissions reduction by reducing production).

Consider now our simplified cost function. The resulting FOCs are

$$-c'(\mu) = \tau - R_\mu(q,\mu)/q \tag{1}$$

$$P = c(\mu) + \tau\mu - R_q(q,\mu) \tag{2}$$

Suppose the different options are used to target the same level of emissions for the sector, $\bar{E}$. This constraint then determines the relationship between emissions intensity and output: $q = \bar{E}/\mu$. The resulting emissions price is endogenous, and combining the two FOCs, we get

$$P(\bar{E}/\mu) = c(\mu) + \left(-c'(\mu) + R_\mu/(\bar{E}/\mu)\right)\mu - R_q \tag{3}$$

2.2 Lump-sum rebating (LSR)

Using lump sum rebates, the regulator allocates all revenue collected from the tax to emitting firms. Rebates are taken as exogenous by firms, because each firm is considered too small to affect the total tax revenue. As a result, $R_q = R_\mu = 0$, and the first-order conditions are:

$$\mu_{\text{LSR}}: \quad -c'(\mu) = \tau; \qquad q_{\text{LSR}}: \quad P(q) = c(\mu) + \tau\mu. \tag{4}$$

The standard results of marginal abatement costs being equalized with the emissions price apply.

If we consider an emissions target for this sector, the market outcome will satisfy

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu. \tag{5}$$

2.3 Output-based rebating (OBR)

With output-based rebating, the regulator allocates emission revenues in proportion to output, based on a benchmark b that is independent of the individual firm's emissions intensity: $R = \tau bq$. Thus, $R_q = \tau b$ and $R_\mu = 0$. The first-order conditions simplify to

$$\mu_{\text{OBR}}: \quad -c'(\mu) = \tau; \qquad q_{\text{OBR}}: \quad P = c(\mu) + \tau(\mu - b). \tag{6}$$

The output-based rebate acts as a subsidy to output, without directly distorting the emissions intensity choice. Thus, for the same emissions price, $\mu_{\text{OBR}} = \mu_{\text{LSR}}$ and $q_{\text{OBR}} > q_{\text{LSR}}$.

For the same sectoral emissions target, the equilibrium will have more output and thus lower emissions intensity than with lump-sum allocation, requiring a higher emissions price ($\tau_{\text{OBR}} > \tau_{\text{LSR}}$), and satisfying

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)(\mu - b). \tag{7}$$

Since the right-hand side of (7) is less than that of (5), we get the well-known result that for the same emissions target, $\mu_{\text{OBR}} < \mu_{\text{LSR}}$ and $q_{\text{OBR}} > q_{\text{LSR}}$.

If rebate is revenue neutral, in equilibrium $b = \mu$, and the first-order condition for output is $q^{\text{RN}}_{\text{OBR}}$: $P(q) = c(\mu)$. Full earmarking leaves no net tax on embodied emissions, and the change in costs depends purely on the change in emissions intensity.

2.4 Abatement-based rebating (ABR)

Different kinds of abatement-based rebating have been considered in the past. For example, Hagem et al. (2020) look at subsidies to abatement expenditures. We will consider a few here, beginning with the simplest form, an emissions tax-financed subsidy to abatement: $R = s(\mu_0 q_0 - \mu q)$, so $R_q = -s\mu$ and $R_\mu = -sq$.

In this case, the profit-maximizing conditions are

$$\mu_{\text{ABR}}: \quad -c'(\mu) = \tau + s; \qquad q_{\text{ABR}}: \quad P(q) = c(\mu) + (\tau + s)\mu. \tag{8}$$

The abatement-based rebate, although it offers a subsidy to emissions intensity reduction, functions as an additional tax on output. Essentially, the abatement subsidy amplifies the effect of the emissions tax on both fronts. Thus, for the same emissions price, the equilibrium will have both less output and lower emissions intensity.

Proposition 1 *For the same sectoral emissions target,* $\tau_{ABR} = \tau_{LSR} - s$*,* $\mu_{ABR} = \mu_{LSR}$*, and* $q_{ABR} = q_{LSR}$*.*

Proof. Since $R_\mu \mu/q - R_q = -sq\mu/q + s\mu = 0$, (3) reduces to (5) with ABR, which implies that $\mu_{\text{ABR}} = \mu_{\text{LSR}}$. The emissions constraint then gives $q_{\text{ABR}} = q_{\text{LSR}}$, and (8) implies $\tau_{\text{ABR}} = \tau_{\text{LSR}} - s,$. ■

In other words, the tax fully absorbs the effect of the abatement rebate, producing the same equilibrium outcome as lump-sum rebating.

Note that the same results go through if the abatement subsidy is negative. For example, at certain stages of evolution in the EU ETS, some industry groups have lobbied for rebates that reflect the emissions that need to be covered (Böhringer and Lange, 2005). If done in an updating form, the rebate becomes an emissions tax-financed subsidy to emissions: $R = s(\mu q)$, which on the margin functions like an abatement tax. Emissions-based rebating (EBR) would thus dampen the effect of the emissions tax on both fronts. For the same emissions price, the equilibrium will have both more output and higher emissions intensity, meaning that for the same emissions target, the carbon price must rise to fully offset the effect of the emissions rebate. Since EBR is generally counterproductive, we will restrict ourselves to considering ABR.

Note that if the rebate is revenue neutral, then $s = \tau\mu q/(\mu_0 q_0 - \mu q) = \tau E/(E_0 - E)$, and (8) simplifies to

$$\mu_{\rm ABR}^{\rm RN}: \quad -c'(\mu) = \tau\frac{E_0}{E_0 - \mu q}; \qquad q_{\rm ABR}^{\rm RN}: \quad P(q) = c(\mu) + \tau\mu\frac{E_0}{E_0 - \mu q} \tag{9}$$

2.5 Intensity-based rebating (IBR)

We next consider variants of intensity based rebating. The first would be its purest form, a rebate dependent only on intensity reductions, invariant to output. The second would offer the intensity-based rebate scaled in proportion to output. The third modifies the rebate as a share of emission payments, as with an intensity-based reduction in the carbon price. Each creates different incentives that are useful to explore.

