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Intensity-Based Rebating of Emission Pricing Revenues

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Abstract

Carbon pricing policies worldwide are increasingly coupled with direct or indirect subsidies where emissions pricing revenues are rebated to the regulated entities. This paper analyzes the incentives created by two novel forms of rebating that reward additional emission intensity reductions: one given in proportion to output (intensity-based output rebating) and another that rebates a share of emission payments (intensity-based emission rebating). These forms are contrasted with output-based rebating, abatement-based rebating, and lump sum rebating. Given the same emission price, intensity-based output rebating incentivizes the most intensity reductions, while abatement-based rebating incentivizes the most output reductions, and output-based rebating puts the least pressure on output (and emissions); intensity-based emissions rebating lies in between these, by implicitly subsidizing emissions while incentivizing intensity reductions. The paper supplements partial equilibrium theoretical analysis with numerical simulations to assess the performance of different mechanisms in a multisector general equilibrium model that accounts for economywide market interactions.

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1 Introduction

Economists have long argued for the introduction of a carbon price as a key component of a cost-effective policy response to addressing climate change. However, worldwide adoption of carbon pricing has been incomplete, with only about one-fifth of global carbon dioxide emissions currently covered by a carbon price, and prices mostly well below estimates of the social cost of carbon.[1] Experts worry that the resulting low levels of carbon prices implemented worldwide are insufficient to drive substantial emission reductions in a timeframe consistent with stabilization of atmospheric temperatures within the targets of the Paris Agreement (Green, 2021).

Wider adoption of carbon pricing is constrained by a number of factors. One key factor is concern over loss of international competitiveness and carbon leakage associated with unilateral implementation of carbon pricing. A domestic carbon price is likely to reduce the competitiveness of internationally traded energy-intensive firms relative to their unregulated foreign counterparts (Dechezleprêtre and Sato, 2017). Resulting changes in domestic and foreign production are predicted to give rise to carbon leakage, where a portion of domestic emission reductions caused by the carbon price is offset by increases in international emissions (Carbone and Rivers, 2020). A second and related constraint to wider adoption of carbon pricing relates to domestic political economy concerns, including public opposition to the increase in price of emission-intensive products and services such as transport or heating (Drews and Van den Bergh, 2016), lobbying by emission-intensive industries toward lower carbon prices (Anger et al., 2014; Baranzini et al., 2017), or concerns over excessive job loss from structural transformation of the economy associated with carbon pricing (Hafstead and Williams III, 2018).

These concerns appear to limit the design space for acceptable carbon prices considerably. More precisely, to satisfy these concerns, an acceptable carbon price would need to achieve large greenhouse gas reductions while remaining low and not significantly affecting the output or price of regulated firms. We think of these conditions as the design trilemma facing carbon pricing, and posit that policy alternatives that successfully achieve each of these conditions

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[1] The World Bank Carbon Pricing Dashboard details existing carbon pricing initiatives worldwide: `https://carbonpricingdashboard.worldbank.org/` (Accessed 20/4/2021).

are more likely to succeed.

One way to reconcile these apparently conflicting goals is to strategically deploy revenues raised from carbon pricing. For example, revenue from carbon pricing can be used to provide output-based rebates to domestic emission-intensive and trade-exposed firms (Fischer, 2001). Such rebates work as output subsidies and reduce the net impacts of a carbon price on the output price of regulated firms, thus helping to limit carbon leakage and (undue) competitiveness losses associated with unilateral carbon pricing (Fischer and Fox, 2012; Böhringer et al., 2012). Output-based rebates may also help alleviate some domestic political economy concerns, by limiting commodity price increases in domestic markets and by reducing structural change caused by the carbon price. However, output-based rebates do not promote additional emission reductions relative to a carbon price alone and thus require politically contentious increases in the carbon price to generate deeper emission cuts.

In practice, various jurisdictions have adopted output-based rebates, likely motivated by addressing the concerns described above. For example, California allocates emission allowances to industrial emitters under its cap-and-trade system in proportion to output,[2] Canada's federal government has adopted an output based permit allocation as part of its industrial carbon pricing system,[3] and Phase III of the European Union Emissions Trading System (EU-ETS) allocates a portion of emission allowances to industrial facilities in proportion to output.[4]

In this paper, we investigate alternative approaches to deploying carbon pricing revenue to address the effectiveness, competitiveness, and political economy concerns we describe above. We consider approaches that achieve greater reductions in emissions than would be achieved by the carbon price alone or through the use of output-based rebates. If carbon pricing is constrained by domestic politics to levels below the social cost of carbon, such approaches may be helpful in increasing the effectiveness of carbon pricing as a greenhouse gas mitigation policy.

As benchmarks, we consider two established policy options: lump-sum rebating (LSR),

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[2] See `https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/allowance-allocation/allowance-allocation-industrial` (Accessed 20/4/2021).

[3] See `https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system.html` (Accessed 20/4/2021).

[4] See `https://ec.europa.eu/clima/policies/ets/allowances_en` (Accessed 20/4/2021).

which does not alter incentives on the margin, and output-based rebating (OBR), which uses the rebate to subsidize output. We compare these standard policies with three more novel rebating variants.

First, we consider abatement-based rebating (ABR), which prices carbon and deploys revenues to subsidize additional emissions abatement. 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 revenues from emissions auctioning to a Green Fund. In both cases, these revenues are used to pay for additional abatement activity.

Second, we propose for consideration a form of rebating that combines elements of OBR and ABR: intensity-based output rebating (IBOR). Here, revenue raised from carbon pricing is used to provide rebates to firms in proportion to output, with larger rebates going to firms that achieve a larger improvement in emission intensity. 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, meaning compensation is increasing with output; recent reforms make such compensation conditional upon additional decarbonization and energy efficiency efforts by the affected companies—that is, upon intensity reductions.[5] We consider a version of this conditionality that would allow larger per-unit rebates for larger intensity reductions.

Third, we analyze a mechanism in which firms are eligible for a reduction in the carbon price they face contingent on reducing emission intensity (intensity-based emissions rebating, IBER). Such an approach has been used, for example, 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.[6] British Columbia also offers a reduced emission tax to firms that successfully reduce their emission intensity through its Industrial Incentive Program.[7]

We use a simple theoretical model of a price-taking representative firm to contrast the

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[5] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1712 (Accessed 3/3/2021).

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

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

economic incentives created by each of the five policy designs. We find that, for a given carbon price, abatement-based rebating and the two intensity-based variants lead to additional reductions in emission intensity, as compared with lump-sum or output-based rebating. If domestic politics or competitiveness concerns constrain carbon prices to below the social cost of carbon, these policy variants may be helpful in increasing the environmental effectiveness of a carbon price with potentially beneficial welfare implications. In contrast to abatement-based rebating, which further discourages output by raising the opportunity cost of emissions, the two forms of intensity-based rebating offer additional support for output, similar to output-based rebating. Thus, intensity-based rebating, like output-based rebating, also helps address concerns over structural frictions associated with output losses of emission-intensive industries. We use our model to rank each of the five policy variants according to how well they protect against reductions in firm output and how much incentive they provide for reductions in emissions. Our ranking suggests that by both protecting output and increasing emission reductions achieved at a given carbon price, intensity-based rebating may be useful in addressing key concerns that prevent wider adoption of effective carbon pricing.[8]

In practice, rebating mechanisms are typically reserved for the sectors that are least able to pass on their carbon costs: emission-intensive industries that are also highly trade-exposed. Thus, in addition to comparing the policies in a partial-equilibrium analytical setting with one sector only, we also implement each policy approach in a multisector computable general equilibrium (CGE) model. The CGE model not only relaxes dimensionality restrictions but also allows us to account for important market interactions via economy-wide substitution and income effects. Furthermore, the CGE setting opens up for a broader welfare analysis where we can trade off economy-wide efficiency impacts of alternative rebating schemes with sector-specific implications. Using the numerical model parameterized to US data, we find important quantitative differences between the policy approaches. Notably, with the same carbon price, abatement- and intensity-based rebating policies lead to two to three times

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[8] A caveat, which we note in a later section of the paper, is that when firms are heterogeneous, IBER does entail additional distortions, due to the mechanism of leveraging emissions payments to incentivize additional reductions. Firms with lower baseline emissions payments get smaller rebates, and firms with higher-than-average baseline emission intensity have a harder time meeting the rebate criteria. As a result, marginal abatement costs will not be equalized across firms.

more emissions abatement in the targeted sectors compared with lump-sum or output-based rebating. Moreover, intensity-based rebating offers similar output protection to output-based rebating. These findings suggest that intensity-based rebating of carbon pricing revenues could help resolve the trilemma facing effective and acceptable carbon pricing design by simultaneously keeping carbon prices low, achieving deeper greenhouse gas reductions, and protecting firms from price increase and output loss.

Our paper builds on a large body of literature that uses theoretical and numerical approaches to contrast alternative designs for carbon pricing policies. Important antecedents to the paper are, in particular, Helfand (1991), Fischer (2001) and Böhringer and Lange (2005), who compare tradable performance standards and output-allocated permits to a uniform carbon price with lump sum rebates using a simple theoretical model, and Hagem et al. (2020), who introduce a rebating scheme focused on abatement expenditures and compare the effects with output-based rebating. Beyond aspects of carbon leakage that call for a multi-region analytical framework, departures from lump-sum allocation can be motivated by a variety of factors, including political constraints, distributional impacts, or interactions with other market distortions. Exploring the rationale of incomplete regulatory coverage, Bernard et al. (2007) derive rules for optimal output-based rebating and Holland (2012) examines second-best performance standards. Goulder et al. (2016) find potential benefits of a clean energy standard compared with a uniform carbon price in the presence of distortionary taxation. Fischer and Fox (2007) use a numerical computable general equilibrium model to quantify the impact of adopting these policy variants on output and emissions in the United States accounting for tax interaction effects. Other studies show the cost of distortions when departing from lump-sum rebating. Holland et al. (2009) compare a low carbon fuel standard with uniform carbon prices, and suggest alternative policy combinations for reducing emissions from transportation fuels. In another empirical application for the US economy, Böhringer et al. (2017) consider the effects of removing emission-intensive industries from the economy-wide carbon pricing system and regulating them instead with intensity standards, which may lead to considerable welfare losses.

Overall, the prior literature suggests that output-based rebates and performance standards can result in markedly different outcomes compared with a carbon tax with lump-sum recycling. Most importantly, output-based rebates 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 preexisting taxes, output-based rebates can become superior in efficiency terms to uniform taxes with lump-sum rebates (if preexisting distortions are sufficiently large).

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 intensity-based rebating schemes we introduce. In addition, this paper combines both a theoretical analysis of these alternative policies and policy-relevant numerical simulations for the US economy. This two-part analysis facilitates understanding the incentives generated by each policy as well as the quantitative importance of these incentives in a real-world setting. In our analysis, we abstract from potential second-best motivations for rebating—that is, we focus on a setting without additional market failures. By comparing the relative magnitude of output protection, intensity reductions, and changes in surplus created by alternative rebating schemes, we highlight the primary effects and costs, which can be weighed against potential benefits of distorting incentives.

2 Theoretical analysis

We use a simple theoretical model to show how different approaches to rebating carbon pricing revenues generate different incentives and outcomes for regulated firms. We consider a representative firm that is a price taker on factor, product, and emission markets. The firm operates with constant returns to scale, and has a unit cost function given by $c(\mu)$, where μ is emission intensity (i.e., emissions per unit of output). Emissions from the firm are $E = \mu q$, where q is output.[9] Production costs are decreasing and convex in emission intensity, reflecting the costly nature of emission abatement ($c_\mu \leq 0$, $c_{\mu\mu} > 0$).

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[9] Hagem et al. (2020) consider a more general functional form for considering OBR and abatement expenditure-based rebating, with some subtle results depending on non-constant returns to scale. Our choice of constant returns reflects a desire both for simplicity in revealing the first-order effects of rebating and also for consistency with the standard assumptions in the numerical model.

We consider a regulator that puts a price τ on emissions. Revenue raised from the emissions price is rebated back to firms, with the size of the rebate being determined by the policy approach as well as the output and emission intensity of firms, such that the rebate is specified by $R(q, \mu)$.

2.1 General representation

Profits for the representative firm are

$$\pi = pq - c(\mu)q - \tau\mu q + R(q, \mu)$$

where p is the price received by the firm. The firm chooses emission intensity and output to maximize profits, leading to the following first-order conditions (FOCs):

$$\begin{aligned} \frac{\partial \pi}{\partial q} &= p - c(\mu) - \tau\mu + R_q(q, \mu) = 0 \longrightarrow p = c(\mu) + \tau\mu - R_q(q, \mu) && (1) \\ \frac{\partial \pi}{\partial \mu} &= -c'(\mu)q - \tau q + R_\mu(q, \mu) = 0 \longrightarrow -c'(\mu) = \tau - \frac{R_\mu(q, \mu)}{q}. && (2) \end{aligned}$$

The FOC for output shows 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. We refer to this quantity (on the right hand side of (1)) as the *full marginal cost.* Let consumer (inverse) demand be given by $P(q)$, where $P_q < 0$. In equilibrium, the quantity demanded will adjust so that $P(q) = p$. Thus, a rebate that increases as the output of the firm increases ($R_q > 0$) will reduce the price of output and lead to more output in equilibrium.

The FOC for emission intensity shows that 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. We refer to the right-hand side of (2), which captures the change in profit from changing emission intensity, as the *opportunity cost of emissions.* Given a level of output, a rebate that increases with abatement ($-R_\mu > 0$) will encourage a reduction in emission intensity.

In comparing across rebating policies, we take two approaches. First, we compare policies with the same emissions price τ, but where emissions are endogenous and can vary across policies. Second, we compare policies that achieve the same level of emissions for the sector, $\bar{E}$. This constraint then determines the relationship between emission intensity and output: $q = \bar{E}/\mu$. The resulting emissions price is endogenous, and combining the two FOCs, we get an equation describing the relationship between μ and the price and rebate functions:

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

In the rest of this section, we focus on the incentives given the same emissions price. Appendix A.1 elaborates the corresponding effects for a given sectoral emissions target, and the results are summarized in Section 2.7.

2.2 Lump-sum rebating (LSR)

Using lump sum rebating, 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, and rebates are allocated according to predetermined criteria (such as historical output or emissions). 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.

2.3 Abatement-based rebating (ABR)

Under abatement-based rebating, revenue raised from the carbon price is used to subsidize additional emission reductions. Different kinds of abatement-based rebating have been considered in the past. For example, Hagem et al. (2020) consider using carbon tax revenue to provide subsidies to abatement expenditures and Jenkins (2014) briefly introduces the idea of using carbon tax revenues to fund emissions abatement. We will consider the most straightforward form of abatement-based rebating, an emissions tax-financed subsidy to abatement:

$R = s(\mu_0 q_0 - \mu q)$, so $R_q = -s\mu$ and $R_\mu = -sq$, where s is the subsidy rate in dollars per unit of emissions reduced, and μ_0 and q_0 refer to historical or counterfactual intensity and output. This rebate mimics the classic textbook version of an abatement subsidy (e.g., Baumol and Oates (1988), Ch. 14), but here it is financed by an emissions tax.[10] The net result is that larger emitters pay more, and larger abaters receive more rebates.

In this case, the profit-maximizing conditions are

$$\mu_{\text{ABR}}: \quad -c'(\mu) = \tau + s; \qquad q_{\text{ABR}}: \quad P(q) = c(\mu) + (\tau + s)\mu. \tag{5}$$

The abatement-based rebate, although it offers a subsidy to emission intensity reduction, functions as an additional tax on output by raising the opportunity cost of emissions embodied in output. If the rebate is revenue neutral—such that all revenue raised by the emission tax is returned back to the sector from which it was raised (denoted with superscript *)—then $s = \tau\mu q/(\mu_0 q_0 - \mu q) = \tau E/(E_0 - E)$, and (5) simplifies to

$$\mu^*_{\text{ABR}}: \quad -c'(\mu) = \tau\frac{\mu_0}{\mu_0 - \mu q/q_0}; \qquad q^*_{\text{ABR}}: \quad P(q) = c(\mu) + \tau\mu\frac{\mu_0}{\mu_0 - \mu q/q_0} \tag{6}$$

Proposition 1 *For the same emissions price, ABR induces a lower emission intensity and a lower level of output than LSR.*

Proof. Let $\beta = E_0/(E_0 - \mu q) > 1$, due to abatement. Then $-c'(\mu^*_{\text{ABR}}) = \tau\beta > \tau = -c'(\mu^*_{\text{LSR}})$, and $c(\mu^*_{\text{ABR}}) + \tau\beta\mu^*_{\text{ABR}}) > c(\mu^*_{\text{LSR}}) + \tau\mu^*_{\text{LSR}})$, both because $\beta > 1$ and $\mu^*_{\text{ABR}} > \mu^*_{\text{LSR}}$. ■

ABR essentially offers credits for reductions relative to an emissions baseline that is fixed. As a result, ABR performs like LSR but with an amplified emissions price. By contrast, the subsequent rebating mechanisms will rely on endogenous forms of benchmarking that alter production incentives.

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[10] Note that in practice it may be administratively infeasible to observe μ_0 or q_0 as also noted in Baumol and Oates (1988).

