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On the Scope for Output-Based Rebating in Climate Policy

When Revenue Recycling Isn't Enough (or Isn't Possible)

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On the Scope for Output-Based Rebating in Climate Policy: When Revenue Recycling Isn't Enough (or Isn't Possible)

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Abstract

The allocation of tradable emissions permits has important efficiency and distributional effects in the presence of preexisting distortions. Three such imperfections are noteworthy for the "downstream" implementation of a domestic emissions trading program for greenhouse gases: 1) distorting labor taxes in the economy, 2) emissions "leakage" due to the lack of comparable emissions pricing abroad, and 3) incomplete coverage of the trading program, which allows domestic leakage. Because regulations that raise the price of covered sector goods exacerbate these problems, a potential response is to combine the emissions price with a rebate to production, such as by output-based allocations (OBA) of emissions permits. We employ a multi-sector computable general equilibrium model based on the GTAP framework to compare different rules for allocating carbon allowances among the major emissions-intensive sectors within a trading program in the U.S. economy. We find that OBA for energy-intensive, trade-exposed sectors can dominate auctioning with revenue recycling, both from a domestic and a global welfare perspective. Granting similar rebates to the electricity sector tends to reduce welfare when those revenues would otherwise be recycled, but it can enhance welfare if the allowance values would otherwise be grandfathered.

Key Words: emissions trading, output-based allocation, tax interaction, carbon leakage

JEL Classification Numbers: Q2, Q43, H2, D58, D61

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Introduction

In designing an emissions cap-and-trade program, allocating the allowances—and the financial values that go with them—is not only an important political question but also a key economic issue. Beyond the distributional questions of who may receive the rents, allocation also can have important effects on economic efficiency. Only in the absence of any other market distortions do auctioned and grandfathered permits lead to the same outcomes. Furthermore, allocation mechanisms that seem distorting in simple settings—because they are updated over time rather than in lump-sum distributions—can enhance efficiency in other settings.

For emissions of the greenhouse gases (GHGs) that contribute to global climate change, the allocation issues become even more important, due in part to the unprecedented scope of these emissions in the economy. The Energy Information Administration (EIA) places a central estimate of the value of allowances in the American Clean Energy and Security Act of 2009 (ACESA) at $160 billion in 2020 (EIA 2009). Not only are the stakes large from a distributional perspective, but climate policy also suffers from interactions with important preexisting distortions in the economy and challenges particular to GHGs, which are global pollutants emitted by many sectors and jurisdictions.

Among U.S. policymakers, an important criticism of the Kyoto Protocol was the lack of binding emissions targets for major emitters among developing countries. In particular, energy-intensive industries worry that a cap-and-trade program for carbon dioxide (CO_2) or any other policy that levies a price on domestic emissions alone will distort the playing field with their competitors in nonparticipating countries. Policymakers express concern that such trade impacts will result in a partial undoing of their efforts to reduce emissions, known as "carbon leakage."

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Nor is leakage strictly an international phenomenon. Distortions also can arise within the domestic economy if the environmental policy is unevenly applied due to technical, administrative, or other concerns. Sectors covered by the cap-and-trade program may fear a reallocation of resources toward the uncovered sectors, which then also would require additional or more stringent regulations.

Bernard et al. (2007) show that when other emitting sectors can be neither regulated nor taxed, the next best policy is to subsidize the output of the regulated sectors. The optimal subsidy then reflects the value of the emissions crowded out by additional output in that regulated sector. Fischer and Fox (2009) extend this analysis to include preexisting tax distortions in the economy. Labor taxes distort the consumption–leisure trade-off, and environmental regulation that further raises consumer prices exacerbates those costs (a collection of the literature is available in Goulder 2002). By limiting those price increases, policy mechanisms that combine an output rebate with the emissions price reduce the tax interaction effect, as well as the leakage effect. Fischer and Fox (2009) solve for optimal rebates in conjunction with a carbon tax and show that they are higher for goods that are stronger complements with employment and stronger substitutes for unregulated goods, such as in energy-intensive, trade-exposed (EITE) manufacturing sectors.

One way to implement such a subsidy in a traditional emissions cap-and-trade program is to update the allocation of permits to firms within the affected sectors based on their output (which we will refer to as "output-based allocation," or OBA). The value of additional permits represents an incentive to produce more, offsetting part of the price increase induced by the emissions regulation itself. Another way is by setting performance standards; in this case, each sector must meet an average emissions requirement. Theoretically, the effect is identical—each firm must surrender permits according to its emissions and receives an allocation according to its output. In a context with tax interactions, researchers have shown that performance standards can outperform a system of grandfathered emissions permits (Goulder et al. 1999; Parry and Williams 1999; Fullerton and Metcalf 2001). However, in practice it is difficult to set performance standards such that marginal costs equalize, unless the permits are also tradable across sectors. It is more difficult to ensure that regulated firms meet a particular emissions target. Even assuming so, it is not assured that performance standards will be preferred to grandfathering; in an application to the Canadian economy, Dissou (2005) finds that performance standards can mitigate losses in gross domestic product, but welfare turns out to be lower relative to grandfathered permits.