2.5.1 Simple intensity-based rebating (SIBR)

The simplest form of IBR is to offer a subsidy to a firm's reduction in emissions intensity below some upper-bound level μ_U: $R = s(\mu_U - \mu)$. On the margin, the rebate is independent of output ($R_q = 0$) and increasing in the intensity reduction ($R_\mu = -s$). The first-order conditions with SIBR simplify to

$$\mu_{\rm SIBR}: \quad -c'(\mu) = \tau + s/q; \qquad q_{\rm SIBR}: \quad P(q) = c(\mu) + \tau\mu. \tag{10}$$

In this version, the rebate only directly subsidizes emissions intensity reduction, although the unit rebate ultimately depends on equilibrium output. However, since the firm is a price taker, that output will be lower as a result of the rebate, when the emissions price is fixed:

Proposition 2 *For the same emissions price, SIBR leads to both lower output and lower emissions intensity than LSR.*

Proof. The intensity condition in (10) shows that the subsidy necessarily increases intensity abatement when τ is fixed. Greater intensity abatement lowers embodied emissions payments, but it raises marginal production costs more: $dP/ds = (c'(\mu) + \tau)\, d\mu/ds =$

$-(s/q)d\mu/ds > 0$, since $d\mu/ds < 0$. Since the equilibrium price rises, q falls. ■

Proposition 3 *For the same sectoral emissions target, SIBR leads to higher output and lower intensity at a lower emissions price than LSR.*

Proof. Given the same emissions target, the rebate drives down the emissions price ($\tau_{\text{SIBR}} = -c'(\mu) - s/q$). The net effect with the subsidy must still be to lower emissions intensity relative to LSR, and thus from the emissions constraint to raise output: (3) simplifies to $P(\bar{E}/\mu) = c(\mu) + (-c'(\mu) - s\mu/\bar{E})\mu$, for which the right-hand side is lower than in (5). ■

Compared to OBR, the question is whether $s\mu^2/\bar{E} > -c'(\mu)b$. Consider revenue-neutral versions of these policies. For OBR, revenue neutrality implies $b = \mu$. For a SIBR mechanism meeting the emissions target with 100% recycling, $s = \tau\mu q/(\mu_U - \mu)$ in equilibrium. Thus,

$$\mu_{\text{SIBR}}^{\text{RN}}: \quad -c'(\mu) = \tau\frac{\mu_U}{\mu_U - \mu}; \qquad q_{\text{SIBR}}^{\text{RN}}: \quad P(q) = c(\mu) + \tau\mu. \tag{11}$$

Proposition 4 *Comparing revenue-neutral policies, for the same sectoral emissions target, SIBR leads to less output and less intensity reduction than OBR.*

Proof. From (11), we derive the emissions price to achieve the equivalent target, leading to

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu\frac{\mu_U - \mu}{\mu_U}.$$

Since $1 > (\mu_U - \mu)/\mu_U > 0$, $P_{\text{OBR}}^{\text{RN}} < P_{\text{SIBR}}^{\text{RN}}$, so the emissions constraint is met with less output and less intensity reduction. ■

2.5.2 Proportional intensity-based rebating (PIBR)

Since emissions intensity is measured per unit of output, one might imagine that the rebate would be allocated per unit of output, meaning the total subsidy would be scaled in proportion to a firm's output. In this case, $R = s(\mu_U - \mu)q$, so the rebate is increasing both in the intensity reduction ($-R_\mu = sq > 0$) and in output ($R_q = s(\mu_U - \mu) > 0$). The first-order conditions with PIBR simplify to

$$\mu_{\text{PIBR}}: \quad -c'(\mu) = \tau + s; \qquad q_{\text{PIBR}}: \quad P(q) = c(\mu) + \tau\mu - s(\mu_U - \mu). \tag{12}$$

Thus, PIBR combines elements of OBR and SIBR.

Proposition 5 *For the same emissions price, PIBR induces a lower emissions intensity and a higher level of output than LSR.*

Proof. The first-order condition for intensity in (12) makes clear that the subsidy increases incentives for intensity abatement, so $\mu_{\text{PIBR}} < \mu_{\text{LSR}}$. Even with lower intensity, the net effect of the rebate is to raise equilibrium output ($q_{\text{PIBR}} > q_{\text{LSR}}$) by driving down the equilibrium price: $dP/ds = (c'(\mu) + \tau - s)\, d\mu/ds - (\mu_U - \mu) = -(\mu_U - \mu) < 0$. ■

Although the additional abatement raises unit production costs, that increase is more than offset by the rebate. Even if the firm left its emissions intensity at μ_{LSR}, its net unit costs would be lower, and to the extent the firm deviates from this intensity, it must be to lower costs further.

Proposition 6 *Comparing revenue-neutral policies, given the same emissions price, PIBR leads to more intensity reduction but less output protection than OBR.*

Proof. Revenue-neutral PIBR implies $s(\mu_U - \mu)q = \tau\mu q$, or $s = \tau\mu/(\mu_U - \mu)$. The first-order conditions in (12) reduce to

$$\mu^{\text{RN}}_{\text{PIBR}}: \quad -c'(\mu) = \tau\mu_U/(\mu_U - \mu); \qquad q^{\text{RN}}_{\text{PIBR}}: \quad P(q) = c(\mu). \tag{13}$$

Since $\mu_U/(\mu_U - \mu) > 1$, for the same τ, $\mu^{\text{RN}}_{\text{PIBR}} < \mu^{\text{RN}}_{\text{OBR}}$. As a result, $c(\mu^{\text{RN}}_{\text{PIBR}}) > c(\mu^{\text{RN}}_{\text{OBR}})$, so $q^{\text{RN}}_{\text{PIBR}} < q^{\text{RN}}_{\text{OBR}}$. ■

Next, for the same emissions target,

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu - s\mu_U \tag{14}$$

so PIBR leads to more intensity reduction and more output than LSR. In equilibrium, PIBR functions much like OBR, and nearly completely so when reveneues are fully rebated:

Proposition 7 *For the same sectoral emissions target, revenue-neutral PIBR leads to identical output and intensity reduction as revenue-neutral OBR, but with a lower emissions price.*

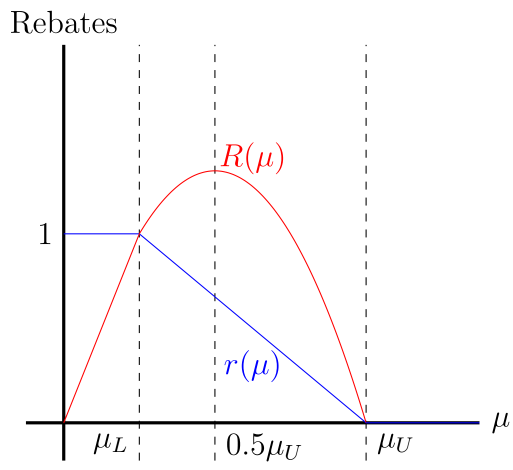


Figure 1: Intensity-based rebate specification

Proof. From (13), the output condition for a revenue-neutral PIBR with the same emissions target is (7), the same as with OBR. From the intensity condition, we solve for $\tau^{RN}_{PIBR} = -c'(\mu^{RN}_{PIBR})(\mu_U - \mu^{RN}_{PIBR})/\mu_U < -c'(\mu^{RN}_{PIBR}) = \tau^{RN}_{OBR}$. ■

In other words, if the rebate is revenue neutral, the rebate just cancels out the embodied emissions payment, as it does with OBR. However, the subsidy to abatement means a lower emissions price is needed to meet the target.