2.4 Output-based rebating (OBR)

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

$$\mu_{\text{OBR}}: \quad -c'(\mu) = \tau; \qquad q_{\text{OBR}}: \quad P(q) = c(\mu) + \tau(\mu - \mu_b). \tag{7}$$

The output-based rebate acts as a subsidy to output, without directly distorting the emission intensity choice. Thus, for the same emissions price, $\mu_{\text{OBR}} = \mu_{\text{LSR}}$ and $q_{\text{OBR}} > q_{\text{LSR}}$. This result is well-established in the literature (Fischer, 2001).

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

2.5 Intensity-based rebating (IBR)

We next consider two variants of intensity-based rebating, in which rebates depend on the emission intensity of the firm.[11] Under intensity-based output rebating, carbon pricing revenue is returned to firms based on intensity and scaled in proportion to output. Under intensity-based emissions rebating, the rebate is used to reduce the carbon price faced by the firm, conditional on the firm achieving an intensity target. Each approach creates different incentives.

2.5.1 Intensity-based output rebating (IBOR)

One way to provide additional incentives to reduce emissions to firms is to make rebates of emission tax revenue conditional on firms achieving reductions in emission intensity. Since emission intensity is measured per unit of output, it is natural that the rebate would be dependent on both the output of the firm and its emission intensity. In this case, $R = z(\overline{\mu} - \mu)q$, where $\overline{\mu}$ is the benchmark emission intensity below which firms qualify for a rebate,

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[11] In Appendix A, we also consider IBR in its purest form, a rebate dependent only on intensity reductions, invariant to output. Comparing revenue-neutral policies, for the same sectoral emissions target, this simple IBR (SIBR) leads to less output and less intensity reduction than OBR.

and z is subsidy rate, measured in dollars per unit of emissions. In this case, the rebate is increasing both in the intensity reduction ($-R_\mu = zq > 0$) and in output ($R_q = z(\overline{\mu} - \mu) > 0$). The first-order conditions with IBOR, assuming $\mu < \overline{\mu}$ to qualify for a rebate, simplify to

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

Thus, IBOR combines elements of ABR, since the subsidy amplifies the incentive effect of the emissions price, and OBR, since the proportional rebate de facto subsidizes output.

Proposition 2 *For the same emissions price, IBOR induces a lower emission intensity and a higher level of output than LSR.*

Proof. The first-order condition for intensity in (8) makes clear that the subsidy increases incentives for intensity abatement, so $\mu_{\text{IBOR}} < \mu_{\text{LSR}}$. Even with lower intensity, the net effect of the rebate is to raise equilibrium output ($q_{\text{IBOR}} > q_{\text{LSR}}$) by driving down the equilibrium price: $dP/dz = (c'(\mu) + \tau - z)\, d\mu/dz - (\overline{\mu} - \mu) = -(\overline{\mu} - \mu) < 0$. $\blacksquare$

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

Proposition 3 *Comparing revenue-neutral policies, given the same emissions price, IBOR leads to more intensity reduction but less output protection than OBR.*

Proof. Revenue-neutral IBOR implies $z(\overline{\mu} - \mu)q = \tau\mu q$, or $z^* = \tau\mu/(\overline{\mu} - \mu)$. The first-order conditions in (8) reduce to

$$\mu^*_{\text{IBOR}}: \quad -c'(\mu) = \tau\overline{\mu}/(\overline{\mu} - \mu); \qquad q^*_{\text{IBOR}}: \quad P(q) = c(\mu). \tag{9}$$

Since $\overline{\mu}/(\overline{\mu} - \mu) > 1$, for the same τ, $\mu^*_{\text{IBOR}} < \mu^*_{\text{OBR}}$. As a result, $c(\mu^*_{\text{IBOR}}) > c(\mu^*_{\text{OBR}})$, so $q^*_{\text{IBOR}} < q^*_{\text{OBR}}$. $\blacksquare$

Proposition 4 *Comparing revenue-neutral policies, given the same emissions price, IBOR leads to more intensity reduction than ABR, assuming $\overline{\mu} \leq \mu_0$.*

Proof. For a given μ, the policy with the higher revenue-neutral subsidy will stimulate more intensity reduction in equilibrium. Revenue-neutral IBOR implies $z^* = \tau\mu/(\overline{\mu} - \mu)$, while revenue-neutral ABR implies $s^* = \tau\mu/(\mu_0(q_0/q_{\text{ABR}}) - \mu)$. $z^* > s^*$ if $\mu_0(q_0/q_{\text{ABR}}) > \overline{\mu}$, which holds if $\overline{\mu} \leq \mu_0$. ■

2.5.2 Intensity-based emissions rebating (IBER)

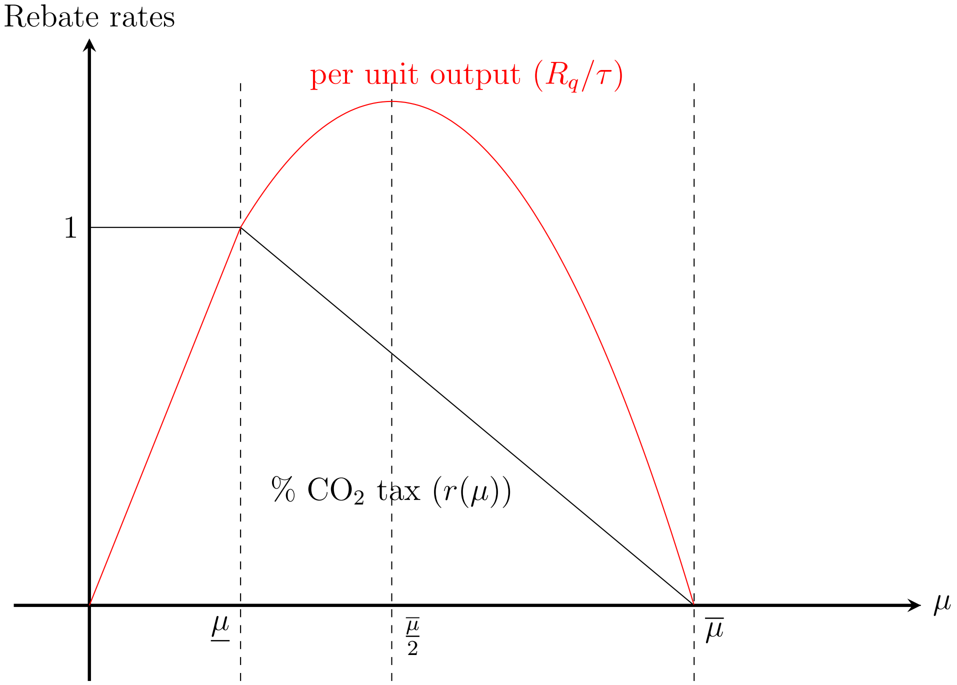
In British Columbia's Industrial Incentive Program and the UK's Climate Change Agreements, intensity-based rebating has been designed to relieve a share of emissions payments, with that share depending on the firm's or plant's emission intensity. This setup differs from a straightforward subsidy to intensity abatement. From the firm's perspective, the subsidy rate is not independent of its emissions. Rather, $R = r(\mu)\tau\mu q$, where $r(\mu) \in [0, 1]$ is the rebate per \$ of emissions tax, a fraction that is contingent on reaching an emission intensity goal, and where $r'(\mu) < 0$. This design implies a marginal rebate per unit of output of $R_q = r(\mu)\tau\mu$ and a marginal rebate from intensity reduction of $-R_\mu = (-r'(\mu)\mu - r(\mu))\,\tau q$. As a result, the profit-maximizing conditions are

$$\mu_{\text{IBER}}: \quad -c'(\mu) = \tau\left(1 - r(\mu) - r'(\mu)\mu\right); \qquad q_{\text{IBER}}: \quad P(q) = c(\mu) + \tau\mu\left(1 - r(\mu)\right) \tag{10}$$

Thus, IBER contains elements of IBOR, with a net increase in abatement and output incentives, with an implicit subsidy to emissions (like a negative ABR). For the same emissions price, given an intensity, we expect more output as compared with 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 emission intensity decisions. As a result, the net effect on the first-order condition for emission intensity depends on whether the marginal rebate from reducing emission intensity ($-r'(\mu) > 0$) exceeds the average rebate per unit of intensity ($r(\mu)/\mu$). If so, then IBER produces more emission intensity reduction as compared with 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 linearly as intensity declines below an upper threshold, $\overline{\mu}$, toward a lower threshold, assumed to be that of a best-available

Figure 1: An example of IBER



technology ($\underline{\mu}$), where $r(\mu) = \rho\frac{\overline{\mu}-\mu}{\overline{\mu}-\underline{\mu}}$, with ρ as a scaling factor to adjust the share of total emission revenues that are rebated in equilibrium. We illustrate the setup in Figure 1. With this form, $-r'(\mu) = \rho/(\overline{\mu}-\underline{\mu})$ and $-r'(\mu)\mu - r(\mu) = \rho\frac{2\overline{\mu}-\mu}{\overline{\mu}-\underline{\mu}}$. Substituting, we simplify the first-order conditions:

$$\mu_{\text{IBER}} : -c'(\mu) = \tau\left(1+\rho\frac{2\mu-\overline{\mu}}{\overline{\mu}-\underline{\mu}}\right); \qquad q_{\text{IBER}} : P(q) = c(\mu) + \tau\mu\left(1-\rho\frac{\overline{\mu}-\mu}{\overline{\mu}-\underline{\mu}}\right). \tag{11}$$

Our design condition becomes $\overline{\mu} < 2\mu$; that is, the average emissions rate is not reduced more than half below the emission intensity threshold. Otherwise, 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.

For IBER, revenue neutrality implies $r(\mu) = 1$, or $\rho = \rho^* \equiv (\overline{\mu}-\underline{\mu})/(\overline{\mu}-\mu)$ in equilibrium.

The first-order conditions in (11) reduce to

$$\mu^*_{\text{IBER}}: \quad -c'(\mu) = \tau\frac{\mu}{(\overline{\mu} - \mu)}; \qquad q^*_{\text{IBER}}: \quad P(q) = c(\mu). \tag{12}$$

Proposition 5 *Comparing revenue-neutral policies, given the same emissions price, IBER leads to less intensity reduction and more output than IBOR, but more intensity reduction and less output than OBR.*

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

We close the section on the IBER policy with a caveat. Unlike the other policies we analyze, the IBER policy does not guarantee that all firms have the same incentive to reduce emissions. If firms are heterogeneous, they will pursue different levels of emission abatement, leading to different rebates and thus different implicit emission price under the IBER policy. Unlike the other policies we analyze in this paper, this means that the IBER policy will result in additional efficiency costs. Understanding these additional costs requires a model with heterogeneous firms. We take up this issue in Fischer et al. (2022).

2.6 Summary of analytical results

Tables 1 summarizes the total and marginal rebates from Section 2.1 for each policy, given an emissions price. Column 2 reveals that once set (e.g., at revenue-neutral equilibrium levels), all policies give a fixed marginal incentive to abate emission intensity with the exception of IBER, for which the incentive is increasing in emission intensity. Column 3 shows that the marginal output incentives are independent of individual output, with the net subsidy depending on the policy rule and ABR resulting in a net tax. Table 2 summarizes the conditions for revenue-neutral rebating, including the equilibrium policy level (scaling factor), the opportunity cost of emissions for intensity reductions, and the resulting unit marginal costs determining the output price. All subsequent analysis will assume rebates are set in this revenue-neutral fashion, which allows the policies to be ranked in terms of their net effects, as illustrated in Figures 2 and 3.

Table 1: Comparing rebating mechanisms

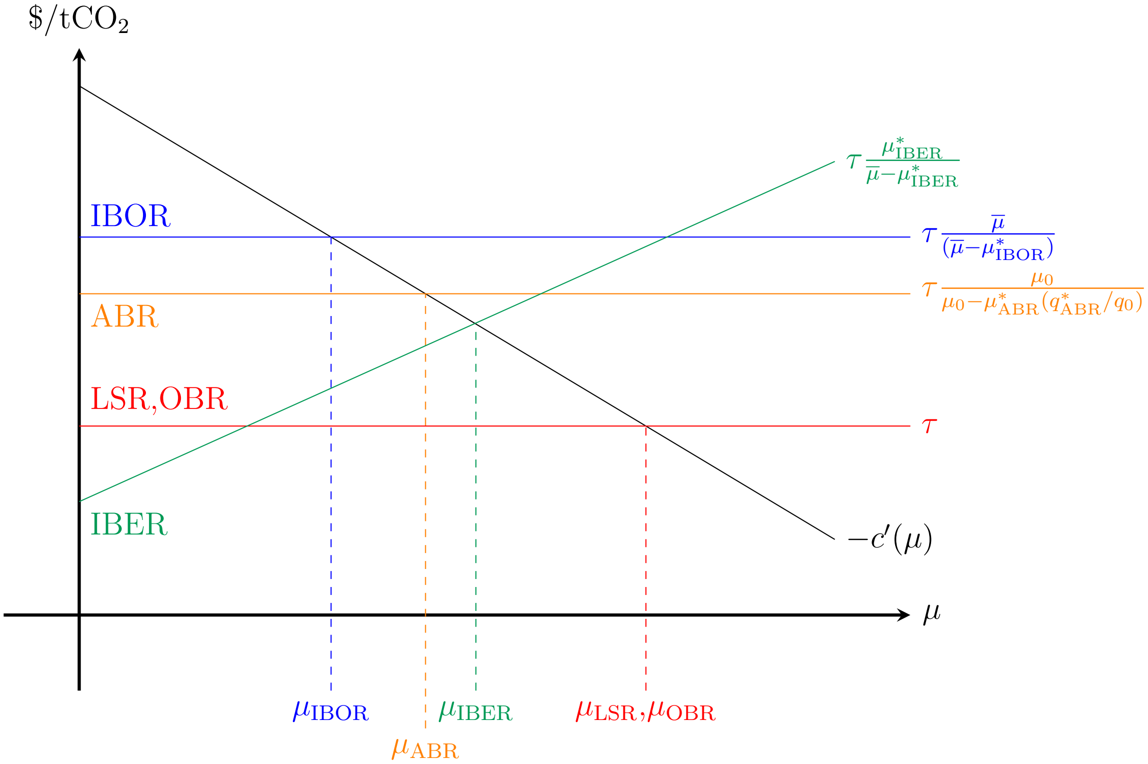
	Total rebate	Marginal rebate	
		Intensity	Output
Type	$R(q,\mu)$	$-R_\mu/q$	R_q
LSR	R	0	0
ABR	$s(\mu_0 q_0 - \mu q)$	s	$-s\mu$
OBR	$\tau\mu_b q$	0	$\tau\mu_b$
IBOR	$z(\overline{\mu}-\mu)q$	z	$z(\overline{\mu}-\mu)$
IBER	$\rho\frac{\overline{\mu}-\mu}{\overline{\mu}-\underline{\mu}}\tau\mu q$	$\rho\frac{2\mu-\overline{\mu}}{\overline{\mu}-\underline{\mu}}\tau$	$\rho\frac{\overline{\mu}-\mu}{\overline{\mu}-\underline{\mu}}\tau\mu$

Table 2: Revenue-neutral rebating mechanisms

Type	Scaling factor	Opportunity cost of emissions	Output price
LSR	$R^* = \tau\mu^*_{\mathrm{LSR}}q^*_{\mathrm{LSR}}$	τ	$c(\mu^*_{\mathrm{LSR}}) + \tau\mu^*_{\mathrm{LSR}}$
ABR	$s^* = \tau\frac{\mu^*_{\mathrm{ABR}}q^*_{\mathrm{ABR}}}{\mu_0 q_0 - \mu^*_{\mathrm{ABR}}q^*_{\mathrm{ABR}}}$	$\tau\frac{E_0}{E_0 - E^*_{\mathrm{ABR}}}$	$c(\mu^*_{\mathrm{ABR}}) + \tau\mu^*_{\mathrm{ABR}}\frac{E_0}{E_0 - E^*_{\mathrm{ABR}}}$
OBR	$\mu^*_b = \mu^*_{\mathrm{OBR}}$	τ	$c(\mu^*_{\mathrm{OBR}})$
IBOR	$z^* = \tau\frac{\mu^*_{\mathrm{IBOR}}}{\overline{\mu}-\mu^*_{\mathrm{IBOR}}}$	$\tau\frac{\overline{\mu}}{\overline{\mu}-\mu^*_{\mathrm{IBOR}}}$	$c(\mu^*_{\mathrm{IBOR}})$
IBER	$\rho^*\frac{\overline{\mu}-\mu^*_{\mathrm{IBER}}}{\overline{\mu}-\underline{\mu}} = 1$	$\tau\frac{\mu^*_{\mathrm{IBER}}}{\overline{\mu}-\mu^*_{\mathrm{IBER}}}$	$c(\mu^*_{\mathrm{IBER}})$

Figure 2 depicts the relative marginal incentives for reducing emission intensity—the opportunity cost to the individual firm of increasing emissions by one unit—given an emissions price and revenue-neutral rebating. For LSR and OBR, the opportunity cost of producing emissions is exactly equal to the emissions price, τ. Proposition 4 revealed that revenue-neutral IBOR, given an emissions price, incentivizes more intensity reductions than either ABR or IBER. Because ABR also drives additional output and emissions reductions compared with intensity-based rebating, ABR has fewer revenues to rebate, meaning that in revenue-neutral applications the equilibrium abatement subsidy may be smaller. Opportunity costs for IBER, as previously noted, are increasing with intensity. Although it is not possible to definitively rank equilibrium outcomes with ABR against IBER, for the purposes of illustration, in Figure 2 we have placed ABR slightly above (consistent with the parameterization of our subsequent numerical exercise).