In an international context, trade distortions can be as important as tax distortions: an emissions trading program that covers all domestic sectors but not trade partners allows carbon to "leak" as production shifts to unregulated producers. Still, for OBAs, earmarking based on emissions needs may not be the best solution. Fischer and Fox (2007) consider the effects of different allocation mechanisms, including OBA, on the efficiency and distributional results of a U.S. carbon emissions trading program when both tax and trade distortions are taken into account. They also consider a form of OBA in which the sectoral distributions are based on value-added, rather than emissions, shares. In a comprehensive domestic cap-and-trade program, this option generates effective subsidies similar to a broad-based tax reduction, performing nearly like auctioning with revenue recycling, which generates the highest welfare. OBA tied to historical emissions supports the output of more polluting industries, which more effectively counteracts carbon leakage, but is more costly in welfare terms, even taking global emissions changes into account. While the other policies always dominate grandfathering, OBA tied to historical emissions does so only at lower levels of policy stringency.[1]

Although OBA can dominate grandfathering in some cases, all the reviewed studies find auctioning with revenue recycling always to be the preferred policy in terms of welfare. However, these studies do not consider differentiated allocation policies—that is, the targeting of rebating to specific sectors most prone to leakage. Nor do they consider the role of incomplete coverage of domestic emissions. Fischer and Fox (2007) do find that combining different rules for determining sector targets with OBA can significantly affect the efficiency of the cap-and-trade program, as well as the degree of leakage. The results of Fischer and Fox (2009) indicate that optimal rebates do vary by sector, suggesting larger rebates are appropriate for EITE sectors; furthermore, the scope of domestic coverage of the cap-and-trade program also influences optimal rebates for upstream energy-intensive sectors, since non–energy-intensive sectors (and their foreign competitors) also are sensitive to the allocation regime.

We thus extend these works by incorporating all three major policy and market imperfections that can justify support for output in combination with an emissions pricing program: (1) lack of comparable policies abroad, (2) incomplete regulatory coverage at home, and (3) tax interaction. In contrast to previous studies, which find a preference for 100 percent

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[1] These latter results echo those of Jensen and Rasmussen (2000), who simulate OBA of emissions permits based on historical emissions for Denmark. They find that OBA limits sectoral adjustment but imposes greater welfare costs than grandfathered permits.

auctioning with revenue recycling, we find that OBA targeted to EITE sectors can generate higher welfare and lower emissions leakage. Granting OBAs to important but less trade-intensive sectors like electricity also can further lower leakage, but at a significant welfare cost if the remaining allowance revenues would otherwise be recycled to lower distorting taxes in the economy. On the other hand, if those allowances would otherwise be grandfathered, OBA to the electricity sector can raise welfare; by keeping prices down and real wages from falling, this policy mitigates interactions with preexisting tax distortions.

Theoretical Background

The theoretical model we use is similar to the optimal tax problem derived in Fischer and Fox (2009). They consider a simple economy with two sectors (one with emissions regulation and one without), two goods, and two factors of production (labor and emissions). Utility is a function of consumption of the two goods, leisure, and damages from emissions. Under the constraint that only one of the goods can be regulated and/or taxed, Fischer and Fox (2009) solve for the optimal tax combination. They find that with the second policy tool available, the optimal emissions tax on the regulated good is the standard Pigouvian tax, equal to the marginal damages. Given that emissions tax, the optimal rebate has two components. First, it internalizes the marginal damages of the emissions generated by the substitution of consumption away from the regulated good toward the unregulated good. Second, the rebate is needed to counteract the tax interaction problem. Thus, a subsidy to the regulated sector to prevent emissions leakage and tax interaction is preferred to full recycling of the environmental tax revenues.

When the emissions regulation is a cap-and-trade program rather than a Pigouvian tax, some subtle differences arise. We therefore reprise this optimal rebate problem in the context of a cap-and-trade regulation. The full model and derivations are presented in the Appendix.

Suppose the government has made a commitment to cap emissions in the regulated sector (sector 1) at a certain level. However, the unregulated sector (sector 2) does not face a cap, emissions tax, or even a production tax. In this case, can subsidizing production in the regulated sector raise welfare?

The essence of the problem can be seen by totally differentiating welfare, recalling that with the cap, emissions in sector 1 do not change. Using the marginal consumer and producer responses, derived from their decentralized optimization problems, the marginal welfare impacts (dW) of a change in the subsidy rate to sector 1 (s_1), relative to the marginal utility of consumption, λ) are shown in the Appendix to be:

$$\frac{dW}{ds_1}/\lambda = -s_1\frac{dC_1}{ds_1} - \left(\frac{D'}{\lambda}\right)m_2\frac{dC_2}{ds_1} + t_L\frac{dL}{ds_1}\ .$$

Where dC_1 and dC_2 are the general equilibrium changes in consumption of good 1 and good 2, respectively, D' is the marginal damage of emissions, m_2 is the emissions intensity of the unregulated sector, t_L is the labor tax rate, and dL is the general equilibrium change in labor supply.

Using the Chain Rule, we see that welfare is increasing in the subsidy to the regulated sector as long as that subsidy does not exceed the marginal benefits of avoided emissions leakage and tax interaction:

$$s_1 \le \underbrace{\left(\frac{D'}{\lambda}\right)m_2\left(-\frac{dC_2}{dC_1}\right)}_{\text{leakage impact}} + \underbrace{t_L\frac{dL}{dC_1}}_{\text{tax interaction}}\ .$$

If the goods are substitutes, $dC_2/dC_1 < 0$ and positive leakage occurs. The net tax interaction effect also tends to be positive, although it depends on the relative prices and substitutability. Intuitively, the subsidy mitigates tax interaction by keeping the prices of the regulated product from rising; on the other hand, the effect is limited, since it does detract from unregulated products and in equilibrium tends to drive up labor taxes by foregoing emissions revenue. Greater substitutability between products then exacerbates leakage, which increases the optimal subsidy, and reduces tax interaction costs, which tempers the optimal subsidy.

A few important general equilibrium effects operate behind the scenes in this approach. One is that the labor tax is endogenous to the emissions policy; the more allowances are allocated, the lower are emissions revenues to the government, which must be made up with a higher labor tax. Thus, the larger the allowance allocations are, the larger the tax interaction effect is—and the optimal subsidy. Furthermore, the labor tax rate also influences the labor supply, and income changes affect consumption and leisure decisions; therefore, an auctioned cap can have different sensitivities of consumption, labor, and emissions to price changes than a grandfathered cap.