2.5.3 Intensity-based emissions rebating (IBER)

In practice, as in British Columbia's Industrial Incentive Program and the UK's Climate Change Agreements, intensity-based rebating has been to relieve a share of emissions payments, with that share depending on the firm or plant's emissions intensity. This setup differs from a straightforward subsidy to intensity abatement. From the firm's perspective, the subsidy rate is not independent of its emissions. Rather, $R = r(\mu)\tau\mu q$, where $r(\mu) \in [0, 1]$and $r'(\mu) < 0$. This design implies $R_q = r(\mu)\tau\mu$ and $R_\mu = (r(\mu) + r'(\mu)\mu)\,\tau q$. We illustrate the set-up in Figure 1. As a result, the profit-maximizing conditions are

$$\mu: \quad -c'(\mu) = \tau\,(1 - r(\mu) - r'(\mu)\mu)\,; \qquad q: \quad P(q) = c(\mu) + \tau\mu\,(1 - r(\mu)) \qquad (15)$$

Thus, IBER contains elements of OBR, SIBR, and EBR. For the same emissions price, given an intensity, we expect more output as compared to LSR. Because the rebate is a reduction in emissions taxes, it acts in part as a subsidy to emissions, and thereby to output. This emissions subsidy also confers to emissions intensity decisions. As a result, the net effect on the first-order condition for emissions intensity depends on whether the marginal rebate from reducing emissions intensity ($-r'(\mu) > 0$), exceeds the average rebate per unit of intensity ($r(\mu)/\mu$). If so, then IBR produces more emission intensity reduction as compared to LSR. Since intensity reduction is a goal of the policy, we assume this design condition holds.

A stylized version of the IBER has the rebate rate increasing as intensity declines below an upper threshold, μ_U, towards a lower threshold, assumed to be that of a best-available technology (μ_L), where $r(\mu) = \rho\frac{\mu_U-\mu}{\mu_U-\mu_L}$, with ρ as a scaling factor. With this form, $r'(\mu) = -\rho/(\mu_U - \mu_L)$ and $r(\mu) + r'(\mu)\mu = \rho\frac{\mu_U-2\mu}{\mu_U-\mu_L}$. Substituting, we simplify the first-order conditions:

$$\mu_{\text{IBER}} : -c'(\mu) = \tau\left(1 + \rho\frac{2\mu - \mu_U}{\mu_U - \mu_L}\right); \qquad q_{\text{IBER}} : P(q) = c(\mu) + \tau\mu\left(1 - \rho\frac{\mu_U - \mu}{\mu_U - \mu_L}\right). \quad (16)$$

Our design condition becomes $\mu_U < 2\mu$; that is, the emissions rate is not reduced more than half below the emissions intensity threshold. Else, if the upper threshold is set too generously, the subsidy to emissions dominates the subsidy to intensity reductions. This condition ensures that for the same emissions price, intensity reductions are further encouraged by IBER, relative to LSR.

Using (16) and simplifying (3), we find that for the same sectoral emissions target,

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu Z(\rho) \quad (17)$$

where $Z(\rho) = \frac{\mu_U-\mu_L-\rho(\mu_U-\mu)}{\mu_U-\mu_L-\rho(2\mu-\mu_L)}$.

Proposition 8 *For the same sectoral emissions target, IBER leads to higher output and lower intensity than LSR, at a lower emissions price.*

Proof. $Z(0) = 1$ and $Z'(\rho) = -\mu(\mu_U - \mu_L)/(\mu_U - \mu_L + \rho(2\mu - \mu_U))^2 < 0$, meaning that scaling up the rebate lowers the right-hand side of (17) relative to (5), ensuring $\mu_{\text{IBER}} < \mu_{\text{LSR}}$

and $q_{\text{IBER}} > q_{\text{LSR}}$ along with the emissions constraint. Given the assumption that $\mu_U < 2\mu$, combining PIBR with $\tau = \tau_{\text{LSR}}$ would lead to lower emissions than with LSR, so the emissions constraint can be met with a lower price, $\tau_{\text{IBER}} < \tau_{\text{LSR}}$. ■

Whether the IBER has higher output (and lower intensity) than OBR depends on whether $\mu Z(\rho) < \mu - b$. To compare to the other options, then, let us consider cases of 100% earmarking.

For IBER, revenue neutrality implies $r(\mu) = 1$, or $\rho = \rho^{\text{RN}} \equiv (\mu_U - \mu_L)/(\mu_U - \mu)$ in equilibrium. The first-order conditions in (16) reduce to

$$\mu^{\text{RN}}_{\text{IBER}}: \quad -c'(\mu) = \tau \frac{\mu}{(\mu_U - \mu)}; \qquad q^{\text{RN}}_{\text{IBER}}: \quad P(q) = c(\mu) \tag{18}$$

Proposition 9 *Comparing revenue-neutral policies, given the same emissions price, IBER leads to less intensity reduction and more output than PIBR, but more intensity reduction and less output than OBR.*

Proof. Since $\tau < \tau \frac{\mu}{(\mu_U - \mu)} < \tau \frac{\mu_U}{(\mu_U - \mu)}$, it must be that $\mu^{\text{RN}}_{\text{OBR}} < \mu^{\text{RN}}_{\text{IBER}} < \mu^{\text{RN}}_{\text{PIBR}}$. Since in each case, $P(q) = c(\mu)$, then $q^{\text{RN}}_{\text{OBR}} > q^{\text{RN}}_{\text{IBER}} > q^{\text{RN}}_{\text{PIBR}}$. ■

Proposition 10 *Given a sectoral emissions target, a revenue-neutral IBER leads to the same allocation of output and intensity as PIBR and OBR, but with a higher emissions price than PIBR, but not as high as OBR.*

Proof. $Z(\rho^{\text{RN}}) = 0$, so (17) simplifies to $P(\bar{E}/q) = c(\mu)$, as with PIBR and OBR. However, from (18), at a given emissions target, the equilibrium emissions price under revenue-neutral IBER is $\tau^{\text{RN}}_{\text{IBER}} = -c'(\mu)\frac{\mu_U - \mu}{\mu} > -c'(\mu)\frac{\mu_U - \mu}{\mu_U} = \tau^{\text{RN}}_{\text{PIBR}}$. Our design condition that $2\mu > \mu_U$ ensures that $\frac{\mu_U - \mu}{\mu} < 1$ and $\tau^{\text{RN}}_{\text{IBER}} < \tau^{\text{RN}}_{\text{OBR}}$. ■

In other words, with 100% rebating, no tax on embodied emissions remains under any of these proportional rebating policies. Therefore, meeting an emissions reduction target simply requires a sufficient amount of intensity reduction, given that only additional production costs will be passed on to consumers. However, the different marginal incentives for emissions intensity reductions, given an emissions price, will determine how market prices for emissions must adjusts to meet the target.

3 Summary of results from the theory

3.1 Comparisons given a price or emissions target

Table 1 summarizes the first-order conditions for each policy, given the same emissions price and assuming revenue-neutral policies, in the order of presentation in Section 2.1.

Table 1: First-order conditions for revenue-neutral rebating mechanisms, given the same emissions price

Rebate	Intensity	Output
LSR	$-c'(\mu) = \tau$	$P(q) = c(\mu) + \tau\mu$
OBR	$-c'(\mu) = \tau$	$P(q) = c(\mu)$
ABR	$-c'(\mu) = \tau\left(\frac{\mu_0 q_0}{\mu_0 q_0 - \mu q}\right)$	$P(q) = c(\mu) + \tau\mu\left(\frac{\mu_0 q_0}{\mu_0 q_0 - \mu q}\right)$
SIBR	$-c'(\mu) = \tau\frac{\mu_U}{(\mu_U - \mu)}$	$P(q) = c(\mu) + \tau\mu$
PIBR	$-c'(\mu) = \tau\frac{\mu_U}{(\mu_U - \mu)}$	$P(q) = c(\mu)$
IBER	$-c'(\mu) = \tau\frac{\mu}{(\mu_U - \mu)}$	$P(q) = c(\mu)$

Table 2 compares the qualitative effects of the different rebate policies to the non-distorting LSR. Note that the direction of emissions will indicate the direction of the required emissions price adjustment to meet an equivalent emissions target, for which the first-order conditions are summarized in the subsequent table. Hence, although intensity and output react in opposite directions for PIBR and IBER, since the emission prices fall when meeting an equivalent emissions target, it must be that emissions are reduced relative to LSR, given an emissions price.