Figure 2: Opportunity cost of carbon emissions and marginal abatement costs for revenue-neutral policies with equal emissions price τ

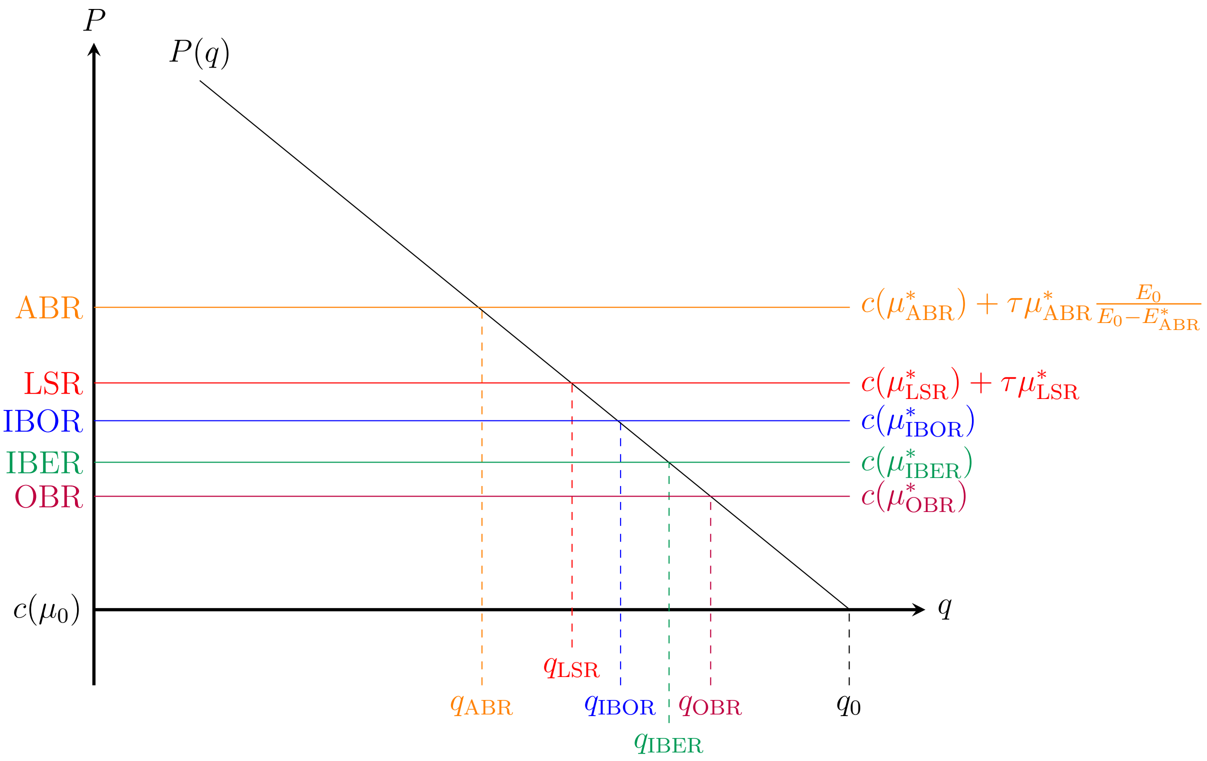


Note: The downward-sloping black line labeled $-c'(\mu)$ reflects the firm's marginal abatement costs. Marginal abatement costs increase with increasing abatement (lower μ). Colored lines represent the opportunity cost of carbon emissions under each policy variant. The firm optimally chooses emission intensity where the opportunity cost of emissions is equal to the marginal abatement cost.

Figure 3 illustrates the output quantity outcomes under the different revenue-neutral policies, with the y-axis originating at no-policy unit costs. With downward-sloping demand, emissions reduction policies that raise unit costs less will lead to less output contraction. The intensity- and output-based rebating policies are ordered according to the revenue-neutral conditions, although the general rebating formulas are given.

When all emissions revenues are rebated, neither OBR, IBER, nor IBOR pass on any embodied emissions costs to consumers. Their relative prices are then determined by the relative amount of intensity abatement that drives their unit costs, as indicated in Figure 2. For the same emissions price, both forms of intensity-based rebating encourage more abatement than OBR (as shown in Propositions 3 and 5), but the emissions-based rebating in IBER diminishes that effect relative to IBOR (as demonstrated in Proposition 5). LSR has full emissions cost pass-through, and ABR does even more by amplifying the emissions tax (1).

Figure 3: Marginal production costs and demand, given an equal emissions price τ and revenue-neutral policies



Note: Consumer (inverse) demand for firm output is illustrated by the downward-sloping black line labeled $P(q)$*. Full marginal cost (including regulatory cost) corresponding to each policy variant is given by the colored lines. Firm output in equilibrium is the intersection of the demand and marginal cost curves.*

In Figure 4, we summarize qualitative rankings of each rebating option under the two dimensions discussed—how much each rebating option incentivizes emission reduction (the opportunity cost of producing emissions) and how much each rebating option mitigates the upward pressure of the policy on the unit costs of firm output (supporting equilibrium output).[12] Attractive policies would generate larger incentives to reduce emissions (i.e., the opportunity cost of producing emissions would be high) and would protect against output loss by generating small impacts on output prices. In our figure, such policies would occupy

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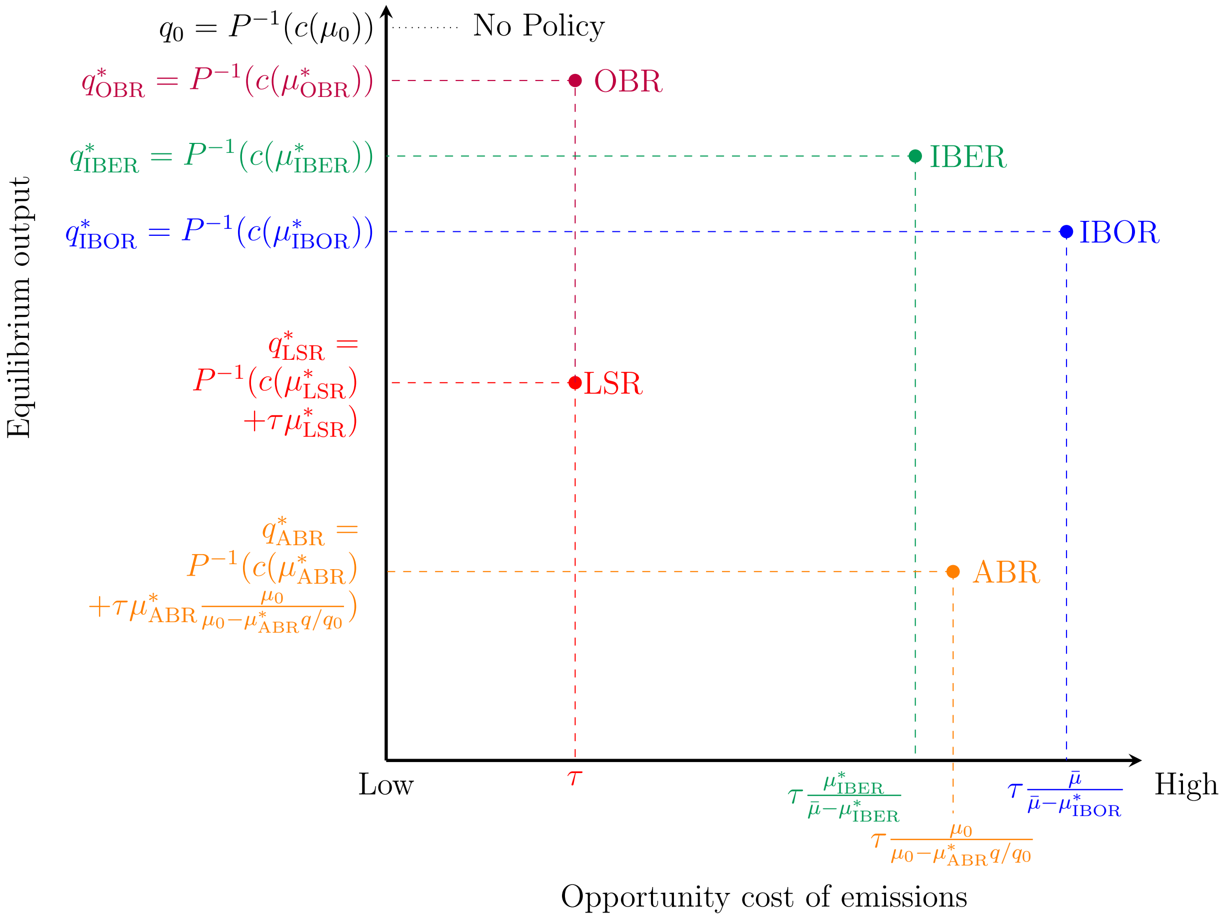
[12] Since the equilibrium price is equalized with marginal production costs, equilibrium output then equals the inverse of the inverse demand function evaluated at the equilibrium unit costs: $q = P^{-1}(c(\mu) + \tau\mu - R_q(q, \mu))$.

Figure 4: Mapping output and opportunity costs of emissions with revenue-neutral rebating options for the same emissions price τ



Note: The figure illustrates the theoretical predictions for the ranking of each rebating option on two dimensions: how much each option mitigates impacts on output price, and how much each option provides incentives for the reduction of emissions. The base emissions price τ is held equal across policies, and the revenue-neutral version of each policy is considered.

the top right quadrant. As we indicate in the prior analysis and in the figure, no policy is dominant on both dimensions. OBR mitigates against price increases better than the other alternatives we analyze, while IBOR provides larger incentives for emission reduction than other rebating options. However, the two intensity-based rebating options are the only ones that outperform LSR on both metrics—that is, the intensity-based policies both mitigate against output price increases in regulated firms and generate larger incentives to reduce emissions compared with LSR.

2.7 Comparing rebating policies for a given emissions target

The flip side of inducing greater emission reductions for a given price means that emissions prices can be lower for a given target. Appendix A.1 examines in detail the outcomes of different rebating options for a given emissions target, recalling that fixing sectoral emissions defines a unique relationship between emission intensity and level of output ($q = \bar{E}/\mu$).The degree of output protection determines the intensity reduction needed, and the rebating regime influences the emissions price required to achieve that.

When output- or intensity-based rebating mechanisms are revenue neutral, in equilibrium no embodied emissions are priced (unit costs are all $c(\mu)$, regardless of τ, as seen in Figure 4). As a result, revenue-neutral OBR, IBER, and IBOR provide equal output protection for a given sectoral emissions target; however, OBR requires the emissions price to rise relative to LSR to induce the necessary increase in intensity abatement, whereas the extra incentives from IBER and especially IBOR allow prices to be lower. Meanwhile, LSR and ABR, even when revenue neutral, still price embodied emissions on the margin. Their output-intensity trade-offs are identical, but ABR drives down the emissions price by the amount of the abatement subsidy.[13]

If policies with lower *consumer prices* are appealing, such as to appease voter or carbon leakage concerns, then the first group of policies with output-based rebating components may be attractive. If policies with lower *emissions prices* are attractive, such as to appease political concerns about carbon pricing, IBER or IBOR—or even ABR—may be preferred to OBR. This line of reasoning was an important factor for abatement-based rebating in Hagem et al. (2020).

Of course, the different directions of emissions or price adjustment will also have important efficiency implications in a multisector setting. If rebate-eligible sectors (say, emission-intensive and trade exposed, or 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 emission prices, whereas IBER (as well as other abatement-oriented rebating mechanisms) will tend to relieve the other sectors of some burden, by putting downward pressure on emission prices. Indeed, getting more emission

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[13] See Proposition 6 in A.1.

reductions from large heavy industries while limiting carbon price pressures on other sectors that are more diffuse—or on households concerned about the cost of their final energy consumption—may carry political benefits.

2.8 Welfare considerations

Ultimately, the welfare effects of any of these interventions depend not only on the standard costs of abatement versus any environmental benefits but also on the potential spillover benefits of interacting with otherwise distorting policies. Output protection may, for example, have benefits in terms of reduced leakage or tax interactions (Fischer and Fox, 2011). Greater reliance on intensity abatement may be associated with other benefits, such as spillovers from induced technological innovation or reduced compliance costs elsewhere. Let $B(q, \mu)$ represent these collective (heretofore unmodeled) net spillover benefits that occur in a broader setting that takes other market failures or distortions into account. Let $CS(q)$ be consumer surplus in this sector, so $CS(q) - c(\mu)q$ is net surplus. Let δ represent the (constant) marginal damage from emissions. Our measure of welfare is then $W = CS(q) - c(\mu)q - \delta\mu q + B(q, \mu)$. Totally differentiating welfare for our partial equilibrium model, we parse the incremental welfare costs of policy-induced changes in output and intensity:

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

where the first-order conditions are used to simplify the second line of the expression.

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. That is, if $\tau = \delta$, $R_q = B_q$, and $R_\mu = B_\mu$, then $dW = 0$, and no further adjustment of q and μ can improve welfare. In practice, however, rebates are not optimized but rather reflect different rules of thumb. Quantifying the uninternalized spillover benefits of output or intensity reductions would be necessary to evaluate the full welfare effects of these rebating rules.

We next use numerical simulations to quantify the efficiency and distributional effects of the different rebating policies in a general equilibrium setting, initially without second-best considerations. This exercise gives an indication of the magnitudes of the efficiency costs that would need to be traded off against uninternalized spillover benefits in a second-best setting. Those external benefits will be addressed explicitly in future work with general equilibrium modeling.

3 Numerical simulations

In this section, we use a computable general equilibrium (CGE) model to quantify the differential economic impacts of alternative rebating rules. Using the numerical model allows us to estimate magnitudes of differences between policy approaches that we consider for a realistic economy, and also to consider general equilibrium interactions between sectors that are within and outside the scope of our partial equilibrium analysis. We briefly summarize the modeling approach and then proceed to reporting results.

3.1 Numerical modeling approach

Our multisector open-economy CGE model adopts a canonical general equilibrium representation of economic activities. Decisions about the allocation of resources are decentralized on competitive markets, and the representation of behavior by producers and consumers in the model 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. Substitution and transformation possibilities in production and consumption are described by means of continuous functional forms with economic responses being driven by empirical estimates of elasticities and initial value shares derived from economic accounts. Below we provide a nontechnical description of key model features. A detailed algebraic exposition is provided in Appendix B.

Figure 8 depicts the fundamental accounting identities of economic flows that can be directly associated with the three classes of general equilibrium conditions: income balance, market clearance, and zero profit. The representative agent receives income RA from primary factors—labor ($\bar{L}$), capital ($\bar{K}$), and specific resources ($\bar{Q}_i$) in the production of fossil fuels

i. The income is spent on aggregate private consumption Y_C, on exogenous investment (savings) demand $\bar{I}$, and on exogenous government demand ($\bar{G}$).

Production Y_i of commodity i by representative firm i is given as a nested constant-elasticity-of-substitution (CES) function that captures price-responsive substitution possibilities between factor and intermediate inputs (see Appendix B Figures 9 – 12). The choice of inputs, in particular the amount and composition of energy carriers, implicitly defines μ for the firm in each sector. Production of final demand commodities enters final demands of the representative agent (private consumption Y_C, investment demand Y_I, and government demand Y_G). All other domestically produced goods are split subject to a constant-elasticity-of-transformation (CET) function between export demand X_i and input demand for the production of the Armington good A_i. Armington production for each good i is based on a CES technology that combines the domestically produced good and imports M_i. Armington outputs A_i in turn serve as intermediate inputs to the production Y_i of all commodities including final demands. The Armington assumption of product heterogeneity distinguishes goods by origin (Armington, 1969). This accommodates both imports and exports of the same commodity reflecting empirical evidence on the crosshauling of trade flows.

In international markets, our country of interest (in this case, the United States) is assumed to be a price taker, meaning changes in the country's import and export volumes have no influence on international prices. In other words, export and import prices in foreign currency – the so-called terms of trade – are made exogenous. A balance-of-payment constraint requires that the total value of exports equal the total value of imports, accounting for an initial trade deficit or surplus.