Finally, rebates also increase the equilibrium emissions price.[2] As production in the regulated sector increases with the subsidy, so do emissions; as a result, to meet the same emissions target, the price must rise.

If we consider the typical case of 100 percent earmarking (and therefore no revenue recycling) so that we restrict $s_1C_1 = \tau_1E_1$, then the labor tax rate equals the government revenue requirement per unit of labor ($t_L = G/L$), and welfare improves with OBA if

$$\tau_1 m_1 \leq \underbrace{\left(\frac{D'}{\lambda}\right) m_2 \left(-\frac{dC_2}{dC_1}\right)}_{\text{leakage impact}} + \underbrace{\frac{G}{L}\frac{dL}{dC_1}}_{\text{tax interaction}} .$$

In sum, rebates are more likely to enhance welfare the stronger substitutes are the goods (larger $-dC_2/dC_1$), the more emissions intensive is the unregulated good relative to the regulated one (m_2/m_1), the less completely priced is the emissions externality ($(D'/\lambda)/\tau_1$), and the stronger is the tax interaction effect. Furthermore, the more that rebates drive up the emissions price, the less likely this condition will be met. For example, OBA is more likely to be welfare enhancing for trade-exposed sectors with more emissions-intensive competitors than in sectors like electricity, which have weak international substitutes, have larger influence on allowance prices, and are often complementary with uncapped domestic sectors.

Numerical Model and Scenarios

While the above analysis establishes that OBA can be welfare enhancing in theory, a detailed computable general equilibrium (CGE) model is needed to quantify the potential welfare, production, emissions, and leakage effects of practical designs for climate policy, particularly in a multijurisdictional setting. In this section, we employ such a model to simulate the effects of a domestic cap-and-trade program for the United States. We then consider how different rebate regimes perform relative to auctioned or grandfathered permits and how those rankings depend on the cap-and-trade program's scope of coverage.

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[2] This result is evident in the Appendix, by totally differentiating the producer first-order condition with respect to emissions. Formally, $d\tau_1/ds_1 = -\left(\partial^2 L_1(Q_1, E_1)/(\partial E_1 \partial Q_1)\right) dC_1/ds_1 > 0$.

Model Description

We employ a modified version of the model that Fischer and Fox (2007) use. This CGE model from the Global Trade Analysis Project (GTAP) offers a richness in calculating trade impacts that allows us to evaluate the distributional and efficiency effects of emissions permit allocation mechanisms, spanning a more diverse and disaggregated set of energy-using sectors than in most climate models. The model does not incorporate dynamic responses, project energy use into the future, or allow for technological change. It does allow, however, for capital reallocation.[3] As such, our results should be considered illustrative of short- to medium-term effects (say, 3–5 years, a relatively short perspective for climate policy) on different sectors of implementing a carbon cap-and-trade program using different allocation mechanisms for emissions permits. Our impacts of interest include CO_2 emissions, production, trade, and employment by sector, as well as carbon leakage and overall welfare, both in the United States and abroad.

The model and simulations in this paper are based on version 5.4 of the GTAPinGAMS package developed by Thomas Rutherford and documented for version 4 of the dataset and model in Rutherford and Paltsev (2000). The GTAP-EG model serves as the platform for the model outlined here. The GTAP-EG dataset used is a GAMS dataset merging the GTAP economic data with information on energy flows. We adapt the framework to employ the latest official release of the GTAP database, version 7.0, which updates the analysis to 2004, the base year of the latest GTAP database. Complainville and van der Mensbrugghe (1998) provide a more complete discussion of the energy data used.

The model is a multi-sector, multi-region general equilibrium model of the world economy as of 2004. We include energy requirements and their corresponding carbon emissions into this framework. The production function incorporates most intermediate inputs in fixed proportion, although it builds energy inputs into a separate energy nest. For the chemicals sector, which includes petrochemicals, we divide its energy use into feedstock requirements, which are

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[3] In the default setting, capital reallocation occurs within, not across, regions. Paltsev (2001) conducts sensitivity analysis with respect to this assumption and finds that the carbon leakage rate does not change significantly with greater international capital mobility.

treated as intermediate inputs, and the remainder, which is treated as energy, using the feedstock use ratios for oil and gas given by Lee (2002). We also use EIA data to set the feedstock ratio.[4]

We incorporate process emissions into the modeling framework for refined petroleum and coal products; chemicals; iron and steel; and non-ferrous metals. We draw these data from EPA sources.[5] Process emissions are produced in fixed proportions with the activity level of the corresponding sector. For other countries and regions in the model, we apply the same intensity of emissions measured in CO_2 per dollar to production. Once we account for energy feedstocks and include process emissions, we benchmark total emissions per country or region to 2004 emissions data from the EIA.[6]

We make certain adjustments to the extractive energy sectors to calibrate supply elasticities. In other sectors, capital is fully mobile; however, in the extractive sectors, capital is divided between a fixed portion (the natural resource) and mobile capital. These splits are adjusted so as to target particular elasticities of supply: 0.8 for crude oil, 2.0 for natural gas, and 2.5 for coal.

Energy use in production is a constant elasticity of substitution function nested to three levels. At the lowest level, oil and gas easily substitute (2.0) for one another to form a composite. The oil and gas composite then is a complement (0.5) with coal, forming a non-electric energy composite. Lastly, non-electric sources have very low substitutability (0.1) for electricity to form the energy composite. Energy in turn is a complement (0.5) to the labor-capital composite from the value-added nest. Within the value-added nest, labor, private capital, and public capital have unitary elasticity. Foreign and domestic varieties are substitutable for one another through a standard Armington structure, with the elasticity of substitution between the domestic variety and foreign composite set to half the elasticity of substitution among foreign

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[4] Lee (2002) proposes a feedstock ratio of 0.9148 for petroleum and coal products used in the U.S. chemicals sector, while EIA data indicate that for 2004 the ratio is 0.5270. We employ the latter. U.S. Energy Information Administration, Manufacturing Energy Consumption Survey for 2006, Tables 1.1 and 2.1. See http://www.eia.gov/emeu/mecs/contents.html.