Table 2: Compared to LSR, given the same emissions price

Rebate	Intensity	Output	Emissions
OBR	=	↑	↑
ABR	↓	↓	↓↓
SIBR	↓	↓	↓↓
PIBR	↓	↑	↓
IBER	↓	↑	↓

Table 3 summarizes the results for a given emissions target, assuming revenue-neutral rebating policies. It orders the policies in terms of highest to lowest output protection and intensity reduction.

Table 3: Equilibrium conditions for revenue-neutral rebating mechanisms given the same sectoral emissions target, ranked by output and then by emissions price

Rank	Rebate	Output	Emissions Price
1	OBR	$P(\bar{E}/\mu) = c(\mu)$	$-c'(\mu)$
	IBER	$P(\bar{E}/\mu) = c(\mu)$	$-c'(\mu)\frac{\mu_U-\mu}{\mu}$
	PIBR	$P(\bar{E}/\mu) = c(\mu)$	$-c'(\mu)\frac{\mu_U-\mu}{\mu_U}$
2	SIBR	$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu\left(\frac{\mu_U-\mu}{\mu_U}\right)$	$-c'(\mu)\frac{\mu_U-\mu}{\mu_U}$
3	LSR	$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu$	$-c'(\mu)$
	ABR	$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu$	$-c'(\mu)\frac{(E_0-\bar{E})}{E_0}$

Note in Table 3 that, in terms of output protection, the less ambitious the reductions, the more SIBR looks like OBR. By contrast, with deeper intensity reductions, revenue-neutral SIBR approaches LSR.

3.2 Discussion of OBR vs IBER

Let us focus on comparing the well-known OBR policy with the novel IBER policy, without restricting ourselves to revenue neutrality. Both can be designed to give the same amount of output (and therefore competitiveness-related leakage) protection.

Given an emissions target, the OBR that provides the same output protection (and same μ) as IBER solves $\mu - \hat{b} = \mu Z(\rho)$, or $\hat{b} = \mu(1 - Z(\rho))$. We can show that these output- and emissions-equivalent policies also have equivalent fiscal implications. The net revenues under this OBR are $\tau_{OBR}(\mu - \hat{b})q = -c'(\mu)Z(\rho)\bar{E}$. The net revenues under IBER are

$$\tau_{\text{IBER}}\bar{E}\left(1 - \rho\frac{\mu_U - \mu}{\mu_U - \mu_L}\right) = -c'(\mu)Z(\rho)\bar{E},$$

since $\tau_{\text{IBER}} = -c'(\mu)/\left(1 + \rho\frac{2\mu-\mu_U}{\mu_U-\mu_L}\right)$.

Thus, the OBR and IBER policies that provide identical output protection for the same level of emissions also raise identical revenues, as implied by Propositions 7 and 10. The main difference, then, is that IBER does it with a lower emissions price:

$$\frac{\tau_{IBER}}{\hat{\tau}_{OBR}} = \frac{\mu_U - \mu_L}{\mu_U - \mu_L + \rho(2\mu - \mu_L)} < 1,$$

given our design assumption that $\mu_U < 2\mu$.

Therefore, if a policy with a lower emissions price is attractive, such as for political feasibility reasons, IBER may be preferred to OBR. This line of reasoning was an important factor for abatement-based rebating in Hagem et al. (2020). However, the different directions of emissions price adjustment will also have important efficiency implications in a multi-sector setting. If rebate-eligible sectors (say, EITE sectors) are trading under a cap with other sectors without conditional rebating, OBR will tend to shift more compliance burden toward the ineligible (non-EITE) sectors by driving up ETS prices, whereas IBER (as well as other abatement-oriented rebating mechanisms) tends to relieve the other sectors of some burden, by putting downward pressure on ETS prices.

3.3 Welfare

Ultimately, the welfare effects depend on the benefits of output protection (e.g., in terms of leakage or other distortions avoided) versus the excess costs of greater reliance on intensity abatement, relative to any spillover benefits (e.g., from technological innovation or reduced compliance costs elsewhere) that might have. Let $CS(q)$ be consumer surplus in this sector, so $CS(q) - c(\mu)q$ is net surplus. Let our measure of welfare then be $W = CS(q) - c(\mu)q - \delta\mu q + B(q,\mu)$, where δ is the (constant) marginal damage from emissions and B represents spillover benefits from interactions with other distortions. The partial equilibrium marginal welfare costs of the regulation are

$$\begin{aligned} dW &= \left(P(q) - c(\mu) - \delta\mu + B_q\right) dq - (c'(\mu) + \delta - B_\mu/q)q d\mu \\ &= \left((\tau - \delta)\mu - R_q + B_q\right) dq + ((\tau - \delta)q + R_\mu - B_\mu)d\mu \end{aligned}$$

Here, we see that the optimal policy would have the emissions price reflect marginal damages, while the marginal rebates should reflect the marginal spillover benefits. In practice, rebates are not optimized but rather reflect different rules of thumb. We next use numerical simulations to quantify the efficiency and distributional effects of the different rebating policies in a general equilibrium setting.

4 Numerical simulations

In this section, we build on the theoretical understanding of alternative approaches to rebating using a numerical computable general equilibrium (CGE) model. The CGE approach describes economic activities by combining assumptions on the optimizing behavior of economic agents with the analysis of equilibrium conditions. Decisions about the allocation of resources are decentralized, and the representation of behavior by producers and consumers follows the standard microeconomic paradigm: producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers with given preferences maximize their well-being subject to budget constraints. Our model implementation builds on the canonical structure of a static multi-sector multi-region CGE model to investigate the economy-wide impacts of carbon abatement policies (Böhringer and Rutherford, 2002). One attractive feature of the modeling framework laid out in Böhringer and Rutherford (2002) is the possibility to operate single regions as small open economies with fixed terms of trade. In our analysis, we take this approach and focus on a single region, USA.

Before we discuss our numerical simulations we briefly summarize the main characteristics of our CGE model. A detailed algebraic exposition is provided in the appendix. Our model features a representative agent who receives income from three primary factors: labor, capital, and fossil-fuel specific resources for primary energy carriers (coal, natural gas, and crude oil). Labor and capital are mobile across sectors. Fossil fuel resources are specific to fossil fuel production sectors in each region. Each production sector uses a nested constant-elasticity-of-substitution (CES) production function, in which capital and labor form a value-added nest, value-added and energy form a nest, and this nest is combined with other material inputs. Commodity and factor markets are assumed to be perfectly competitive such that they clear without frictions. Final consumption demand is determined by a representative agent who maximizes welfare subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. Consumption demand of the representative agent is given as a CES composite that combines consumption of a CES energy composite and a CES composite of other (non-energy) consumption goods.