As is customary in applied general equilibrium analysis, base-year data together with exogenous elasticities determine the free parameters of the functional forms. Our central case model parameterization deploys the most recent Global Trade Analysis Project (GTAP) data (version 10) for the US economy, 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). We do not include preexisting taxes to abstract from second-best effects such that the simulation results should adhere closely in qualitative terms to the theoretical predictions outlined above, while capturing the quantitative differences between

Table 3: Benchmark sector output, trade, and emissions

	Y		D		X		M		CO_2		Int
Name	abs	pct	abs	pct	abs	pct	abs	pct	abs	pct	abs
Non-EITE sectors											
Natural gas	146	0.3%	157	0.5%	29	1.4%	39	1.4%	101	1.8%	692
Electricity	456	0.9%	460	1.4%	1	0.0%	5	0.2%	2286	41.0%	5013
Coal	89	0.2%	71	0.2%	20	1.0%	1	0.0%	10	0.2%	112
Crude oil	318	0.6%	603	1.9%	6	0.3%	290	10.6%	41	0.7%	129
Rest of economy	27762	55.8%	28184	86.8%	1477	70.6%	1899	69.2%	1725	31.0%	62
EITE sectors											
Refined petroleum products	778	1.6%	698	2.2%	152	7.3%	72	2.6%	119	2.1%	153
Pulp and paper	439	0.9%	436	1.3%	31	1.5%	28	1.0%	38	0.7%	87
Non-metal minerals	181	0.4%	194	0.6%	12	0.6%	25	0.9%	59	1.1%	326
Iron and steel	227	0.5%	254	0.8%	26	1.2%	53	1.9%	42	0.8%	185
Non-ferrous metals	209	0.4%	214	0.7%	58	2.8%	64	2.3%	12	0.2%	57
Chemicals	1201	2.4%	1188	3.7%	281	13.4%	268	9.8%	94	1.7%	78
Final demand sectors											
Consumption	12011	24.1%	NA	NA	NA	NA	NA	NA	1045	18.8%	87
Government	2575	5.2%	NA	NA	NA	NA	NA	NA	NA	NA	NA
Investment	3403	6.8%	NA	NA	NA	NA	NA	NA	NA	NA	NA

Note: Y refers to production, D is domestic consumption, X is exports, and M is imports in billions of dollars. CO_2 is domestic emissions of carbon dioxide in millions of metric tonnes. Int is CO_2 intensity in tonnes of CO_2 emissions per \$1,000 of production. abs is the value in dollars or tonnes as described above. pct is the sector share of the total economy in percentage terms.

rebating options based on empirical data.[14]

With the United States as the country for investigation, we aggregate the 65 sectors in GTAP to 11 sectors reflecting the specific requirements of our research question. In the composite data set, we distinguish energy-producing and transforming sectors (coal, gas, crude oil, electricity, and oil refining), energy-intensive and trade-exposed industries (iron and steel, nonferrous metals, nonmetallic minerals, chemicals, pulp and paper), and an aggregate sector (rest of the economy) reflecting the remainder of the economy. In the results below, we group these 11 sectors into two composite segments: an aggregate of emission-intensive and trade-exposed industries (EITE) and an aggregate non-EITE sector (NEITE).[15] Investment and government demand are exogenous and held fixed across the different simulations that we conduct. Key economic variables describing the economy are presented in Table 3.

In our simulation, we introduce each type of policy described above sequentially. In

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

[15] While electricity and refined petroleum products are not always considered as highly trade exposed, they are often still singled out for special treatment. The EU has refineries on its carbon leakage list. Canada includes electricity in its industrial output-based performance standards.

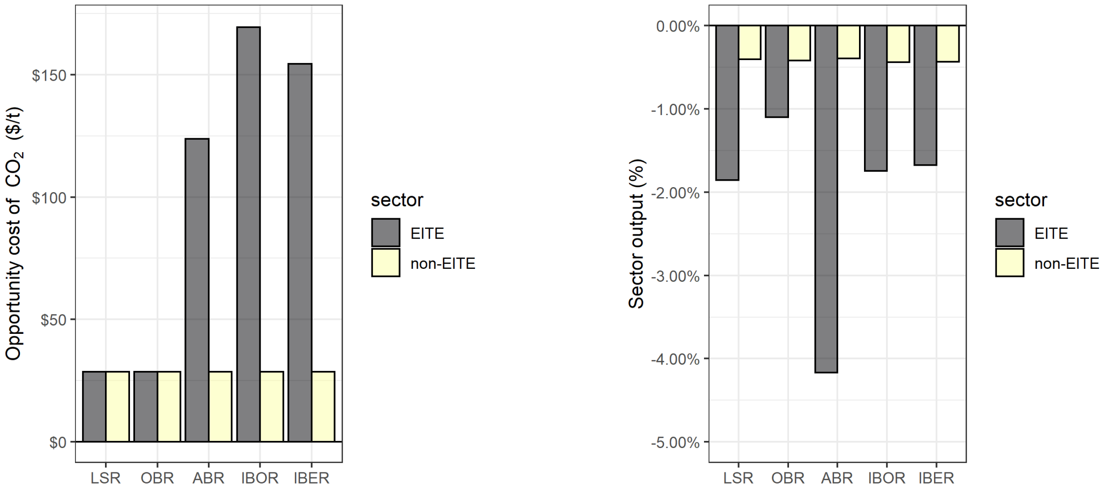
each case, we impose a common price on CO_2 emissions throughout the economy. We then apply the policy variants described above to the EITE sectors. In each case, the policy variants are considered in their revenue-neutral form, implying that all revenues raised from the CO_2 tax in the EITE sectors are used to provide rebates of different types to firms in these sectors. Consequently, the opportunity cost of CO_2 emissions and incentives to curtail output differ across policy variants and across sectors. We note that 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.

3.2 Main results

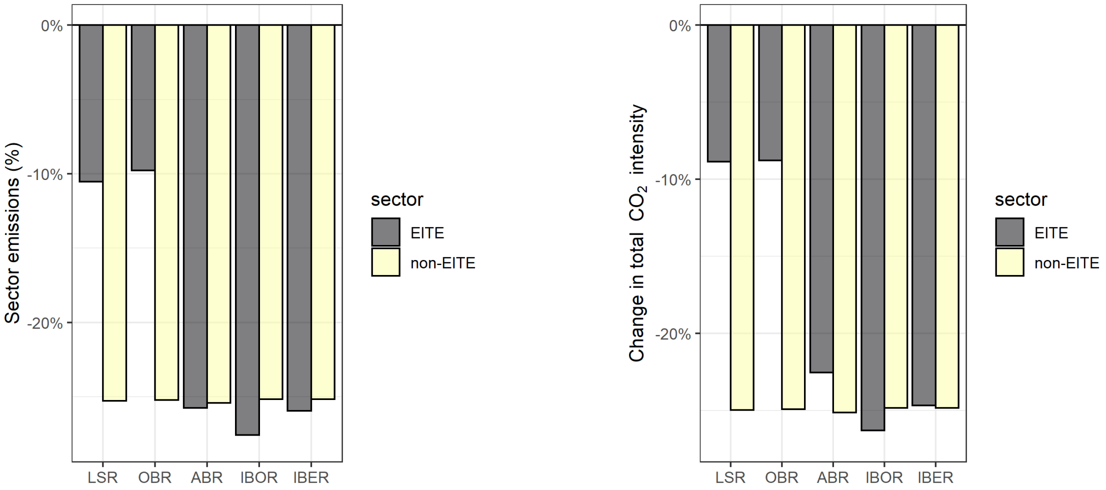
We compare policies where the CO_2 price τ is identical across policy variants. We choose τ such that under the LSR policy, the emissions price is sufficient to achieve a 20 percent reduction in economy-wide emissions. As shown in Figure 5a, our model suggests that a 20 percent reduction in economy-wide emissions under the LSR scenario is achieved with a carbon price of $\tau = \$28/tCO_2$ applied uniformly across all sectors of the US economy. As described above, the CO_2 price is imposed across all sectors of the economy, while the various rebating options are restricted to the EITE sectors. With an exogenously set CO_2 price, the overall level of economy-wide emissions is endogenous, and indeed we show (Figure 7) that emissions are reduced by a different amount under different rebating approaches. It is important to note the departure from the theoretical analysis in the prior section, in which we consider reductions in emissions in the EITE sectors only, and do not model economic activity or emissions in non-EITE sectors. We also conduct simulations in which each policy variant achieves the same level of overall CO_2 reductions. In these simulations, the resulting emission price is endogenous, and varies across policy variants. We report these simulations in Appendix C and note that the main conclusions are very similar to those presented here.

Because the LSR policy does not generate additional incentives for reducing emissions or output, it is the benchmark to which we compare other policies. Under the LSR policy,

Figure 5: Numerical model results.



(a) Opportunity cost of CO_2 **(b)** Sector output



(c) Sector CO_2 **(d)** Sector CO_2 intensity

Note: Carbon price rebating scenarios are illustrated on the horizontal axis and abbreviations are defined in the text. Each of the policies uses the same level of economy-wide CO_2 *price. The numerical model is disaggregated into 11 production sectors and 3 demand sectors, as shown in Table 3. For reporting, production sectors are aggregated into EITE and non-EITE aggregates. Panel 5a shows the opportunity cost associated with emissions of* CO_2*. Panel 5b shows the impact of each policy on sector output. Panel 5c shows the impact of each policy on sector* CO_2 *emissions. Panel 5d shows the impact of each policy on sector* CO_2 *intensity.*

our model suggests that the output of the EITE sectors falls by about 1.75 percent, and the output of non-EITE sectors falls by about 0.4 percent. Emissions in the EITE sectors under the LSR policy fall by about 10 percent, and emissions in the non-EITE sectors (which include electricity generation) fall by about 25 percent (see Figure 5).

Incentives for emissions abatement under the OBR policy are determined uniquely by the emissions price, and they are equal across sectors in which the rebate is applied as well as the other sectors. However, the OBR policy imposes an implicit subsidy on output in the composite EITE sector, resulting in a smaller curtailment in output in this sector relative to under LSR (Figure 5b). As a result, emissions are higher in the EITE sector under the OBR policy relative to the LSR policy (Figure 5c).

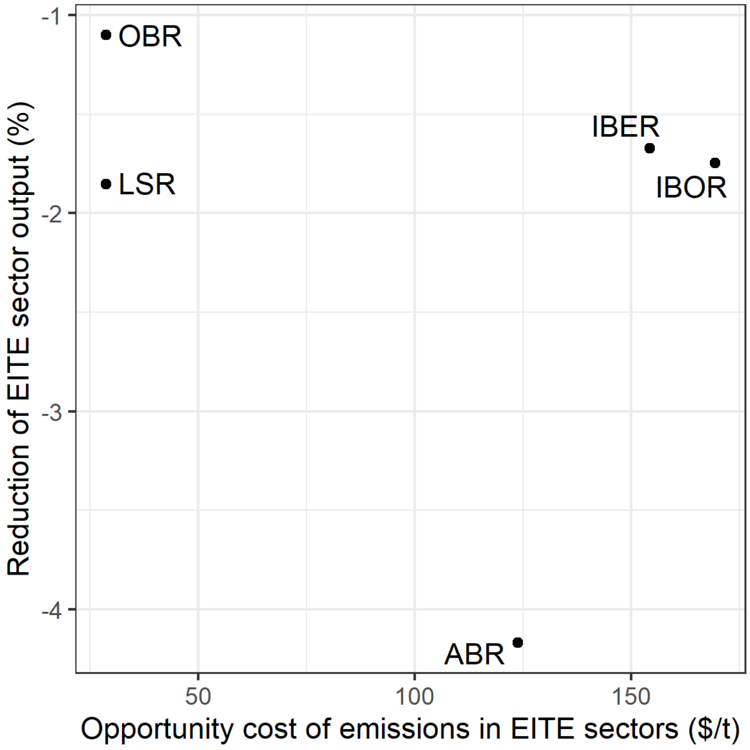
For the ABR policy, all revenue raised from the CO_2 price in the composite EITE sector is used to provide abatement subsidies to firms in this sector. As a result, the opportunity cost of CO_2 emissions in the composite EITE sector is raised substantially under this policy. In the revenue-neutral implementation, the size of the abatement subsidy is endogenous and depends on the amount of abatement achieved. As shown in Figure 5c, emissions in the composite EITE sector fall by about 25 percent under the ABR policy, resulting in a total opportunity cost of abatement in the composite EITE sector of roughly \$120/tCO_2 (Figure 5a). The high opportunity cost of abatement results in substantial curtailment of output in that sector—by nearly 4 percent (i.e., more than the double the EITE output loss under LSR)—along with large emission reductions (Figure 5b).

The IBOR policy provides a rebate to firms in the EITE sectors 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 5a). In the revenue-neutral implementation, the size of the intensity rebate is endogenous and depends on the emission intensity of the firm relative to a benchmark. In the simulation reported here, EITE emission intensity falls by approximately 27 percent, while the opportunity cost of abatement in the EITE sector under IBOR is approximately \$160/tCO_2. Thus, the IBOR policy achieves much larger reductions in EITE sector CO_2 emissions compared with the OBR and LSR policies. The IBOR 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 under the

LSR policy.

Under the IBER policy, firms in the EITE sectors 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 the one hand, firms face a reduced CO_2 price; on the other hand, increases in emission intensity trigger a higher CO_2 price. The net effect of these two opposing dynamics, assuming that the design condition ($\overline{\mu} < 2\mu$) holds, is an increase in the opportunity cost of CO_2 emissions relative to LSR, as indicated in Figure 5a, which shows an opportunity cost of abatement in the EITE sectors of \$150/tCO_2. As a result, the IBER policy induces much deeper reductions in CO_2 emissions compared with the LSR or OBR policies. IBER includes an implicit output rebate, similar to OBR and IBOR, so as with these variants, output in the EITE sectors is stimulated relative to LSR (Figure 5b).

Figure 6: Comparison of rebating options on incentives to abate and output protection in EITE sectors



Our numerical model thus confirms the theoretical results of Section 2. Notably, the intensity-based rebating policies provide a larger incentive to reduce emissions and consequently achieve a greater reduction in emissions in the targeted (EITE) sectors than LSR or

OBR approaches, as well as a smaller loss in output in targeted sectors than using lump-sum rebating. We illustrate this in Figure 6, which is the empirical analogue to Figure 4; as in the theoretical analysis, intensity-based options are in the top-right quadrant of the figure. This suggests promise for this policy approach as a tool to promote deeper CO_2 mitigation without politically unacceptable increases in emissions price or output loss from regulated firms.

Figure 7 shows that the welfare costs of intensity-based and abatement-based rebating policies are somewhat larger than for lump-sum rebating or output-based rebating policies.[16] In our simulations, the intensity- and abatement-based rebating policies achieve somewhat larger overall emission reductions than the conventional approaches, but at a larger cost. The (average) cost per unit of emission reductions is larger (at about \$15/t CO_2) for the abatement- and intensity-based approaches compared to for lump sum and output-based rebating (which reduce emissions at an average cost of about \$12/t CO_2).[17] Thus, these approaches could be justified only in the presence of other market failures that we exclude from our model (such as incomplete coverage of emissions resulting from unilateral implementation, or interactions with other taxes) or because political or other barriers preclude implementation of the first-best policy approach.

3.3 Additional numerical analysis

In this section, we report on a number of additional analyses conducted with the numerical model. We include simulations that test the robustness of our key conclusion: that intensity-based rebating approaches can help reconcile the difficulty of achieving deep greenhouse gas reductions with low emissions prices and without politically challenging price increases or output reductions in targeted sectors. Detailed results are reported in Appendix C; in this section, we limit the discussion to the motivation for the analysis as well as the key conclusions.

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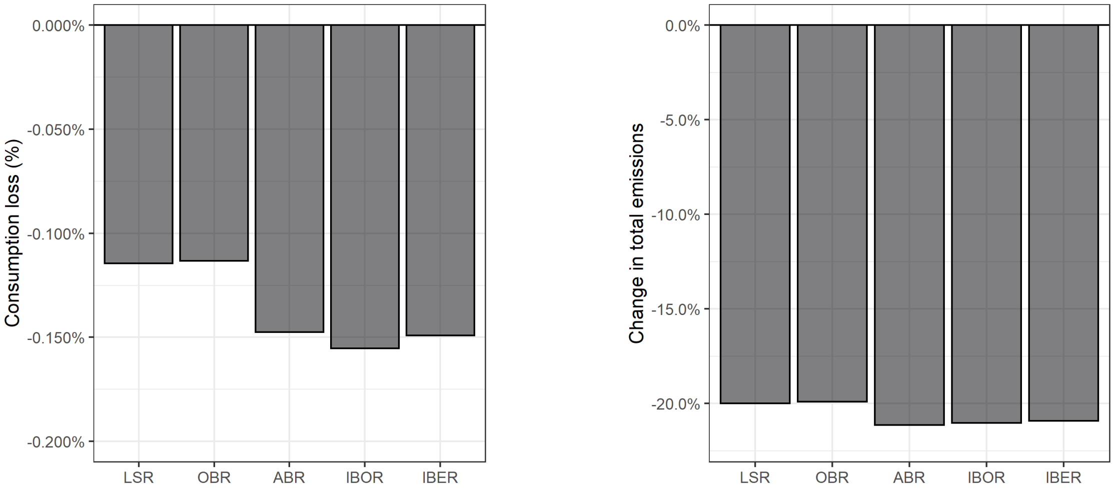
[16] The representative consumer in the model does not consume leisure, so welfare change is measured directly from changes in consumption.

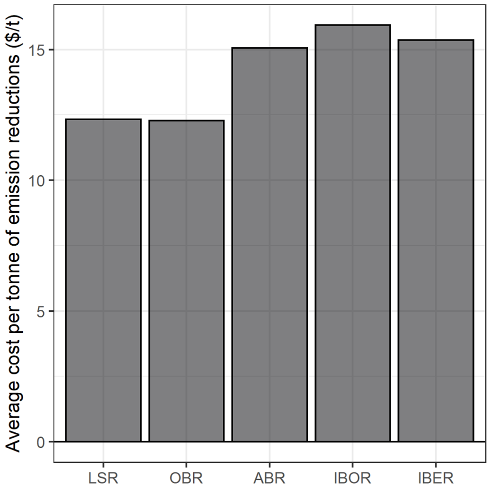
[17] Note that in Figure 7, the welfare cost of OBR is slightly smaller than LSR. This counter-intuitive result is due to emissions in OBR being slightly higher than under LSR. In Appendix C, we simulate policies that achieve identical emission reductions, and find – consistent with theory – that the OBR policy imposes larger welfare costs than LSR.