[5] Process emissions in millions of metric tons of CO_2 equivalent for 2004 are as follows: chemicals: 49.8; iron and steel: 50.9667; non-ferrous metals: 7.7667; non-metallic minerals: 61.0000; petroleum and coal: 3.8667. “Data Annex to Interagency Report on Competitiveness and Emission Leakage”. See http://www.epa.gov/climatechange/economics/economicanalyses.html#interagency.

[6] Emissions are scaled up by a range of 10.8–40.1 percent to match EIA emissions data. Energy Information Administration, *International Energy Annual 2006*, table H.1co2. See http://www.eia.doe.gov/iea/.

varieties. We derive the latter elasticities from econometrically based estimates as given by Hertel et al. (2004).

Consumption is a composite of goods, services, and, in our modification, leisure. The energy goods oil, gas, and coal enter into final demand in fixed proportions in the energy nest and are unitary elastic with electricity. This composite is then substitutable at 0.5 with other final demand goods and services. Goods and services (including energy) are then substitutable against leisure; the derivation is given by Fischer and Fox (2007) and Fox (2002).

Government demand is represented by a similar demand structure and private consumption, with the exception of the labor–leisure component. Government demand is held fixed through all of the experiments, although the funding mechanism (adjustment of a lump-sum tax or the tax on labor) varies as noted below.

Three features added to the GTAP-EG structure allow us to model the impact of the policy scenarios. First, we add a carbon price that is applied to the covered sectors. Second, we incorporate the appropriate structure for simulating an output-based allocation scheme. Third, we give the household a labor–leisure choice so that labor taxes are distorting, allowing us to conduct simulations that recycle revenue from pollution permits to offset the distorting tax instrument. Since we have no data on labor taxes within the GTAP-EG database, we assume a labor tax rate of 40 percent within Annex B countries and a 20 percent tax rate within all other countries and the rest of the world.

To incorporate the pollution permit requirement, we introduce the carbon permit as a Leontief technology in an additional composite fossil fuel nest to production in the covered sectors. The composite of permit and energy input is then included in the production block for the output good. In this manner, one permit is demanded for each unit of carbon that enters into production, and we can track pollution permits through the model.

To model output-based allocation, we incorporate a distortion in the form of an endogenous tax into the sector’s production function. This tax allows us to mimic the impact on the firm of an output-based subsidy. The value of the subsidy is determined by constraints that establish the carbon price and the per-unit allocation.

Policy Scenarios

Our scenarios for targets and allocation options are largely inspired by the ACESA legislation and other proposals. However, we do not model the legislation precisely, since the full proposals include a variety of companion features including offsets, technological support and standards that our model ignores.

Sector Coverage

We consider two kinds of sector coverage: a first scenario in which the United States adopts an economy-wide emissions trading program, as in ACESA, and a secondary scenario in which it adopts an emissions trading program similar in form to the EU Emissions Trading Scheme (EU ETS) in terms of its sector coverage. This latter scenario follows the middle-of-the-range of earlier proposals that target major point-source emitters.[7] In both cases, we assume unilateral implementation by the United States (i.e., the EU ETS is not present). We model the regulation as a simple carbon permit requirement on the use of all final energy goods in the model—coal, refined petroleum products, or natural gas—as well as process emissions.

The energy-intensive sectors always subject to the cap are two energy sectors, electricity (ELE) and refined petroleum and coal products, as well as the following five energy-intensive manufacturing industries, also known as the energy-intensive, trade-exposed (EITE) sectors:

- chemical industry (CRP);
- non-metallic minerals (NMM), which include cement, glass and ceramics;
- paper, pulp, and print (PPP);
- iron and steel industry (I_S); and
- non-ferrous metals (NFM), including copper and aluminum.

Energy-intensive sectors represent 54 percent of U.S. CO_2 emissions, according to the data. The aggregate of non-energy-intensive sectors (non-EI) includes other manufacturing, extractive industries, services, transportation, and final demand. Services represent the majority

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[7] Among the major climate change legislation put forth in the 110th and 111th Congresses, coverage has ranged from the electricity sector alone in Feinstein–Carper (S. 317: Electric Utility Cap and Trade Act of 2007 and S. 1177: Clean Air Planning Act of 2007) and Carper–Alexander (S. 2995: Clean Air Act Amendments of 2010) to major sources or sectors in Lieberman–McCain (S. 280: Climate Stewardship and Innovation Act of 2007) and Kerry–Snowe (S. 485: Global Warming Reduction Act of 2007); and from the Sanders–Boxer bill (S. 309: Global Warming Pollution Reduction Act), which leaves the decision to EPA; to a comprehensive upstream program in Bingaman–Specter (S.1766: Low Carbon Economy Act of 2007) and several proposals in the 111th Congress, including ACESA. For example, Lieberman–McCain foresees that only emitters responsible for more than 10,000 metric tons of CO_2, or about 2,700 metric tons of carbon, are subject to a cap-and-trade system.

of the economic value, while transportation and final demand represent over 80% of the non-EI emissions.

Covered sectors are assumed to be covered in their entirety. Since our database provides only aggregate information, this assumption may overstate somewhat the magnitude of covered pollution, depending on the distribution of firm size within each of these sectors. On the other hand, it might also understate coverage somewhat if some firms outside these sectors would be included in an EU-style regulation.

Defining the Cap

We set the basic policy goal to be equivalent to a 20 percent reduction of CO_2 emissions for the covered sectors from the base-year level (2004 in our case). This target is roughly similar to the goals for 2020 set out in ACESA (of 17 percent reduction below 2005), the companion Senate proposals (20 percent reduction below 2005), and in the European Union (20 percent reduction below 1990). All further references to pollution in this paper are to the carbon equivalent of these CO_2 emissions.