In international trade, the single region - in our case USA - is treated as small relative to the world market. We thus assume that changes in the region's import and export volumes have no effect on international prices. Following the proposition of (Armington, 1969), domestic and foreign goods are distinguished by origin. A balance-of-payment constrains the total value of exports to be equal to the total value of imports plus an initial base-year deficit or surplus. Emissions of CO_2 are proportional to each type of primary energy.

As is customary in applied general equilibrium analysis, base-year data together with exogenous elasticities determine the free parameters of the functional forms. For model parameterization, we use the most recent GTAP data set (version 10) which includes detailed balanced accounts of production, consumption, trade, and CO_2 emissions together with key elasticities for the base-year 2014 (Aguiar et al., 2019). In our parametrization, we do not include pre-existing taxes which leaves us with a first-best reference situation such that the simulation results should adhere closely to the theoretical predictions outlined above, while capturing the quantitative differences between rebating options.[4]

For the simulation analysis, we aggregate the GTAP dataset with 65 sectors to 7 sectors reflecting the specific requirements of our research question. In the composite dataset we distinguish five energy-producing and transforming sectors (coal, gas, oil, electricity, and refined oil products), an energy-intensive trade-exposed manufacturing sector, and an aggregate sector reflecting the remainder of the economy. In the results below, we group these sectors into two groups: an energy intensive and trade exposed (EITE) and an aggregate non-EITE sector (NEITE). In some results, we also refer to final demand sectors (C).

We introduce each type of policy described above sequentially into the model. In each case, we impose a common price on CO_2 emissions throughout the economy. We then apply the policy variants described above to the energy-intensive trade-exposed manufacturing sector. In each case, the policy variants are considered in their revenue-neutral form, implying that all revenue raised from the CO_2 tax in this sector is used to provide rebates of different types to firms in this sector. Consequently, the opportunity cost of CO_2 emissions as well as incentives to curtail output differ across policy variants and across sectors. We note that

[4] Of course, the model is a general equilibrium model, whereas the theory focuses on partial equilibrium outcomes, so some potential for discrepancy does exist.

while it is natural to compare revenue-neutral variants of these policies, the revenue-neutral formulation is the most extreme version of each variant, since *all* revenue raised from carbon pricing in the EITE sector is used to provide rebates to firms in this sector. In practice, it may be more natural to reserve only a portion of revenue from the carbon price for rebating, which would lessen the differences between policy variants.

Similar to the theoretical exposition above, we have two approaches to comparing across policy variants. First, we compare policies with a common CO_2 price across variants. Second, we compare policies that achieve the same overall reduction in emissions across variants. In both cases, the starting point for comparison is the policy with lump sum rebates. We choose a carbon price for this policy that achieves a 20 percent reduction in economy-wide CO_2 emissions. As shown in Figures 2a and 2b, a 20 percent reduction in economy-wide emissions under the LSR scenario is achieved in this model with a carbon price of $\$32/tCO_2$ applied uniformly across all sectors.

We first discuss the policies implemented in a way that the carbon price is equal across each policy variant; results from simulating these policies are shown on the left hand side of Figure 2.

Incentives for emissions abatement under the OBR policy are determined uniquely by the emission price, and are equal across both sectors in which the rebate is applied as well as other sectors. However, the OBR policy imposes an implicit subsidy on output in the EITE sector, resulting in a much smaller curtailment in output in this sector relative to LSR (Figure 2c). As a result, emissions are higher in the EITE sector under the OBR policy, relative to the LSR policy (Figure 2e).

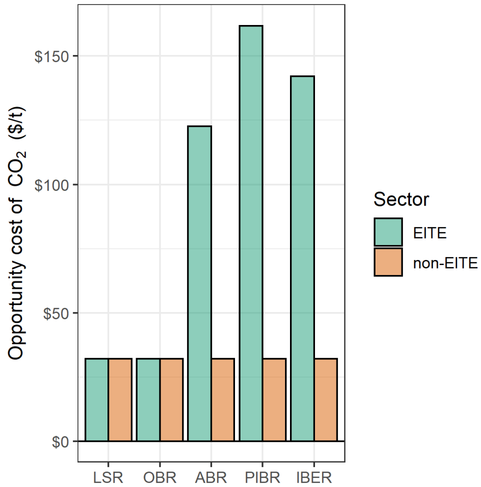
For the ABR policy, all revenue raised from the CO_2 price in the EITE sector is used to provide abatement subsidies to firms in this sector. As a result, the opportunity cost of CO_2 emissions in the EITE sector is raised substantially under this policy. In the revenue-neutral implementation, the size of the abatement subsidy is endogenous and depends on the amount of abatement achieved. As shown in Figure 2e, emissions in the EITE sector fall by about 27% under the ABR policy, resulting in an abatement subsidy that is roughly $\frac{1}{1-0.27} = 140\%$ of the emission price, for a total opportunity cost of abatement in the EITE sector of roughly 2.4 times the economy-wide price (Figure 2a). This high opportunity cost of abatement results in substantial curtailment of output in that sector – by almost 15% – along with large emission reductions (Figure 2c). Because of the large distortion imposed by the ABR policy, Figure 3a shows that the welfare loss under this policy variant is particularly large.

The PIBR policy provides a rebate to firms in the EITE sector proportional to output conditional on achieving reductions in emission intensity. As a result, the opportunity cost of emissions is higher in the EITE sector under this policy (Figure 2a. In the revenue-neutral implementation, the size of the intensity rebate is endogenous and depends on the emissions intensity of the firm relative to a benchmark. In the simulation reported here, EITE emission intensity falls by approximately 18%, such that the opportunity cost of abatement in the EITE sector under PIBR is approximately four times the baseline level (Equation (13). The PIBR policy also incorporates an implicit subsidy to firm output, since the rebate is proportional to firm output. As a result, EITE output falls by less than the LSR policy.

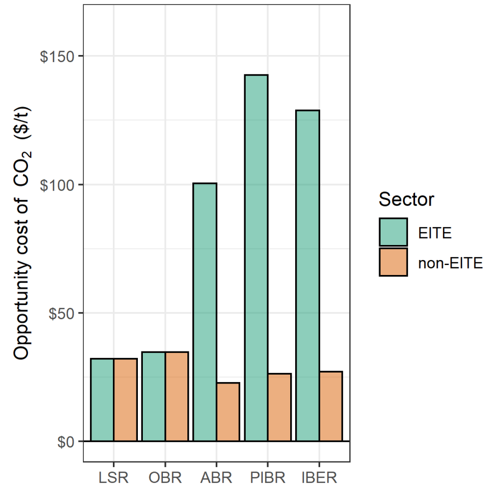
Under the IBER policy, firms in the EITE sector that achieve a reduction in emission intensity face a reduced CO_2 price. The opportunity cost of emissions in this sector thus reflects two dynamics: on one hand, firms face a reduced CO_2 price; on the other increases in emissions intensity trigger a higher CO_2 price. The net effect of these dynamics, assuming the design condition ($\mu_U < 2\mu$) holds, is an increase in the opportunity cost of CO_2 emissions relative to LSR, as indicated in Figure 2a. IBER includes an implicit output rebate, similar to OBR and PIBR, so like these variants, output in the EITE sector is stimulated relative to LSR (Figure 2c).