Figure 7: Consumption losses, emissions reductions, and average costs for alternative policies



(a) Consumption-related welfare

(b) Economy-wide emissions



(c) Average cost of CO_2 reductions under each policy

Note: Carbon price rebating scenarios are illustrated on the horizontal axis and abbreviations are defined in the text. Each of the policies uses the same level of economy-wide CO_2 *price. Welfare is determined as the Hicksian equivalent variation in income. The welfare measure does not include the social benefit of* CO_2 *emissions reductions and is thus incomplete. The average cost per tonne of emission reductions is calculated by dividing the consumption loss in dollars by the change in emissions in tonnes.*

Treatment of electricity sector: In our main results, the electricity sector is not treated as an EITE sector (it is not highly traded). However, in some real-world cases, the electricity sector is given special treatment under carbon pricing. Because of its large contribution to US emissions, and because it offers substantial cost-effective CO_2 mitigation opportunities, treatment of the electricity sector is important in determining model results. In Section C.5, we show how model results are affected when the electricity sector is included in the set of EITE sectors. While inclusion of the electricity sector in the set of EITE sectors results in large numerical changes in results, the ranking of policy instruments and general conclusions from the analysis are preserved—notably, that the intensity-based policy variants achieve deeper CO_2 reductions than the LSR and OBR policies in the EITE sectors, and that the intensity-based policies attenuate negative impacts of carbon pricing on output relative to the LSR policy.

Results for different countries: Our main numerical analysis calibrates the CGE model to US data. To ensure that our conclusions are not driven by factors idiosyncratic to the US economy, we replicate our analysis after recalibrating our model to benchmark data from other countries in the GTAP data set. We show our analysis in Section C.3 for all G20 countries. While the numerical results differ from the results based on US data, the qualitative conclusions of the analysis remain unchanged: the intensity-based policy variants achieve deeper CO_2 reductions in the targeted EITE sectors compared with the LSR and OBR policies and result in smaller curtailment in output in these sectors relative to the LSR benchmark.

Detailed subsector results: In our main numerical results, we aggregate six energy-intensive trade-exposed sectors (chemical manufacturing, iron and steel manufacturing, nonferrous metal manufacturing, nonmetal mineral manufacturing, oil refining, and pulp and paper manufacturing) into one aggregate sector for reporting purposes. In Section C.4, we report disaggregate results for each EITE subsector. Again, we find that sector output falls by a smaller amount under the intensity-based rebating variants compared with under the LSR policy, and that intensity-based policy variants achieve deeper greenhouse gas reductions in EITE sectors compared with LSR and

OBR policies.

Results with different stringencies: Our main numerical analysis focuses on a 20 percent reduction in economy-wide emissions. In Section C.2, we show how our conclusions are affected under different choices of policy stringency, by simulating economy-wide CO_2 reductions between 1 and 40 percent. In the revenue-neutral scenario that we consider, in which all revenue raised from carbon pricing in the EITE sectors is used to provide rebates in those sectors, the largest difference between the LSR policy and other approaches occurs at low levels of economy-wide CO_2 reductions. As the ambition of the policy is increased, the differences between policy variants shrink. Over the entire range of stringency that we simulate, we find the same overall ranking of policy variants, and the same qualitative conclusions emerge from our analysis: intensity-based approaches to rebating can preserve output relative to the LSR policy and result in larger cuts in CO_2 emissions in the covered sectors.

4 Conclusions

Due to concerns over political feasibility associated with unilateral policy adoption, many carbon pricing policies have incorporated some form of output-based rebates into their designs. In this paper, we examine several alternative approaches to rebating carbon pricing revenues that may increase the opportunity cost of CO_2 emissions and attenuate output losses in the regulated sectors. These approaches result in more emission reductions in targeted sectors than a "standard" carbon price alone and, as a result, may help improve the ability of policymakers to pursue ambitious carbon reductions under political constraints. We use both theoretical analysis and numerical analysis to contrast these approaches to carbon policy. Our results show that abatement-based rebating, output-proportional intensity-based rebating, and emissions-proportional intensity-based rebating all provide greater incentives for emission reduction than output-based rebating or lump-sum rebating. In addition, intensity-based rebating options also increase firm output relative to lump-sum rebating. With emissions pricing being implemented as a cap-and-trade system, the alternative 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 policymakers seeking deeper greenhouse gas reductions than current approaches, while still maintaining political feasibility.

Of course, conditional rebating mechanisms do not come without efficiency costs, since they prioritize intensity reductions over other cost-effective means for reducing emissions. In particular, intensity-based rebating systems lead to diverging marginal abatement costs across sectors, and even across firms within the same sector in the case of intensity-based emissions rebating. Our analysis has focused on a first-best setting without initial market distortions in order to clarify the fundamental economic implications of alternative rebating schemes. In subsequent work, we plan to explore the implications of such rebates in a second-best setting, including initial distortions such as preexisting taxes and subsidies. Further research will be also necessary to investigate the relative attractiveness of the different rebating schemes to foster global cost-effectiveness of unilateral action by combating carbon leakage through policy-induced changes in international prices. Such research calls for a multi-region setting, which goes beyond the scope of our current paper.

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A Theory appendix

A.1 Same sectoral emissions target

If we compare policies with a consistent emissions target, $\bar{E}$, for the regulated sector, then the sector output-intensity trade-off is $q = \bar{E}/\mu$, and the market outcome will satisfy (3).

A.1.1 Lump-sum and abatement-based rebating

For lump-sum rebating, simplifying (3) we have

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu. \tag{13}$$

With the same sectoral emissions target, ABR produces the same result as LSR, as the equilibration of the emissions price fully absorbs the effect of the abatement rebate:

Proposition 6 *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 (13) with ABR, which implies that $\mu_{\text{ABR}} = \mu_{\text{LSR}}$. The emissions constraint then gives $q_{\text{ABR}} = q_{\text{LSR}}$, and (5) implies $\tau_{\text{ABR}} = \tau_{\text{LSR}} - s$. ■

Note that mirror effects result if the abatement subsidy is negative. For example, at certain stages of evolution in the EU Emission Trading Scheme, some industry groups have lobbied for larger rebates for larger emitters (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 emission 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 have restricted ourselves to considering ABR.

A.1.2 Output- and intensity-based rebating

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

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

Since the right-hand side of (14) is less than that of (13), we get the well-known result that for the same emissions target, $\mu_{\text{OBR}} < \mu_{\text{LSR}}$ and $q_{\text{OBR}} > q_{\text{LSR}}$. In an equilibrium that both is revenue neutral and meets the same sectoral emissions target (denoted by superscript **), then $P(\bar{E}/\mu^{**}_{\text{OBR}}) = c(\mu^{**}_{\text{OBR}})$.

Implementing IBOR with the same emissions target, the following must hold:

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu - s\overline{\mu} \tag{15}$$

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

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

Proof. From (9), substituting the value for z^*, the output condition for a revenue-neutral IBOR with the same emissions target is $P(\bar{E}/\mu^{**}_{\text{IBOR}}) = c(\mu^{**}_{\text{IBOR}})$, the same as with OBR. From the intensity condition, we solve for $\tau^{**}_{\text{IBOR}} = -c'(\mu^{**}_{\text{IBOR}})(\overline{\mu} - \mu^{**}_{\text{IBOR}})/\overline{\mu} < -c'(\mu^{**}_{\text{IBOR}}) =< -c'(\mu^{**}_{\text{OBR}}) = \tau^{**}_{\text{OBR}}$. ■

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.

For IBER, using (11) and simplifying (3), we find that for the same sectoral emissions target,

$$P(\bar{E}/\mu) = c(\mu) - c'(\mu)\mu Z(\rho) \tag{16}$$

where $Z(\rho) = 1 - \rho\mu / \left(\overline{\mu} - \underline{\mu} + \rho(2\mu - \overline{\mu})\right)$ is the share of marginal abatement costs that are passed through to consumers. If $\rho = 0$, there is no rebating and the outcome is identical to LSR; if the rebate is revenue neutral, then ρ is such that $Z(\rho) = 0$.

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 $Z'(\rho) < 0$, meaning that scaling up the rebate lowers the right-hand side of (16) relative to (13), ensuring $\mu_{\text{IBER}} < \mu_{\text{LSR}}$ and $q_{\text{IBER}} > q_{\text{LSR}}$ along with the emissions constraint. Given the assumption that $\overline{\mu} < 2\mu$, combining IBOR 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 $\mu Z(\rho) < \mu - \mu_b$. To compare with the other options, then, let us consider cases of 100 percent earmarking.

Proposition 9 *Given a sectoral emissions target, a revenue-neutral IBER leads to the same allocation of output and intensity as IBOR and OBR, but with a higher emissions price than IBOR, but not as high as OBR.*

Proof. $Z(\rho^*) = 0$, so (16) simplifies to $P(\bar{E}/q) = c(\mu)$, as with IBOR and OBR. However, from (12), at a given emissions target, the equilibrium emissions price under revenue-neutral IBER is $\tau^{**}_{\text{IBER}} = -c'(\mu)\frac{\overline{\mu}-\mu}{\mu} > -c'(\mu)\frac{\overline{\mu}-\mu}{\overline{\mu}} = \tau^{**}_{\text{IBOR}}$. Our design condition that $2\mu > \overline{\mu}$ ensures that $\frac{\overline{\mu}-\mu}{\mu} < 1$ and $\tau^{**}_{\text{IBER}} < \tau^{**}_{\text{OBR}}$. ■

In other words, with 100 percent 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 emission intensity reductions, given an emissions price, will determine how market prices for emissions must adjust to meet the target.

A.1.3 Summary of rebating policies for equal emissions

Table 4 summarizes the results for equal emissions when rebating policies are revenue-neutral (scenarios denoted by superscript **). The table orders the policies first in terms of output protection (highest to lowest) and then emissions price (highest to lowest).

Table 4: Equilibrium conditions for revenue-neutral rebating mechanisms given the same sectoral emissions target, ranked by output and then by emissions price

	Rebate	Output price, $P(\bar{E}/\mu^{**}_i)$	Emissions price, τ^{**}_i
1	OBR	$c(\mu^{**}_{\text{OBR}})$	$-c'(\mu^{**}_{\text{OBR}})$
	IBER	$c(\mu^{**}_{\text{OBR}})$	$-c'(\mu^{**}_{\text{OBR}})\frac{\overline{\mu}-\mu^{**}_{\text{OBR}}}{\mu^{**}_{\text{OBR}}}$
	IBOR	$c(\mu^{**}_{\text{OBR}})$	$-c'(\mu^{**}_{\text{OBR}})\frac{\overline{\mu}-\mu^{**}_{\text{OBR}}}{\overline{\mu}}$
2	LSR	$c(\mu^{**}_{\text{LSR}}) - c'(\mu^{**}_{\text{LSR}})\mu^{**}_{\text{LSR}}$	$-c'(\mu^{**}_{\text{LSR}})$
	ABR	$c(\mu^{**}_{\text{LSR}}) - c'(\mu^{**}_{\text{LSR}})\mu^{**}_{\text{LSR}}$	$-c'(\mu^{**}_{\text{LSR}})\frac{(E_0-\bar{E})}{E_0}$

Recall that the sectoral target maps an equilibrium emission intensity to a unique level of output ($q = \bar{E}/\mu$). When output- or intensity-based rebating mechanisms are revenue neutral, in equilibrium no embodied emissions are priced. Therefore, the output-intensity trade-offs are identical, as seen in the third column (see Propositions 3 and 8).As a result, revenue-neutral OBR, IBER, and IBOR provide equal output protection for a given sectoral emissions target; however, the policies lead to different equilibrium prices, as viewed in the fourth column. OBR leads to the highest emissions price to induce the required increase in intensity abatement, while IBER allows prices to be lower—and IBOR lower yet—since the rebate itself drives intensity abatement.[18]

LSR and ABR, even when revenue neutral, still price embodied emissions on the margin, and they create the same equilibrium output-intensity trade-off for a given emissions target. Since ABR amplifies the emissions price, ABR achieves the same target as LSR with an emissions price that is reduced by the amount of the abatement subsidy (Proposition 6).

A.2 Revenue-equivalent OBR and IBER

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 $\tau_{\text{OBR}}(\mu - \hat{b})q = -c'(\mu)Z(\rho)\bar{E}$. The net revenues under IBER are

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

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

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 9. The main difference, then, is that IBER does it with a lower emissions price:

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

given our design assumption that $\overline{\mu} < 2\mu$.

A.3 Simple intensity-based rebating (SIBR)

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

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[18] We have focused on revenue-neutral outcomes, but we can also show that OBR and IBR policies with equivalent output protection and a given sectoral target also have equivalent fiscal implications (Proposition A.2). Again, the main difference is the equilibrium emissions price.

conditions with SIBR simplify to

$$\mu_{\text{SIBR}}: \quad -c'(\mu) = \tau + s/q; \qquad q_{\text{SIBR}}: \quad P(q) = c(\mu) + \tau\mu. \tag{17}$$

In this version, the rebate only directly subsidizes emission 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 10 *For the same emissions price, SIBR leads to both lower output and lower emission intensity than LSR.*

Proof. The intensity condition in (17) 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 11 *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 emission 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 (13). ■

Compared with 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 percent recycling, $s = \tau\mu q/(\overline{\mu} - \mu)$ in equilibrium. Thus,

$$\mu^*_{\text{SIBR}}: \quad -c'(\mu) = \tau\frac{\overline{\mu}}{\overline{\mu} - \mu}; \qquad q^*_{\text{SIBR}}: \quad P(q) = c(\mu) + \tau\mu. \tag{18}$$

Proposition 12 *Comparing revenue-neutral policies, for the same sectoral emissions target, SIBR leads to less output and less intensity reduction than OBR.*

Proof. From (18), we derive the emissions price to achieve the equivalent target, leading to

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

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

B 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 5–10.

Figures 8, 9, 10, 11, and 12 depict the model diagrammatically. Figure 8 shows the basic structure of the model, in which a representative consumer supplies primary factors of production to domestic industries, who produce goods for export and domestic consumption. Figures 9 and 10 show the structure of the nested-constant elasticity of substitution production functions in non-fossil fuel and fossil fuel producing sectors, respectively. In each case, representative firms use capital, labor, energy, and materials to produce goods for export or domestic markets. These factors are mobile across sectors. In the case of fossil fuel sectors, production requires the input of a fossil fuel–specific resource. Figure 11 illustrates that the Armington good consists of a domestic and imported variety, while Figure 12 shows that final demand is made up of energy and non-energy goods.