We require all policy scenarios to meet this target reduction only in the covered sectors. However, with leakage, the benefits of each policy will vary, due to the different net reductions in emissions. While a fixed domestic cap is a more plausible policy design, to conduct welfare and sensitivity analysis, we require each policy to meet the same global emissions target, which allows for a more proper comparison of cost-effectiveness.

Permit Allocation

We consider a total of six allocation regimes. In one set, the default is that all allowances that are not allocated by OBA are auctioned, with the revenues recycled to lower labor taxes (“A”). In the other set, any allowance values not allocated based on output are grandfathered or otherwise distributed lump sum in the economy to households, firms, or any combination thereof (“G”). In this model, note that the apportionment of grandfathered allowances does not affect behavior; it merely determines the distribution of the rents, all of which are assumed to flow ultimately to households.

Then we consider three different kinds of allocation strategies:

(0): No output-based allocations.

(1): This scenario is a stylized version of the allocations just to EITE sectors in ACESA. Output-based allocations are given only to firms in energy-intensive manufacturing. Within each

EITE sector, total allocations are 80 percent of historical emissions, but they are distributed in proportion to output.[8] Furthermore, these historical emissions include direct energy and process emissions, as well as indirect emissions from electricity use.

(2): This scenario adds a stylized version of the allocation to the electricity sector in ACESA, which grants allowances to local distribution companies with a mandate to pass along the cost savings.[9] In our representation, OBAs are offered to firms in energy-intensive manufacturing and all electricity generation. Each EITE sector receives in total 80 percent of its *direct* historical emissions. Indirect emissions are not included because the electricity sector gets its own output-based allocation of 80 percent of its historical emissions, which it will pass on in lower prices to EITE and all other sectors. (ACESA adjusts the EITE indirect emissions allocations for the electricity-sector allocations).

Table 1. Allowance Allocation Scenarios

Abbreviation	*Scenario Description*
A0	100% auction with revenue recycling
A1	OBA to EITE (80% of baseline direct+indirect emissions), remaining 85% auctioned
A2	OBA to EITE+ELE (80% of baseline direct emissions), remaining 50% auctioned
G0	100% lump-sum allocation
G1	OBA to EITE, remaining 85% grandfathered
G2	OBA to EITE+ELE, remaining 50% grandfathered

Table 1 summarizes the six allocation scenarios. In all cases, permits are traded across the covered sectors, and government revenue is held constant through a labor tax. Table 2 presents the allocations calculated by the model for each sector, by scenario. Obviously, the largest difference in the two OBA scenarios is the allocation to the electricity sector, which takes two-fifths of the cap, meaning only half of the cap remains for revenue recycling or grandfathering, whereas five-sixths remain when OBA is restricted to the EITE sectors, even when they are granted allowances for both their indirect and direct emissions, on average.

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[8] The average allocation equals $.8M_0 / Q_1$, where M_0 is historical emissions and Q_1 is the new equilibrium output level; thus, the average allocation here may not necessarily equal average emissions under the cap.

[9] Although the legislation directs the local distribution companies to lower the fixed portion of the bill, it is unclear to what extent customers will recognize actual marginal cost changes; as a result, OBA may be a reasonable approximation.

Table 2. Allocations by Sector and Scenario

	Baseline direct emissions	*A1 and G1*		*A2 and G2*	
		Quantity allocated	*Percent of cap*	*Quantity allocated*	*Percent of cap*
Electricity	688,787	0	0%	551,029	41%
Refined Products	44,625	0	0%	0	0%
Chemical industry	84,342	104,151	8%	67,473	5%
Non-metallic minerals	35,850	34,838	3%	28,680	2%
Paper-pulp-print	17,288	30,781	2%	13,831	1%
Iron and steel industry	28,439	34,426	3%	22,751	2%
Non-ferrous metals	6,152	16,260	1%	4,921	0%
Energy-Intensive	*905,482*	*220,455*	*16%*	*688,685*	*51%*
Remaining	772,898	1,122,248	84%	654,018	49%
Total	**1,678,380**	**1,342,704**	**100%**	**1,342,704**	**100%**

Results

Consistent with the theoretical intuition, we find that even with labor tax distortions, auctioning permits to the covered sector and recycling the revenues is *not* the dominant strategy. Rather, OBA for energy-intensive manufacturing proves less costly and allows less leakage. However, the desirability of applying OBA to the electricity sector depends on how revenues would otherwise be used. We find that A2 is more distorting than A0, which represents a broader-based tax cut than redistribution through targeted rebating. However, G2 is better than G0, because lower ELE prices reduce labor tax interaction effect, and it also can dominate G1 in certain circumstances.

Effects of 20 Percent Domestic Reduction Target

Overall Economic Effects

Table 3 illustrated the effects on summary economic indicators for the United States. When the remaining allowances would be auctioned and the revenue recycled to lower labor taxes, OBA to the EITE sectors alone (A1) generates the smallest decrease in domestic economic welfare, as measured by equivalent variation (EV) and excluding any value of foreign emissions changes. Full auctioning (A0) follows, while including ELE in the OBA program (A2) is more costly than no OBA. However, conditional on remaining revenues being grandfathered, the more comprehensive OBA (G2) outperforms no OBA (G0). Full grandfathering (G0) is the most costly option, with twice the welfare decrease of the revenue-recycling scenarios.