We now turn to the policies that achieve an equal economy-wide level of CO_2 abatement. Sector-level results corresponding to these simulations are provided in the right-hand column of Figure 2. Because in this case, emissions are equal across all policy variants, welfare comparisons in Figure 3 are meaningful.

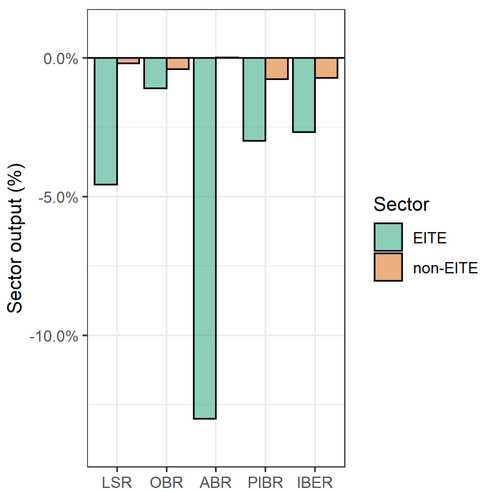
In the case of OBR, the endogenous emission price must rise higher to reach the same level of emission reductions (Figure 2b). This occurs because OBR causes output to increase in the EITE sector relative to LSR (Figure 2d). The higher emission price results in lower emission intensity across both EITE and non-EITE sectors. In the first-best setting, the additional subsidy to output reduces welfare relative to LSR (Figure 3b). OBR causes output in the



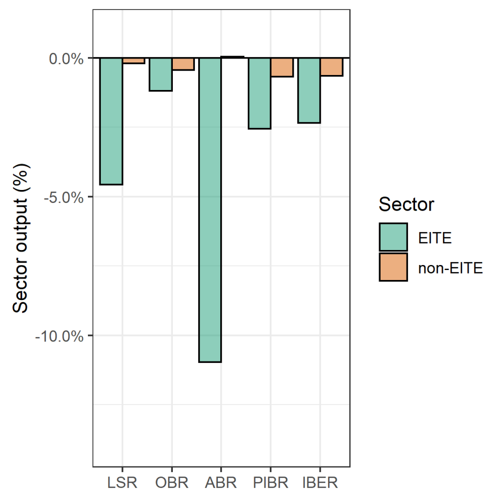
(a) Equal price: CO_2 price



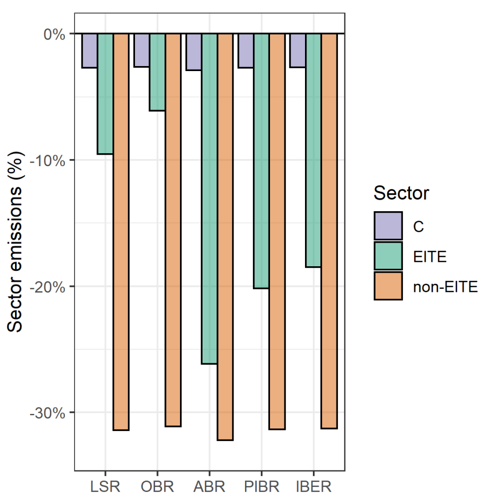
(b) Equal emissions: CO_2 price



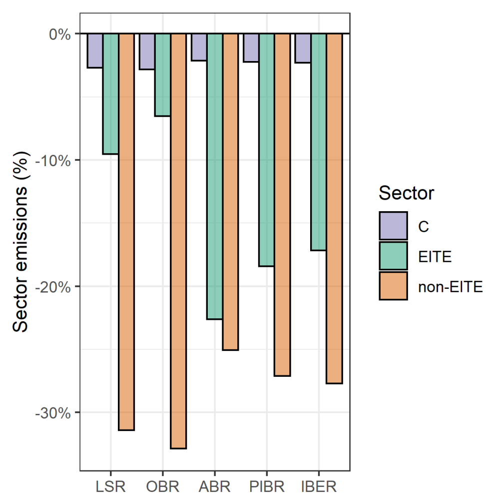
(c) Equal price: sector output



(d) Equal emissions: sector output



(e) Equal price: sector CO_2



(f) Equal emissions: sector CO_2

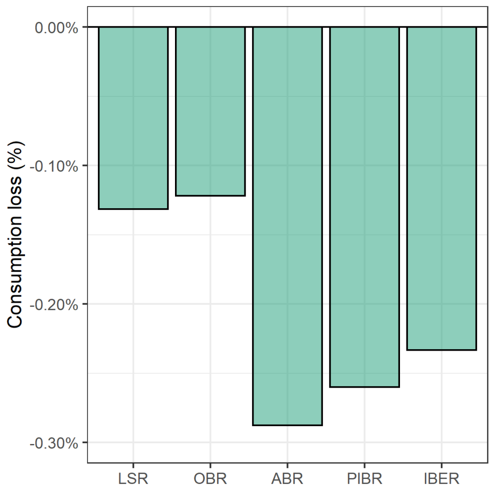
Figure 2: Numerical model sector-level results. Figures on the left-hand side simulate policies with equal CO_2 prices. Figures on the right-hand side simulate policies that achieve equal CO_2 emissions. Producing sectors are exhaustively grouped into two groups: EITE sectors and non-EITE sectors. Sector c is the final demand sector.

EITE sector to fall by less than LSR because of the implicit subsidy, but causes output in the non-EITE sectors to fall by more than LSR, because of the higher carbon price.

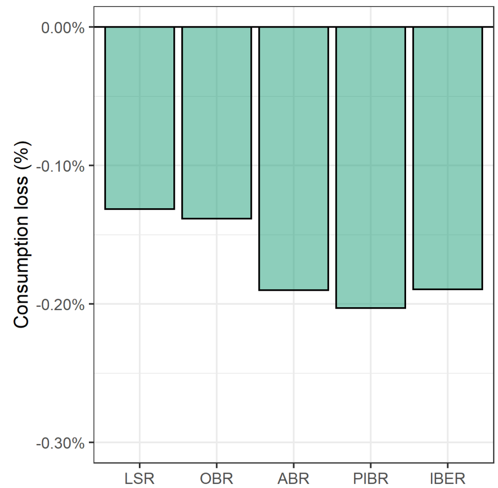
In the case of ABR, the additional abatement in the EITE sector achieved by the abatement subsidy allows economy-wide emissions prices to fall and reach the same economy-wide emission target. As a result, the opportunity cost of emissions is higher in the EITE sector, but lower in the non-EITE sector, relative to LSR (Figure 2b). ABR as a result causes more emission reduction and output curtailment in EITE sectors, and less emission reduction and output loss in non-EITE sectors, relative to LSR (Figures 2d and 2f). The shift in effort across sectors relative to the first-best LSR policy imposes an additional welfare cost (Figure 3b).