Figure 8: Diagrammatic model structure

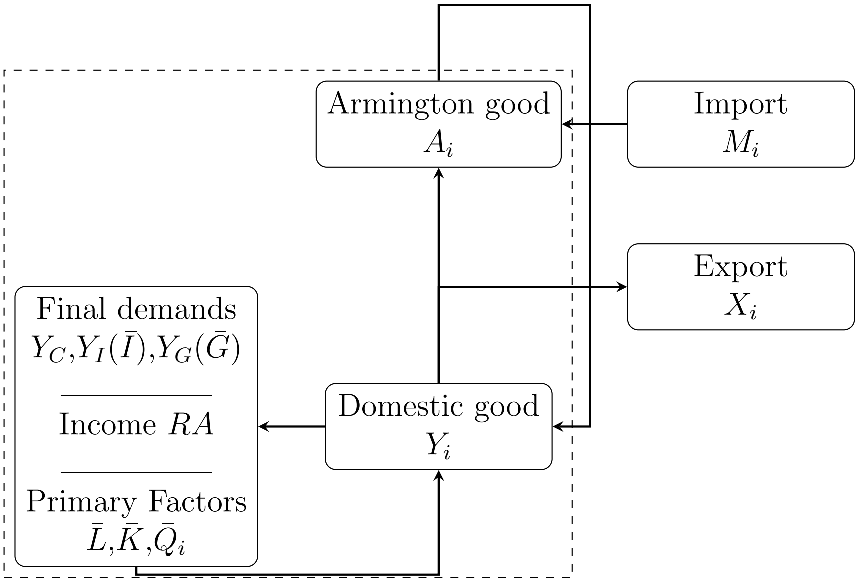


Figure 9: Production structure for a representative industry

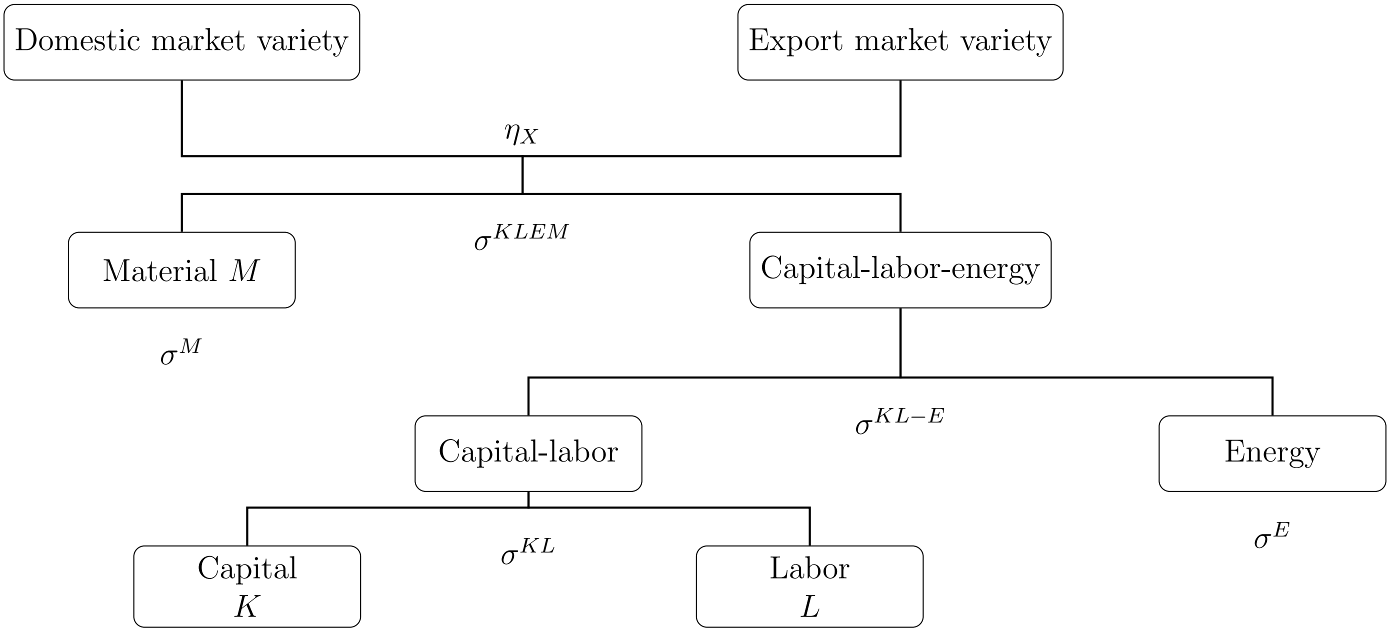


Figure 10: Production structure for fossil fuel industries

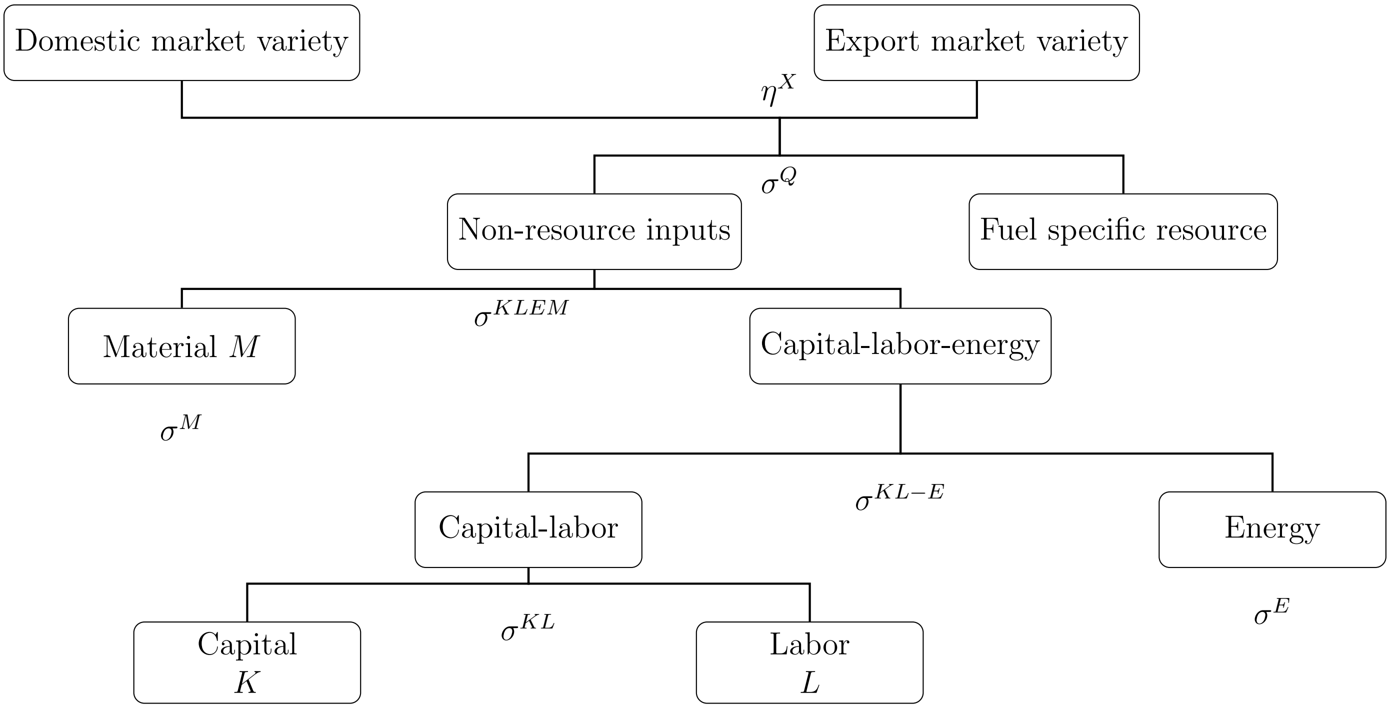


Figure 11: Production structure for Armington good

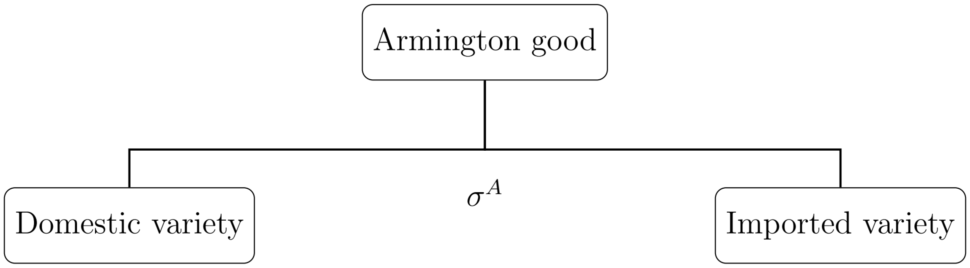
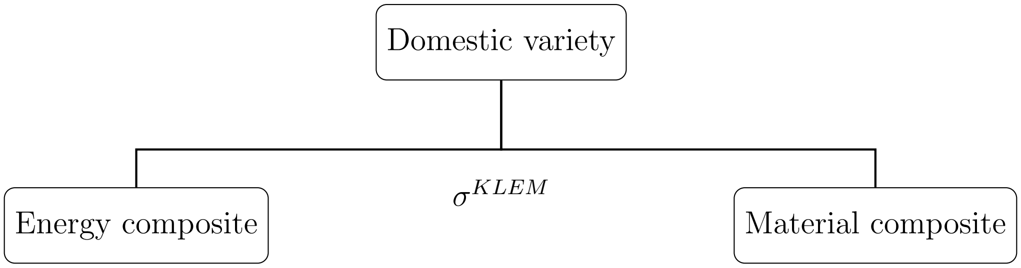


Figure 12: Production structure for final demand good



B.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 ($i \in FF$)

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

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

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

4. Armington aggregate

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

5. Output transformation

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

B.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)

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

B.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 5: 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 6: 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 7: Price variables

p_i	Output price of good i
p_i^D	Domestic supply price of good i
p^{FX}	Price of foreign 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 emissions price

Table 8: 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}^E	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 9: 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^E	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 10: 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

C Additional numerical simulation results

C.1 Simulation results with equal economy-wide emission reductions

In Figure 13, we conduct simulations of each policy in which the economy-wide CO_2 price is endogenously set such that each policy variant achieves the same level of economy-wide reductions in CO_2 emissions. In contrast, the main text reports on simulations in which the economy-wide CO_2 price is equal across all policy variants.

C.2 Stringency of climate policy

The main results presented the impacts of different policy designs on various outcomes for a hypothetical scenario in which emissions are reduced 20 percent relative to a no-policy counterfactual. In this section, we use the numerical model to estimate how outcomes vary depending on the stringency of the climate policy, measured by the economy-wide reduction in CO_2 emissions. We show results for reductions in CO_2 emissions from 1 to 40 percent below a no-policy counterfactual. In these simulations, we hold the overall level of emissions across policies constant, such that the emission price is endogenous. In Figure 15a, we calculate the opportunity cost of CO_2 in the EITE and non-EITE sectors for each policy variant, relative to the LSR design. In EITE sectors, the ABR, IBOR, and IBER designs provide much greater incentives for CO_2 mitigation, however, because carbon pricing revenue falls with increasing CO_2 reduction, leaving less financial means available to provide incentives for additional reductions. As stringency increases, the gap between LSR and other policies is reduced.

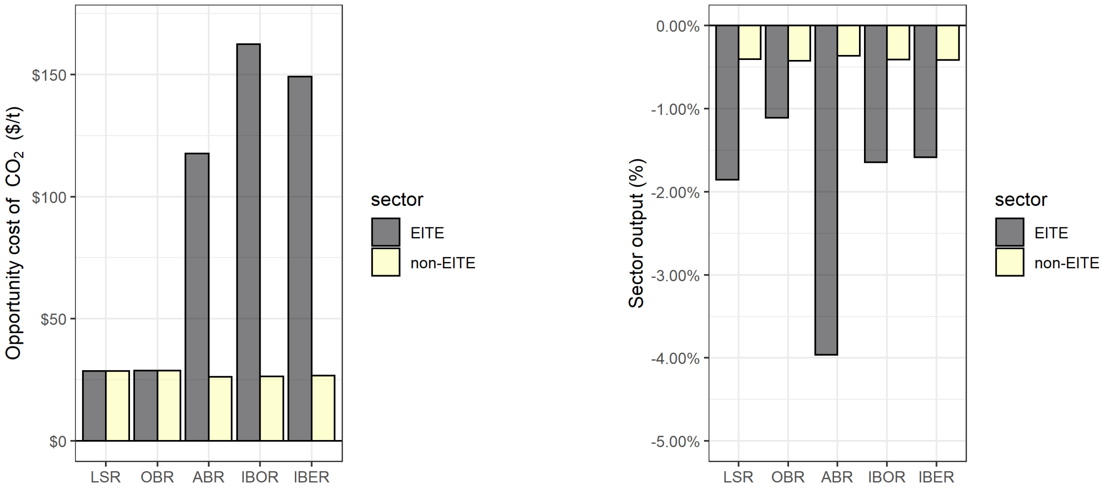
Differences in the opportunity cost of CO_2 emissions illustrated in Figure 15a cause firms to reduce emissions and output. Figure 15b shows output of firms in EITE and non-EITE sectors at different levels of stringency. The ABR policy incentivizes EITE firms to reduce output, and as a result, there is a substantial reduction in output in EITE sectors for this policy relative to the LSR policy. As stringency increases, less revenue is available to provide incentives for abatement reductions in EITE sectors, and the policy converges toward LSR. For OBR, IBOR, and IBER policies, each policy includes an implicit subsidy to output in EITE sectors, and as a result, output is reduced by less than under the LSR policy. Figure 15c shows how emissions are affected by each policy, relative to LSR. In the EITE sectors, ABR, IBOR, and IBER policies provide an additional incentive to reduce emissions relative to LSR. As stringency increases, revenue available for abatement subsidies is reduced, and these policies converge toward LSR.

Figure 15d shows how stringency affects the welfare costs of each policy relative to the LSR policy. As stringency of policies is increased, the welfare impacts of the policies converge toward the LSR policy.

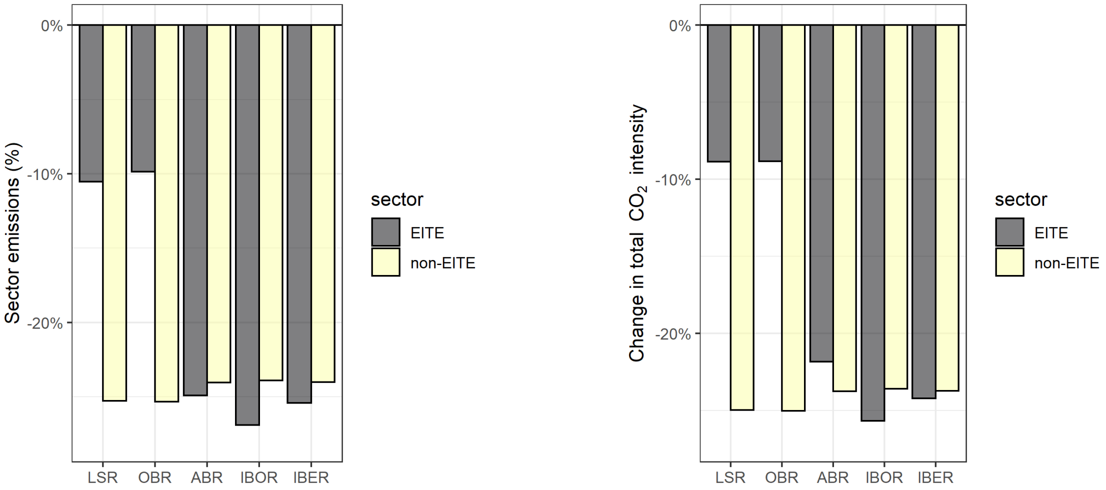
C.3 Sensitivity to country-specific data

Our central case simulations are for US economy. However, because of structural differences across regions, there may be concern that the quantitative conclusions may not hold broadly. In this section, we provide simulation results for each of the G20 countries to determine how sensitive our findings are to different economic structures. Figure 16 shows the impact of each policy variant on output in the EITE sectors, relative to the LSR variant. While the numerical magnitudes differ, the overall conclusions hold from our analysis based on the United States. Specifically, the intensity-based policies result in lower reductions in output of the EITE sectors compared with the LSR policy. Figure 17 shows the impact of each policy variant on emissions in the EITE sectors, relative to the LSR policy. Again, while the numerical magnitudes vary across countries, the overall conclusion that emerges from the multicountry analysis is that the intensity-based policies deliver deeper reductions in the targeted EITE sectors compared with the LSR policy. For the policy stringency that we focus on (a 20 percent cut in economy-wide emissions) our results suggest that the intensity-based policies deliver between 50 and 250 percent more emission reductions in targeted sectors compared with the LSR variant. Overall, while the quantitative results differ by country, the ranking of policy instruments and general qualitative conclusions, as described by the theoretical model, remains consistent across countries.

Figure 13: Numerical model results with equal economy-wide emission reductions



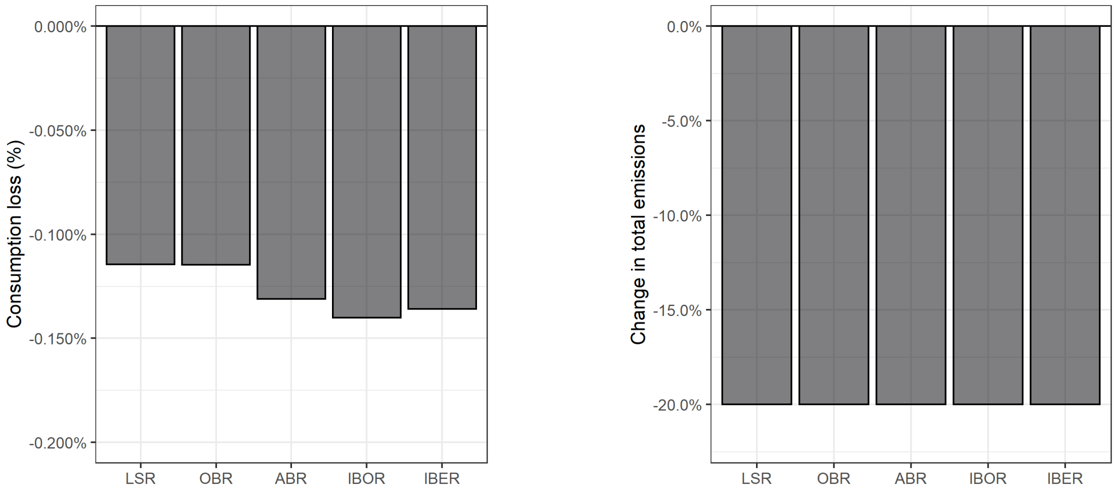
(a) Opportunity cost of CO_2 **(b)** Sector output



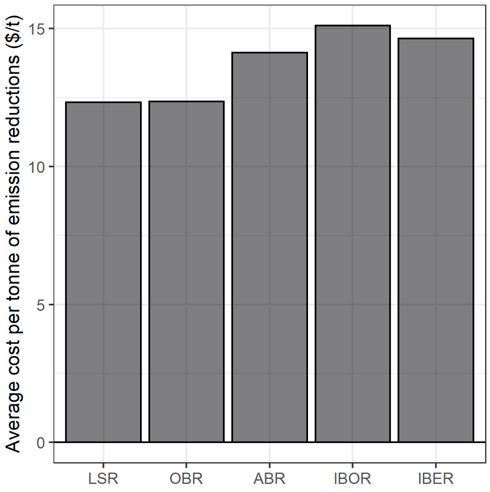
(c) Sector CO_2 **(d)** Sector CO_2 intensity

Note: Carbon price rebating scenarios are illustrated on the horizontal axis. Each of the policies achieves the same level of economy-wide CO_2 *emission reductions. The numerical model is disaggregated into 11 production sectors and 3 demand sectors, as shown in Table 3. For reporting, production sectors are aggregated into EITE and non-EITE aggregates. Panel 13a shows the opportunity cost associated with emissions of* CO_2*. Panel 13b shows the impact of each policy on sector output. Panel 13c shows the impact of each policy on sector* CO_2 *emissions. Panel 13d shows the impact of each policy on sector* CO_2 *intensity.*

Figure 14: Welfare impacts and economy-wide emissions reductions for alternative policies.