Table 3. Percentage Change Summary Economic Indicators for the United States

	A0	*A1*	*A2*	*G0*	*G1*	*G2*
Welfare (equivalent variation, excluding emissions values)	-0.160	-0.125	-0.179	-0.325	-0.269	-0.286
Production	-0.559	-0.571	-0.567	-0.957	-0.915	-0.826
Employment	0.17	0.13	0.02	-0.48	-0.43	-0.40
Real wage	0.52	0.39	-0.04	-1.96	-1.76	-1.64
Labor tax change (percentage points)	-3.24%	-2.74%	-1.82%	1.09%	1.00%	0.99%
Terms of trade	0.414	0.480	0.502	0.489	0.544	0.549
Permit price ($/metric ton CO2)	$33.16	$34.26	$43.91	$32.08	$33.28	$42.92

The primary welfare benefit from A1 compared to A0 comes from fewer losses in consumption. Indeed, on most other metrics of economic changes—production, employment, and real wages—A0 is the strongest performer. With revenue recycling of unallocated allowance values, labor taxes fall and employment rises; the real wage also rises, with the exception of the case of A2. On the other hand, when other allowances are all grandfathered, G2 posts smaller decreases in production, employment, and the real wage. The OBA scenarios also generate larger improvements in the terms of trade.[10]

As the theory suggests, OBA raises the marginal cost (allowance price) of emissions abatement because fewer reductions arise from output substitution. This effect is most striking when rebates are given to the electricity sector, which is the largest emitter, driving up carbon prices by a third. However, it is interesting to note that the increase in allowance price is quite small when OBA is granted just to the EITE sectors, even though that includes indirect emissions; allowance prices rise 3 percent relative to no rebating. The grandfathering scenarios have slightly lower carbon prices than auctioning due to the larger economic contraction without revenue recycling, but the effects of OBA are essentially the same.

Carbon Leakage

With respect to leakage, we report two different indicators, both depicted in Figure 1. One is the EITE leakage rate, which is the change in emissions among the foreign EITE sectors divided by domestic reductions among the EITE sectors. Without OBA, these sectors face a much higher leakage rate of 28 percent on average, and OBA cuts this rate by more than half.

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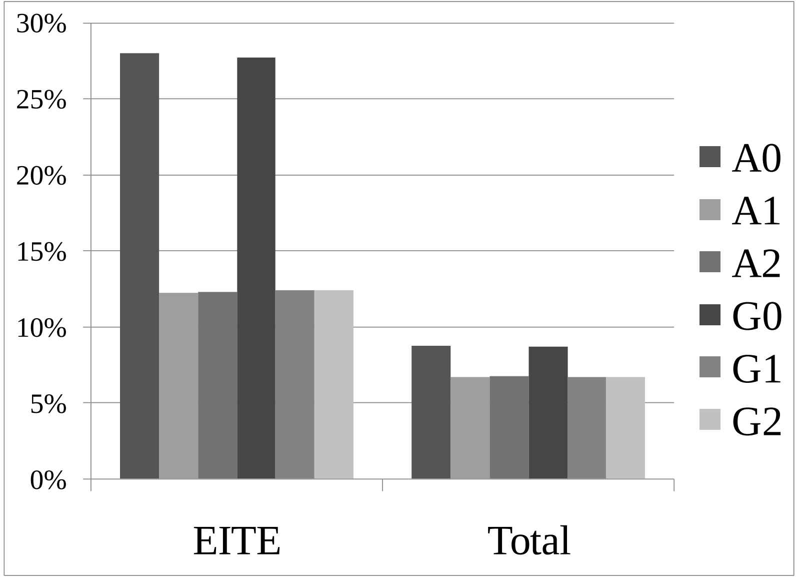
[10] Terms of trade within the numerical model are calculated as the trade-weighted ratio of exports over imports on the world market, exclusive of tariffs and transport costs, essential free alongside ship prices.

Underlying this average are leakage rates of nearly 70 percent for iron and steel and non-ferrous metals without OBA, but negligible leakage rates for pulp, paper, and print, likely due to the large influence of print in that aggregation.

The overall leakage rate is the change in total foreign emissions divided by total domestic U.S. reductions. With a comprehensive domestic cap, this metric indicates the global emissions changes. Electricity emissions have the largest share in this group, which thus has a lower starting leakage rate. Without OBA, overall leakage is estimated to be less than 10 percent, and the OBA scenarios reduce this rate by 2 percentage points. The choice of auctioning or grandfathering has little effect on leakage rates.