The opportunity cost of CO_2 emissions in the EITE sector is higher under the PIBR policy than the ABR policy (Figure 2b). This is because the PIBR policy rebates on intensity relative to a benchmark, whereas the ABR policy rebates on emissions relative to a benchmark, and emissions fall more than intensity (since output reductions contribute to emission reductions). However, despite the high opportunity cost of CO_2 emissions in the EITE sector, the PIBR policy results in less output reduction in that sector, because of the implicit output subsidy inherent to the policy (Figure 2d). In contrast, the PIBR policy results in a larger reduction in emission intensity in the EITE sector compared to ABR (Figure 4b). This larger reduction in emission intensity is costly, and results in the PIBR policy generating a larger welfare cost than other policies (Figure 3b).

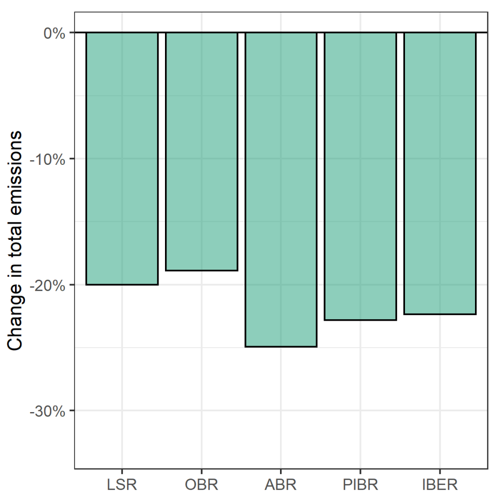
Similar to the PIBR policy, the IBER policy provides an implicit subsidy to output in the EITE sector, and also increases the opportunity cost of CO_2 emissions in that sector. Our model simulations suggest the two policies result in similar outcomes under a revenue-neutral implementation, with the intra-sectoral distorition relative to LSR slightly muted under the IBER policy compared to PIBR, such that the welfare cost of PIBR is somewhat reduced.



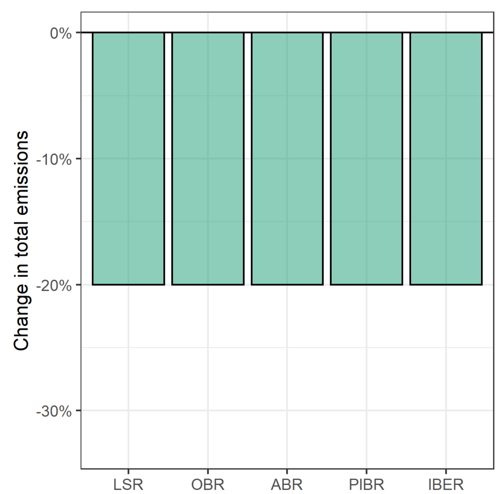
(a) Equal price: welfare



(b) Equal emissions: welfare



(c) Equal price: economy-wide emissions



(d) Equal emissions: economy-wide emissions

Figure 3: Welfare impacts and total emissions of alternative policies. Welfare is determined as the Hicksian equivalent variation in income. The welfare measure does not include the social cost of CO_2 emissions. In the equal price scenarios on the left-hand side, emissions are different across policy variants, so welfare comparisons are incomplete.

5 Conclusion

Due to concerns over competitiveness losses associated with unilateral policy adoption, many carbon pricing policies worldwide have incorporated some form of output-based rebates into their designs. Likewise, to improve cost-effectiveness, many regulatory policies are rate-based and imposed via a system of tradable credits. Economically, these two approaches yield similar outcomes, and analysis suggests that these hybrid approaches to carbon pricing can be helpful in maintaining output and reducing emission leakage associated with unilateral carbon policy implementation.

However, as more countries worldwide adopt carbon policies, and as policy ambition increases, other policy approaches may become attractive. In this paper, we examine several approaches to rebating carbon pricing revenue that increase the opportunity cost of CO_2 emissions, as well as supporting output in the regulated sectors. These approaches result in more emission reductions than a "standard" carbon price alone, and as a result may help improve the ability of policy makers to pursue ambitious carbon reductions under certain types of political constraints. We use both theoretical analysis as well as numerical analysis to contrast these approaches to carbon policy. Our results from both approaches show that abatement-based rebating, proportional intensity-based rebating, and intensity based emissions rebating all provide greater incentives for emission reduction than output based rebating or lump sum rebating. In addition, proportional intensity based rebating and intensity based emission rebating also increase firm output relative to lump sum rebating. In a context of emissions trading, these approaches also lead to lower prices for emission allowances, in contrast to output-based rebating. These outcomes suggest that intensity-based approaches may be useful to policy makers seeking deeper greenhouse gas reductions than current approaches, while still maintaining competitiveness and political feasibility.

To introduce and analyze new approaches to carbon pricing revenue recycling that aim to achieve additional greenhouse gas reductions, we concentrate on the incentives these policies generate in the first best setting. In subsequent work, we plan to explore the welfare implications of these policy approaches in second best settings, where pre-existing taxes, carbon leakage, and political economy may motivate policies other than simple carbon pricing.

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A Algebraic summary of the CGE model

Our computable general equilibrium (CGE) model is formulated as a system of nonlinear inequalities. The inequalities correspond to the three classes of conditions associated with a competitive equilibrium: zero-profit conditions for all economic activities, market-clearance conditions for all commodities and factors, and an income-expenditure balance for the representative agent. Complementary to the equilibrium conditions are three classes of economic decision variables: activity levels, prices for commodities and factors, and income levels.In equilibrium, each of these variables is linked to the respective inequality condition: an activity level to a zero-profit condition, a price to a market-clearance condition, and an income level to an income-expenditure balance.

We use the notation Π_i^u to denote the profit function of sector i where u denotes the associated production activity. We apply Hotelling's lemma to represent compensated demand and supply functions, and we express the constant-elasticity-of-substitution cost functions in calibrated share form. Indices i and j index commodities, including a composite final consumption good C, a composite public good G, and a composite investment good I. The label EG represents the set of energy goods and the label FF denotes the subset of fossil fuels. The notations used are summarized in Tables 4-9.

A.1 Zero-profit conditions

1. Production of goods except fossil fuels ($i \notin FF$)

$$\Pi_i^Y = p_i - \Bigg\{ \Big(\sum_{j \notin EG} \theta_{ji} p_j^A\Big)^{1-\sigma_i^{KLEM}} - \theta_i^{KLE} \Bigg[\theta_i^{KLE} p_{E,i}^{1-\sigma_i^{KLE}} + (1-\theta_i^E) \Big(\theta_i^L w^{1-\sigma_i^{KL}} + (1-\theta_i^L) r^{1-\sigma_i^{KL}} \Big)^{\frac{1-\sigma_i^{KLE}}{1-\sigma_i^{KL}}} \Bigg]^{\frac{1-\sigma_i^{KLEM}}{1-\sigma_i^{KLE}}} \Bigg\}^{\frac{1}{1-\sigma_i^{KLEM}}} \leq 0$$

2. Production of fossil fuels ($i \in FF$)

$$\Pi_i^Y = p_i - \left[\theta_i^Q {q_i}^{1-\sigma_i^Q} + (1-\theta_i^Q)\left(\theta_{Li}^{FF} w + \theta_{Ki}^{FF} r + \sum_j \theta_{ji}^{FF}(p_i^A + p^{CO_2} a_j^{CO_2})\right)^{1-\sigma_i^Q}\right]^{\frac{1}{1-\sigma_i^Q}} \leq 0$$