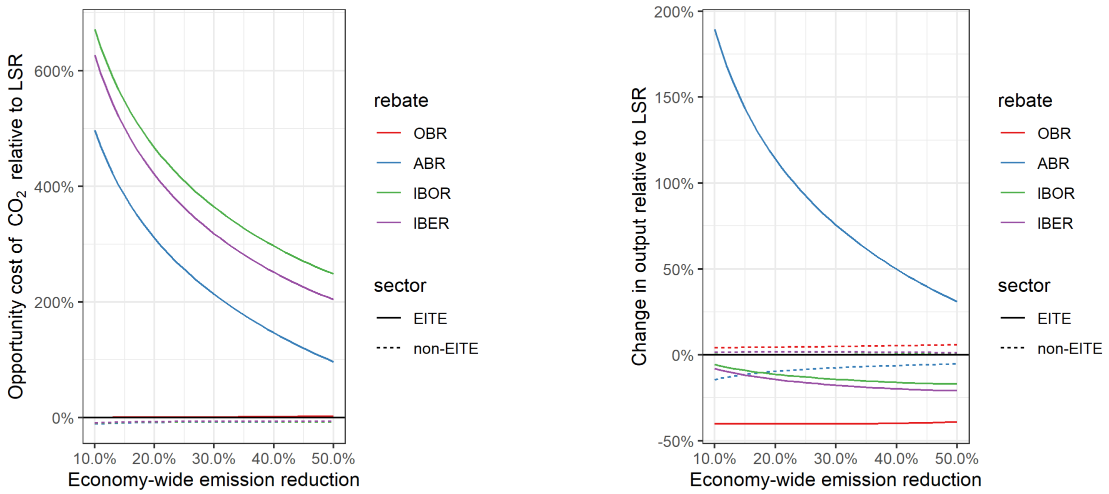
(a) Welfare **(b)** Economy-wide emissions



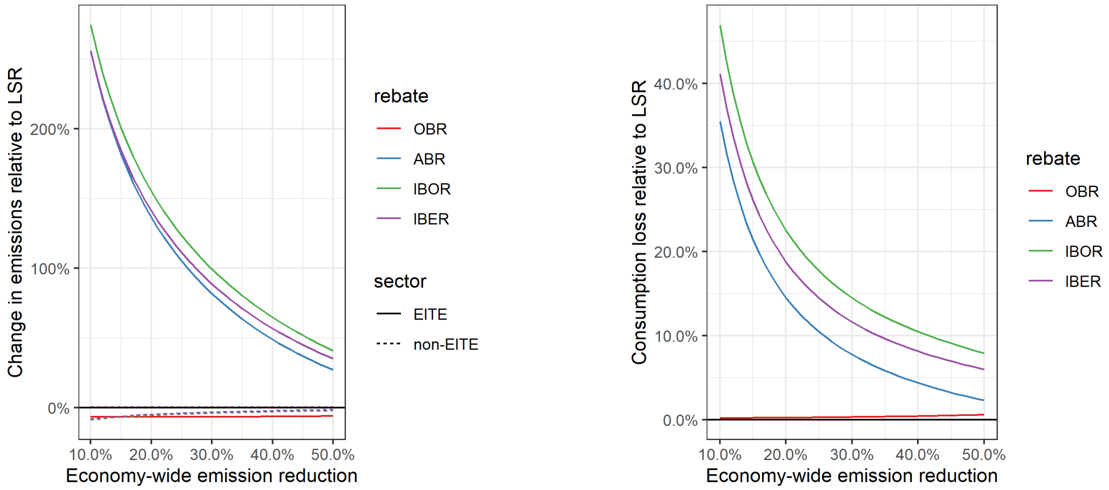
(c) Average cost of CO_2 reductions under each policy

Note: Carbon price rebating scenarios are illustrated on the horizontal axis. Each of the policies achieves the same level of economy-wide CO_2 *emission reductions. Welfare is determined as the Hicksian equivalent variation in income. The welfare measure does not include the social benefit of* CO_2 *emissions reductions and is thus incomplete.*

Figure 15: Relationship between stringency of carbon pricing and outcomes by policy design



(a) Emissions price **(b)** Output



(c) Emissions **(d)** Welfare

Note: Each panel reports the results from numerical simulations with different economy-wide emission reduction targets. Panel 15a shows the opportunity cost CO_2 *emissions by sector under different rebating approaches relative to the opportunity cost of* CO_2 *emissions under lump-sum rebating. Panel 15b shows the impact of carbon pricing on output by sector under different rebating approaches relative to the impact of carbon pricing on output under lump-sum rebating. Panel 15c shows* CO_2 *emissions by sector under different rebating approaches relative to* CO_2 *emissions under lump-sum rebating. Panel 15d shows the impact of carbon pricing with different rebating approaches on welfare relative to the impact of carbon pricing with lump-sum rebating on welfare.*

Figure 16: Output of EITE sectors under carbon pricing with different rebate schemes relative to LSR in different countries

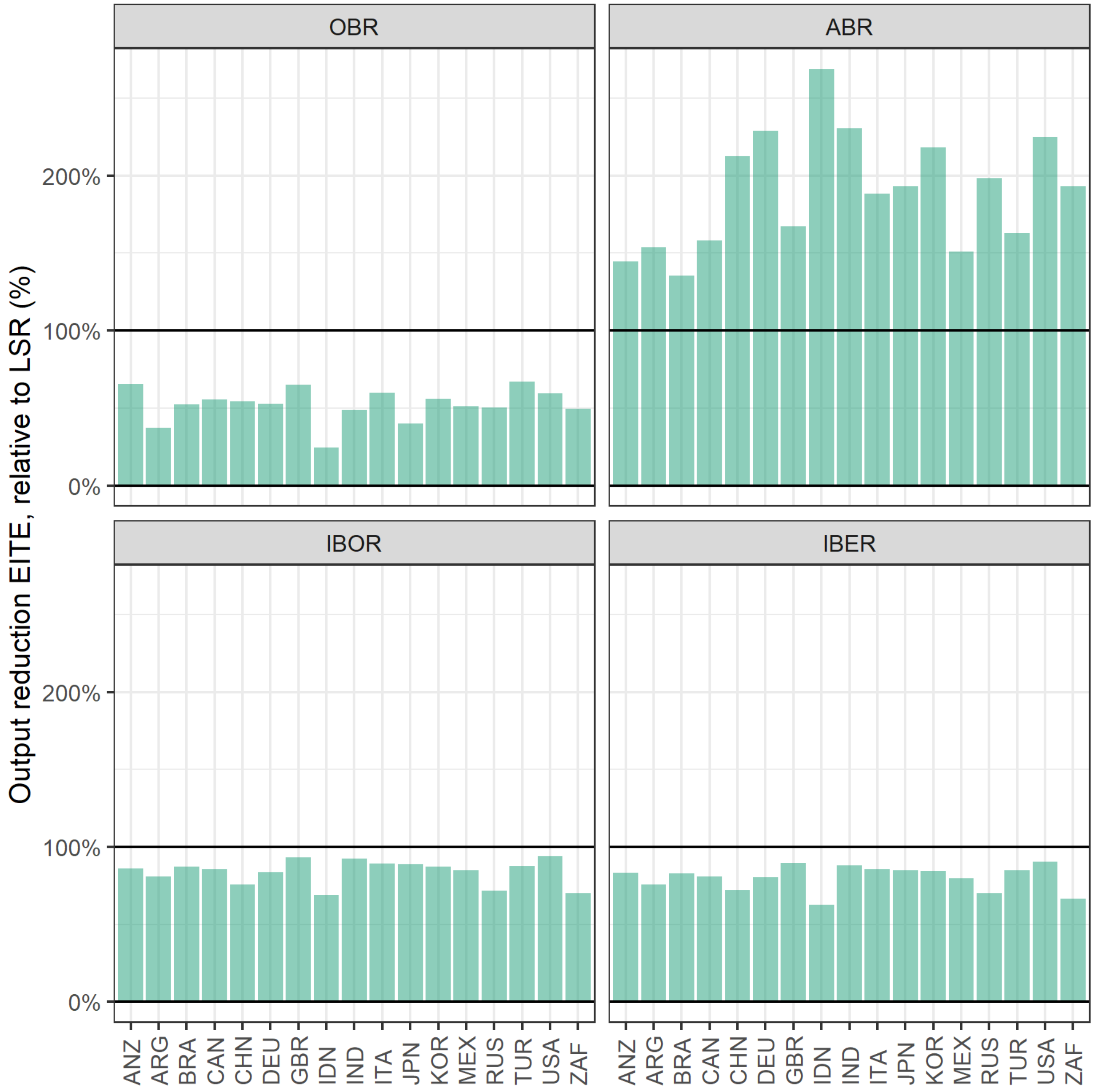
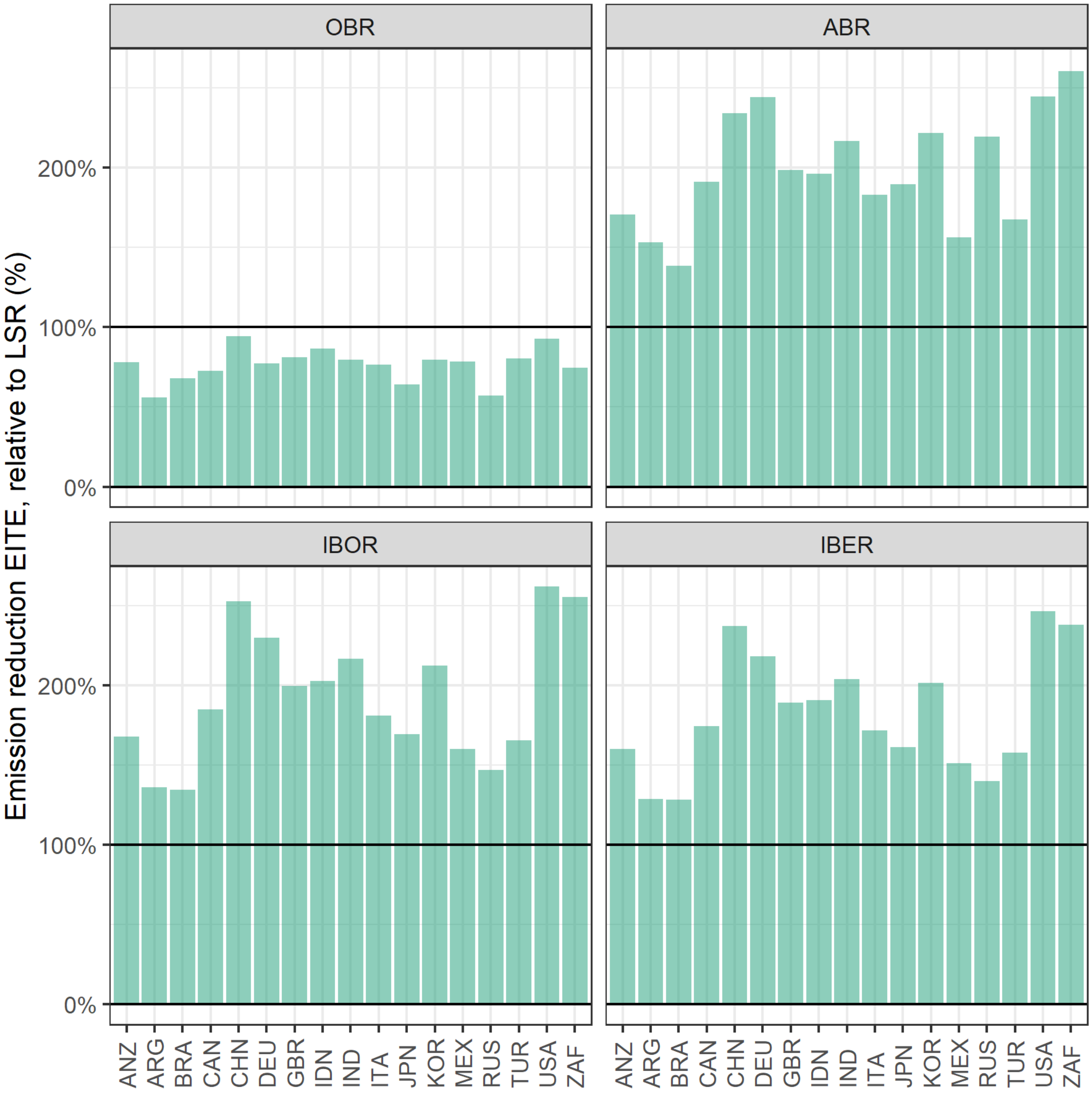


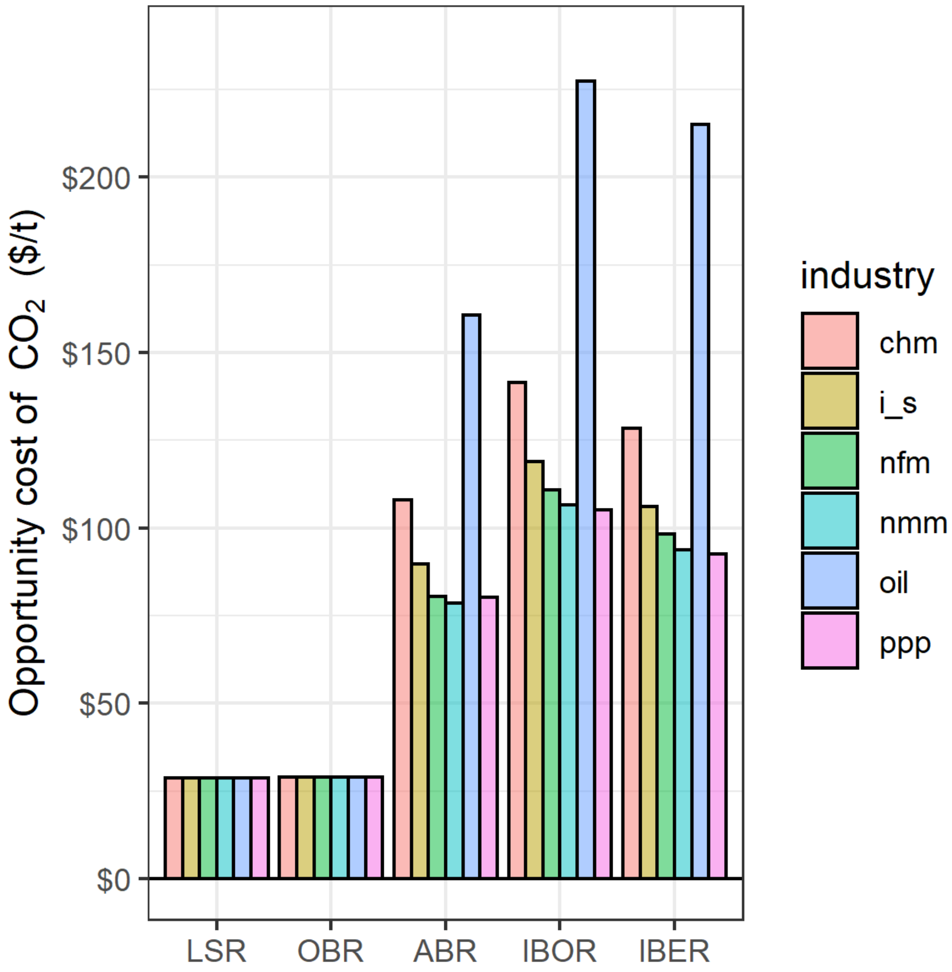
Figure 17: CO_2 emission reduction in EITE sectors under carbon pricing with different rebate schemes relative to LSR in different countries



C.4 Sector-level results

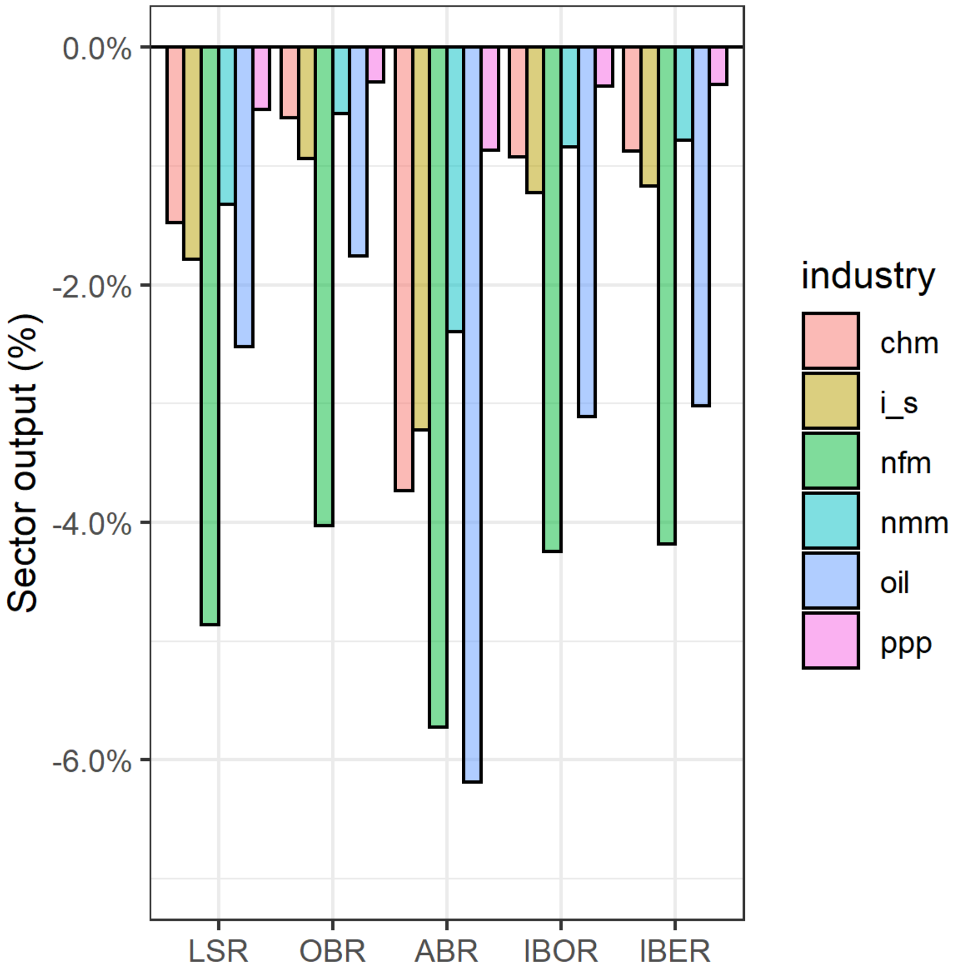
For ease of exposition, the main results grouped all sectors exhaustively into EITE and non-EITE groups. In this section, we disaggregate results for EITE subsectors, corresponding to the main simulations in Figure 5. Figures 18 to 20 show that within the EITE sector aggregate, there is substantial heterogeneity in how individual sectors respond to different policies. For each policy variant we examine, the oil sector and chemicals sector reduce emissions by a smaller amount than other sectors (Figure 20). As a result, the opportunity cost of CO_2 is higher under these sectors for ABR, IBOR, and IBER policy variants (Figure 18). Sector output falls by the largest amount for the nonferrous metals and oil sectors, and varies substantially among policy variants (Figure 19). In general, the main conclusions hold within the disaggregated EITE subsectors; notably, the intensity-based and abatement-based policies provide a larger incentive for reducing output and thus larger CO_2 emission reductions than the LSR and OBR policies, and at the same time, the intensity-based policies cause less reductions in EITE sector output compared with the LSR policy.