Figure 1. Leakage Rates by Policy Scenario



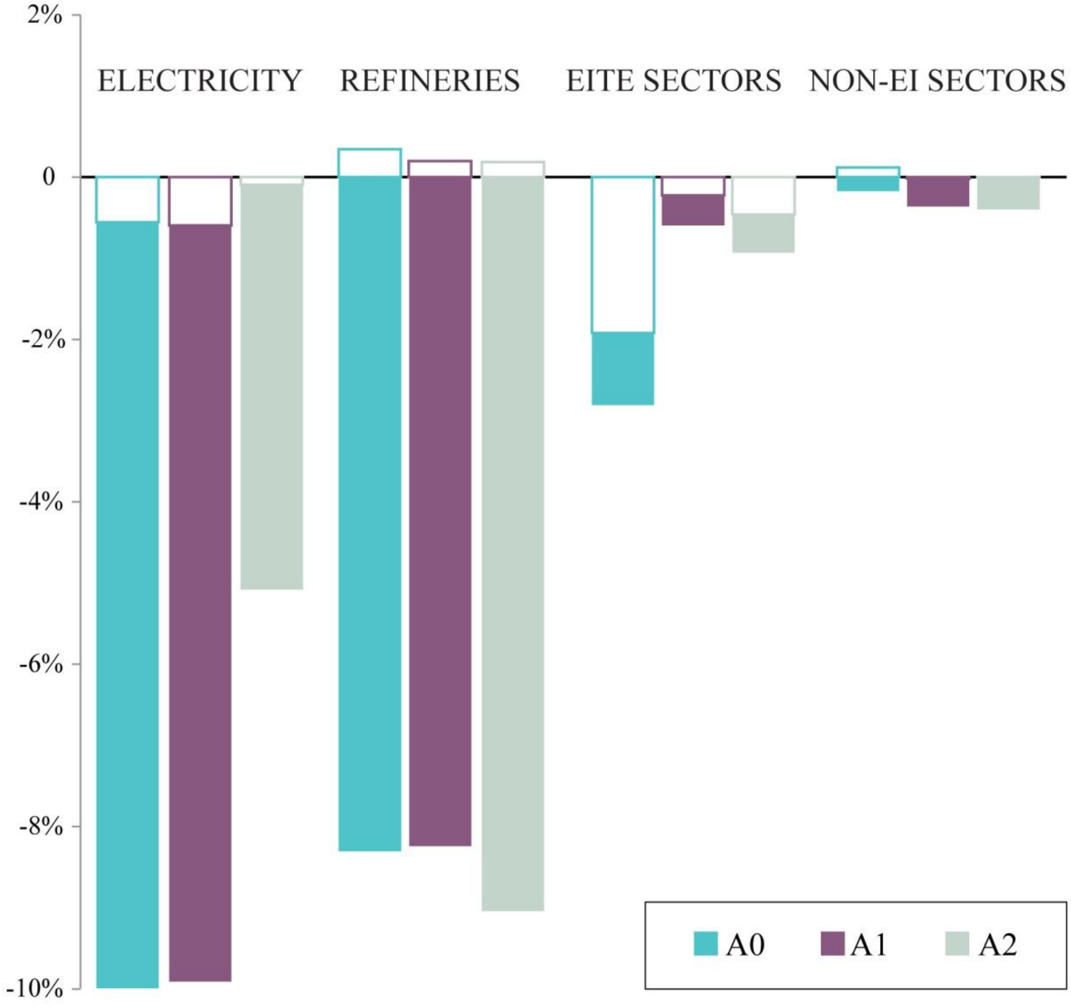
Distribution of Effects Across Sectors

The choice of auctioning versus grandfathering, while it has important macroeconomic effects, has little effect on relative prices, and therefore the distribution of abatement, production, and trade. By contrast, OBA works by changing the relative prices of energy-intensive goods. Consequently, it also influences the price of energy goods, both through the effects on the allowance price and through demand changes.

For example, in the A0 and G0 scenarios, electricity prices rise a 23%. Offering OBA to the EITE sectors raises this increase to 24%, while extending OBA to ELE eliminates almost all the considerable rise in electricity prices, leaving them less than 4% higher than the no-policy baseline. As the largest emitter, the electricity sector is the largest source of reductions: cutting its emissions by a third, ELE provides 70 percent of overall abatement in the A0 scenario. By contrast, the EITE sectors combined are responsible for 7 percent of reductions. Thus, it is not surprising that A2/G2 have much stronger effects on carbon and energy prices than A1/G1. When ELE is afforded OBA, it causes a dramatic rise in the price of fossil fuels (inclusive of permit costs), particularly coal, and it increases the relative price of natural gas, which is less carbon intensive than the other fuels. The increased demand for natural gas to meet emissions targets drives up permit-exclusive prices, whereas crude oil prices fall. (Note that non-hydro renewable energy, being a tiny fraction of generation in our 2004 base year, plays little or no role in this model.) The price of refined products (inclusive of permit costs) rises 27%, as opposed to 20-21% in the other scenarios. As a result of these energy price increases, refined products and non-EI sectors, particularly transportation and final demand, achieve deeper reductions in the A2/G2 scenarios.

The notion of competitiveness can be represented by different metrics, including output, jobs, and trade. Since production changes can also be associated with conservation and changing consumption patterns, the component of competitiveness most closely related to leakage (at a sectoral level) is the share of production changes that are attributable to changes in net exports. Figure 2 gives the percentage change in production and the change in net exports, as a share of production, broken down by sector groups. Full auctioning or grandfathering causes large decreases in production for electricity and refineries, but the vast majority is due to consumption changes. Production among EITE sectors falls about 3% on average, but two-thirds of this change is due to changes in net exports. Non-energy-intensive sectors see a slight expansion in net exports. OBA for the EITE sectors produces the smallest output loss for those sectors, given any use of the remaining revenues. This comes at a cost of decreasing production in non–energy-intensive sectors. Extending OBA to electricity halves the output contraction in the electricity sector, but actually reduces the competitiveness of the EITE sectors.

Figure 2. Percentage Change in Production (Solid Bars) and Portion Attributed to Changes in Net Exports (Hollow Bars) by Sector Group



Since labor is a substitute for energy in production, the employment effects of climate policies can vary. Table 4 gives the percentage change in employment by sector group. Employment in EITE sectors actually expands relative to no policy under A1 and G1, and employment in the electricity sector expands under A2 and G2. However, both of these expansions come at a cost of decreasing employment in non–energy-intensive sectors and overall. By far, the more costly allocation decision overall is the choice to grandfather remaining revenues, which has a stronger effect of depressing the real wage and contracting labor supply.

Table 4. Percentage Change in Employment

Sector	A0	A1	A2	G0	G1	G2
Electricity	-4.9	-4.7	1.4	-5.8	-5.5	0.7
Refined products	4.0	4.3	4.4	2.9	3.3	3.7
EITE	-0.7	1.4	0.7	-1.5	0.6	0.2
Non-EI	0.2	0.1	0.0	-0.4	-0.5	-0.4
Total	**0.17**	**0.13**	**0.02**	**-0.48**	**-0.43**	**-0.40**

Welfare and Sensitivity Analysis with Global Targets

This section combines welfare analysis with two main forms of sensitivity analysis. One is to assess the policy rankings across different stringencies of the emissions targets. Another is to consider the effects of less comprehensive sectoral coverage in the cap. Previous studies have elaborated on issues of the sensitivity of related CGE models to, e.g., the parameterization of the labor supply sensitivity, which influences the extent of tax interactions (Fischer and Fox 2007), and the parameterization of global fossil fuel supplies, which affects leakage (Burniaux and Martins 2000; Babiker and Rutherford 2005).