3. Sector-specific energy aggregate ($i \notin FF$)

$$\Pi_i^E = p_i^E - \left(\sum_{j \in EG} \theta_{ji}^{EG}(p_j^A + p^{CO_2} a_j^{CO_2})^{1-\sigma_i^{EG}}\right)^{\frac{1}{1-\sigma_i^{EG}}} \leq 0$$

4. Armington aggregate

$$\Pi_i^A = p_i^A - \left(\theta_i^A {p_i^D}^{1-\sigma_i^A} + (1-\theta_i^A){p^{FX}}^{1-\sigma_i^A}\right)^{\frac{1}{1-\sigma_i^A}} \leq 0$$

5. Output transformation

$$\Pi_i^X = \left(\theta_i^X {p^{FX}}^{1-\eta_i} + (1-\theta_i^X {p_i^D}^{1-\eta_i}\right)^{\frac{1}{1-\eta_i}} - p_i \leq 0$$

A.2 Market-clearance conditions

6. Labor

$$\overline{L} \geq \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial w}$$

7. Capital

$$\overline{K} \geq \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial r}$$

8. Natural resources ($i \in FF$)

$$\overline{Q}_i \geq Y_i \frac{\partial \Pi_i^Y}{\partial q_i}$$

9. Output

$$Y_i \geq \sum_j A_j \frac{\Pi_j^A}{\partial p_i^D}$$

10. Armington aggregate

$$A_i \geq \sum_j Y_j \frac{\Pi_j^Y}{\partial p_i}$$

11. Sector-specific energy aggregate

$$E_i \geq Y_i \frac{\Pi_i^Y}{\partial p_i^E}$$

12. Private Consumption

$$p_C Y_C \geq INC$$

13. Public consumption

$$Y_G \geq \overline{G}$$

14. Investment

$$Y_I \geq \overline{I}$$

15. CO_2 emissions

$$\overline{CO2} \geq \sum_i A_i a_i^{CO_2}$$

16. Balance of payment (market clearance for foreign exchange)

$$\overline{B} + \sum_i X_i \frac{\Pi_i^X}{\partial p^{FX}} \geq \sum_i A_i \frac{\Pi_i^A}{\partial p^{FX}}$$

A.3 Income-expenditure balance

17. Income balance of representative agent (household)

$$INC = w\overline{L} + v\overline{K} + \sum_{j \in FF} q_j \overline{Q}_j - p_I \overline{I} - p_G \overline{G} + p^{FX} \overline{B} + p^{CO_2} \overline{CO2}$$

Table 4: Sets and indexes

i, j	Indexes for sectors and goods
EG	All energy goods: Coal, crude oil, natural gas, refined oil, and electricity
FF	Primary fossil fuels: Coal, crude oil, natural gas

Table 5: Activity variables

Y_i	Production in sector i
E_i	Aggregate energy input in sector i
X_i	Output transformation for good i
A_i	Armington aggregate for good i
INC	Household (disposable) income

Table 6: Price variables

p_i	Output price of good i
p_i^D	Domestic supply price of good i
p^{FX}	Price of foreing exchange
p_i^E	Price of aggregate energy in sector i
p_i^A	Price of Armington good i
w	Wage rate
r	Price of capital services
q_i	Rent to natural resources ($i \in FF$)
p^{CO_2}	CO_2 emission price

Table 7: Cost shares

θ_{ji}	Cost share of intermediate good j in sector i
θ_i^{KLE}	Cost share of value-added and energy in sector i
θ_i^E	Cost share of energy composite in the KLE aggregate in sector i ($i \notin FF$)
θ_i^L	Cost share of labor in value-added composite of sector i
θ_i^Q	Cost share of natural resources in sector i ($i \in FF$)
θ_{Ti}^{FF}	Cost share of good i ($T = i$) or labor ($T = L$) or capital ($T = K$) in sector i ($i \in FF$)
θ_{ji}^{EG}	Cost share of energy good j in the energy composite in sector i ($i \notin FF$)
θ_i^A	Cost share of domestic variety in Armington good i
θ_i^X	Revenue share of exports for domestic production value of good i

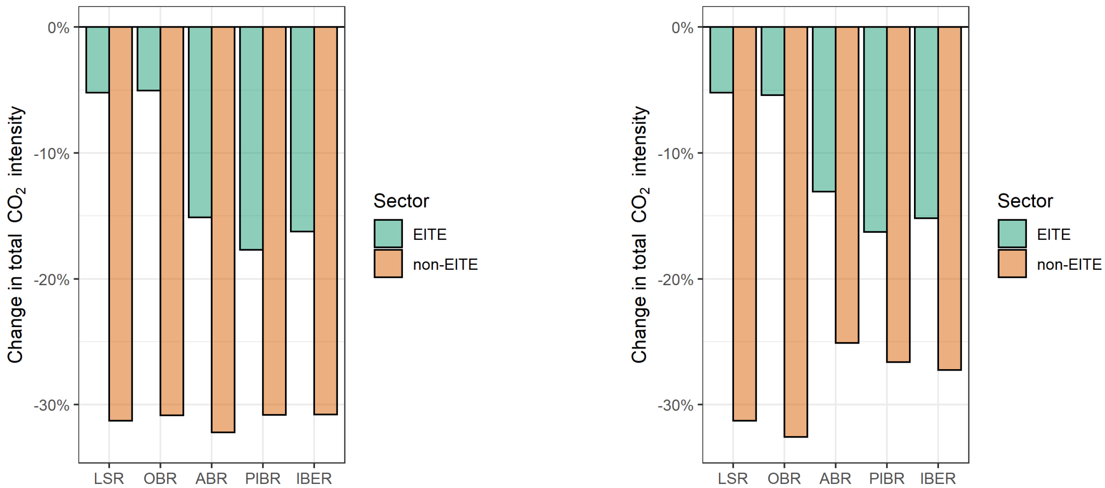
Table 8: Elasticities

σ_i^{KLEM}	Substitution between KLE composite and material inputs in production
σ_i^{KLE}	Substitution between energy and value-added in production
σ_i^{KL}	Substitution between labor and capital in value-added composite
σ_i^Q	Substitution between natural resources and other inputs in fossil fuel production
σ_i^{EG}	Substitution between energy goods in the energy aggregate
σ_i^A	Substitution between the import good and the domestic good of the same variety
η_i^X	Transformation between export supply and domestic supply

Table 9: Endowments and emissions coefficients

$\overline{L}$	Aggregate labor endowment
$\overline{K}$	Aggregate capital endowment
$\overline{Q}_i$	Endowment of natural resource i
$\overline{G}$	Public good provision
$\overline{I}$	Investment demand
$\overline{B}$	Balance of payment deficit or surplus
$\overline{CO2}$	CO_2 emission constraint
$a_i^{CO_2}$	CO_2 emissions coefficient for fossil fuel i

B Additional Figures



(a) Equal price: intensity

(b) Equal emissions: intensity

Figure 4: Emissions intensity by sector for alternative policies.