Figure 18: Disaggregated numerical model results showing opportunity cost of CO_2 emissions



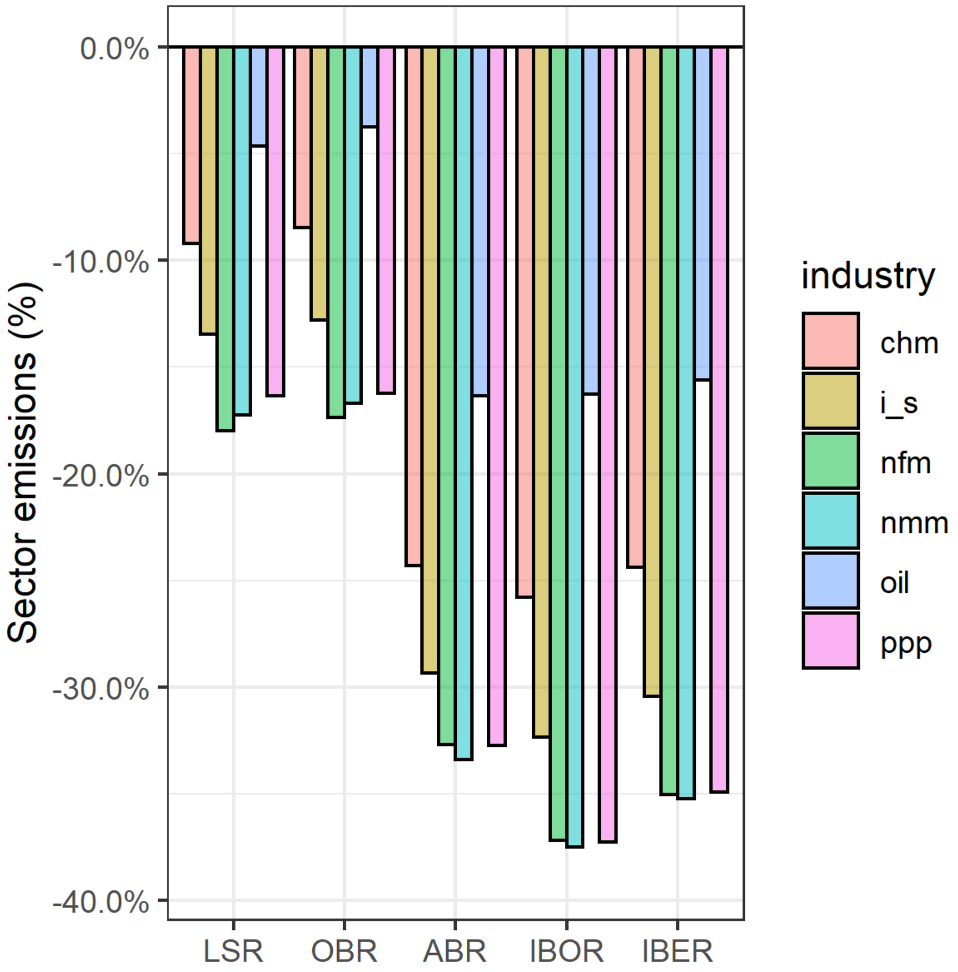
Note: The figure corresponds to Figure 5a in the main text and shows the opportunity cost of CO_2 *emissions in each industry that makes up the EITE sector aggregate.*

Figure 19: Disaggregated numerical model results showing sector output change from carbon pricing.



Note: The figure corresponds to Figure 5b in the main text and shows the impact of carbon pricing on output in each industry that makes up the EITE sector aggregate.

Figure 20: Disaggregated numerical model results sector emission change from carbon pricing.



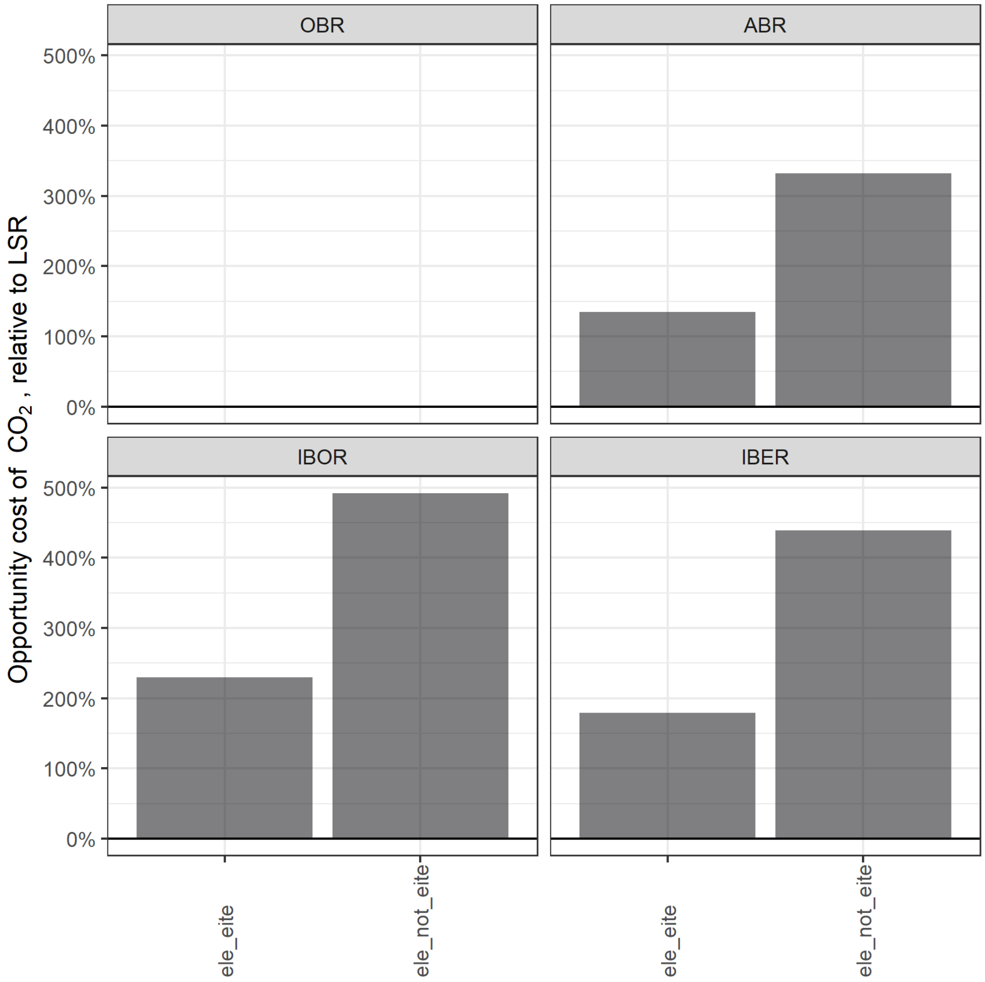
Note: The figure corresponds to Figure 5c in the main text and shows the effect of carbon pricing on CO_2 *emissions in each industry that makes up the EITE sector aggregate.*

C.5 Treatment of electricity sector

In our main results, we excluded the electricity sector from the set of EITE sectors, consistent with the way that EITE sectors are typically defined (electricity is not highly traded typically). However, in some cases, the electricity sector is included in the set of EITE sectors. For example, in the Canadian federal carbon price, output-based rebates are extended to the electricity sector as well as other energy-intensive sectors. Because of the large emissions contribution of the electricity sector in the United States, and because of the unique sensitivity of the electricity sector to carbon pricing (by cost-effectively displacing coal-fired electricity generation), our results are highly impacted by this decision. In this subsection, we show how the results of our policy analysis are affected depending on the treatment of the electricity sector. We simulate each policy variant such that the policy achieves a 20 percent economy-wide reduction in emissions. We contrast results when the electricity sector is and is not included in the set of EITE sectors.

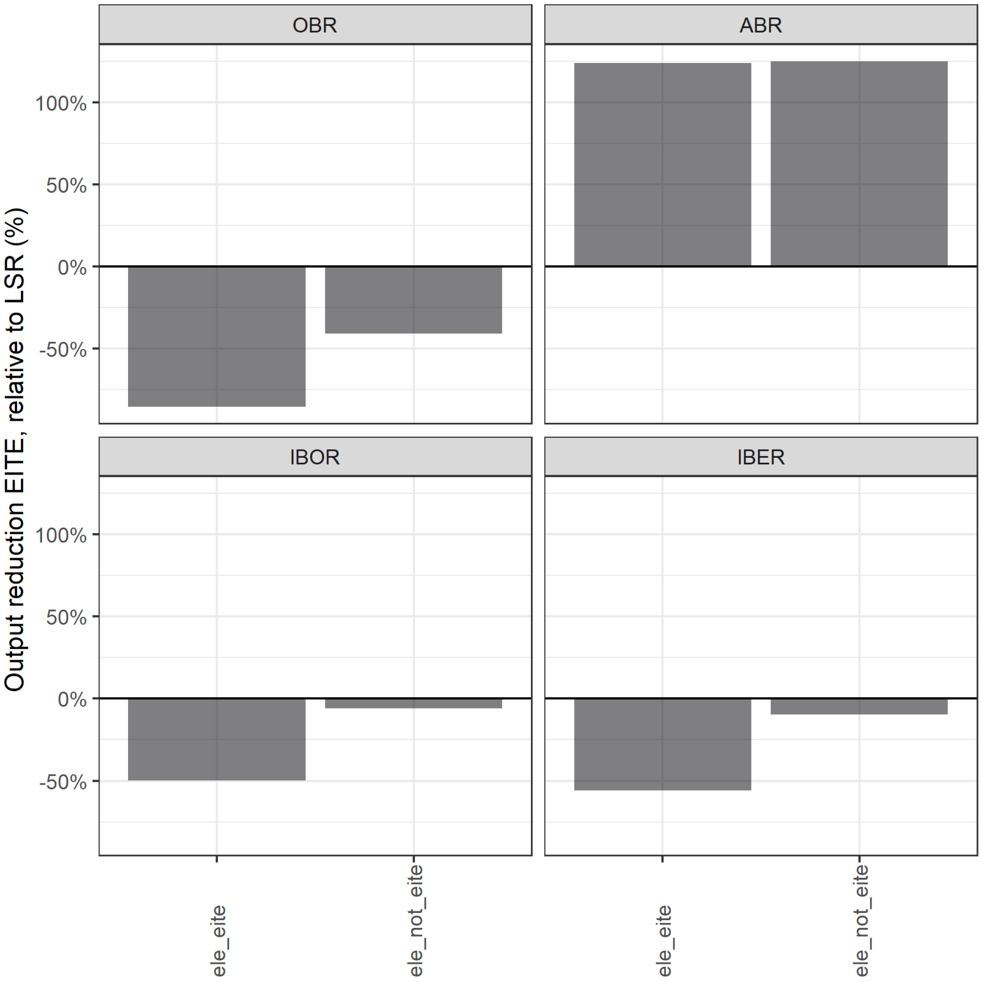
Results are provided in Figures 21–23. When the electricity sector is included in the EITE sectors, emissions in those sectors fall substantially when carbon prices are applied (and emissions in non-EITE sectors, which now exclude electricity, fall by less). Output in EITE sectors actually increases under intensity-based policies when the EITE sector includes electricity. Finally, carbon prices are much lower in the EITE sectors when the electricity sector is included as an EITE sector. Despite the large numerical changes resulting from differences in the treatment of the electricity sector, the rankings and qualitative conclusions remain essentially the same: notably, that the intensity-based policy variants achieve larger reductions in emissions in the targeted sectors compared with LSR and OBR, and they achieve smaller reductions in sector output compared with LSR.

Figure 21: Numerical model results highlighting the sensitivity of treatment of the electricity sector on opportunity cost of CO_2 associated with different carbon pricing rebates.



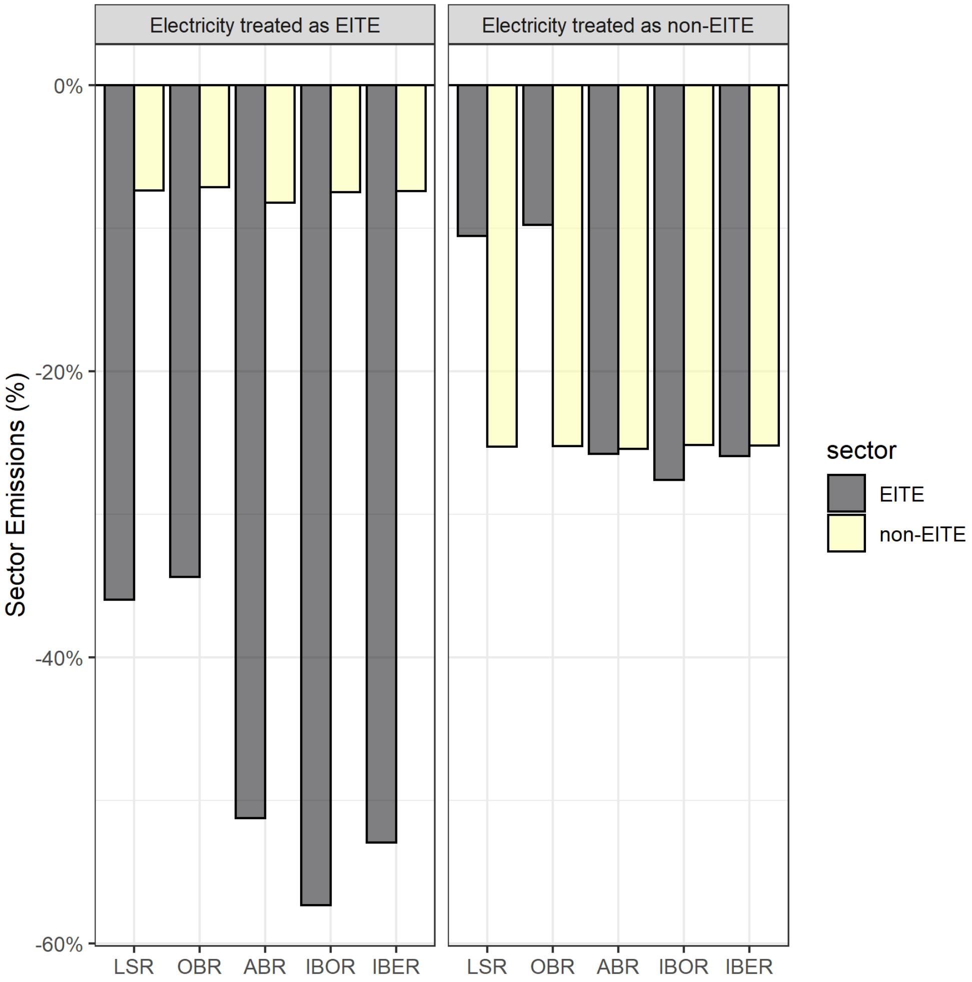
Note: The left-hand panel shows results when the electricity sector is treated as an EITE sector and eligible for rebates as described in the text. The right-hand panel shows results when the electricity sector is treated as a non-EITE sector. All policies achieve the same level of economy-wide CO_2 *emissions (20 percent reduction from baseline levels).*

Figure 22: Numerical model results highlighting the sensitivity of treatment of the electricity sector on the effect of different carbon pricing rebates on sector output.



Note: The left-hand panel shows results when the electricity sector is treated as an EITE sector and eligible for rebates as described in the text. The right-hand panel shows results when the electricity sector is treated as a non-EITE sector. All policies achieve the same level of economy-wide CO_2 *emissions (20 percent reduction from baseline levels).*

Figure 23: Numerical model results highlighting the sensitivity of treatment of the electricity sector on the effect of different carbon pricing rebates on sector CO_2 emissions.



Note: The left-hand panel shows results when the electricity sector is treated as an EITE sector and eligible for rebates as described in the text. The right-hand panel shows results when the electricity sector is treated as a non-EITE sector. All policies achieve the same level of economy-wide CO_2 *emissions (20 percent reduction from baseline levels).*

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