The previous set of scenarios compared the effects of combining a fixed domestic cap with alternate allocation strategies. To evaluate the full welfare effects requires some valuation of the environmental benefits, since each policy scenario involves a different level of global emissions. However, such a valuation is difficult to do consistently, since each scenario also involves different carbon prices, income, etc. Therefore, to rank the policies from a welfare perspective, we depart from the assumption of a fixed domestic cap and instead require each scenario to meet the same global emissions reduction target; with the environmental benefits thus held constant, the economic welfare measures offer a consistent metric of cost-effectiveness.

Target Stringency

We next explore the sensitivity of the results to the stringency of the unilateral target, requiring each scenario to meet the same *global* emissions reductions as the A0 scenario for a given target in the United States.

The welfare gains from a U.S. perspective are illustrated in Figure 3 for comprehensive coverage. Here, we find that A1 is the least costly scenario for meeting the same global emissions reductions, but A2 also consistently generates smaller welfare costs than A0, which was not obvious with the domestic target calculations. Grandfathering is significantly more costly than the auction scenarios, with G0 always the most costly; G2 seems slightly less costly at more modest targets, while G1 is preferred at more stringent ones. This crossover is explained in large part by a change in the relative effectiveness at deterring leakage.

Figure 4 plots the overall leakage rate, which is rising in the stringency of the target. Since global emissions are fixed for a given domestic target with A0, the leakage rate also indicates the extent to which the United States must undertake reductions. Auctioning or grandfathering makes little difference here. The broader OBA policies (A2 and G2) generate less leakage at more modest targets, but as those get more stringent, OBA only for the EITE sectors (A1 and G1) are associated with less leakage.

Figure 5 shows the corresponding CO2 prices, which are increasing and convex in the policy stringency. Notably, the A2 and G2 policies raise prices substantially, while the other scenarios have slightly lower prices than A0. Thus, although the OBA in A1 creates pressure to raise the carbon price, given a domestic cap, the gains from less leakage mean that the net effect for meeting the same global emissions target is to lower the carbon price.

Figure 6 presents the welfare sensitivity to changes in the stringency of the comprehensive cap from a global perspective.[11] Global net welfare is highest in the full auction scenario, although A1 is a close second until the U.S. target stringency reaches 26 percent, at which point A1 dominates A0.[12] On the other hand, G0 is always the most costly policy in welfare terms, so if revenues would not otherwise be recycled, G1 or G2 is preferred, depending on whether the policy is more or less stringent. Of course, many of these global tradeoffs are driven by the welfare effects in the United States; looking at the welfare of the rest of the world, we see a clear ranking of no OBA at all, then OBA to EITE and ELE, and lastly OBA to EITE. The use of the remaining revenues is less important, though we observe a slight preference for grandfathering over auctioning.

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[11] We give equal weight to all changes in EV; other weights and aggregations are possible, which could affect the rankings (Boehringer, Carbone and Rutherford 2011).

[12] Given that optimal rebates among the EITE sectors are positive, some combination of rebates would improve global welfare relative to the auction (Fischer and Fox 2009); the implied rebates in this scenario, however, are not optimally derived.

Figure 3. Sensitivity of U.S. Welfare Changes to Stringency of Emissions Reduction Target, Compared to Auctioned Comprehensive Cap (Millions of 2004 USD)

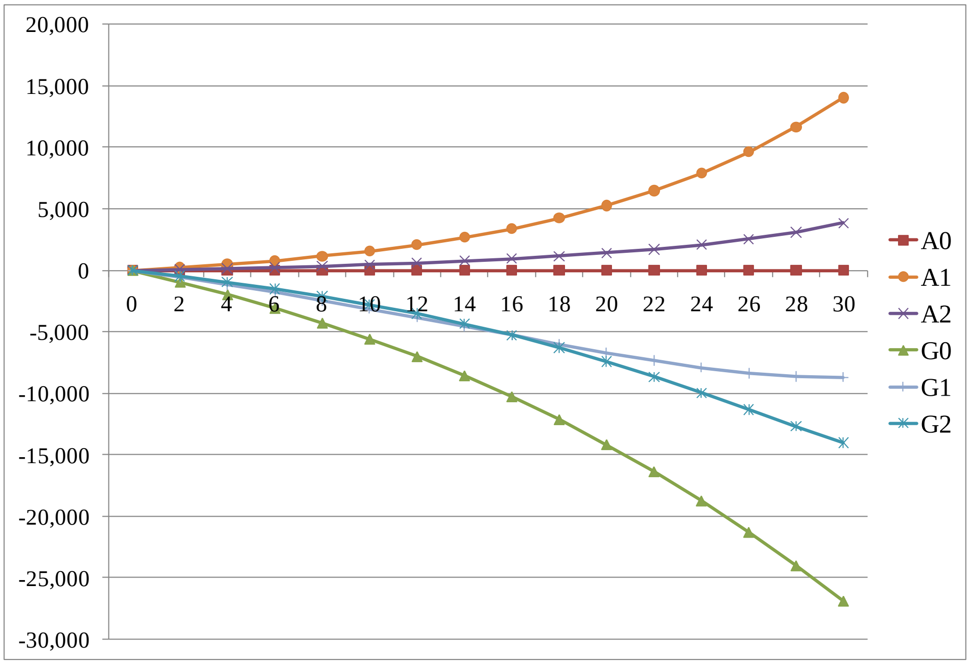


Figure 4. Sensitivity of Leakage Rate to Stringency of Emissions Reduction Target (Percent of U.S. Reductions)

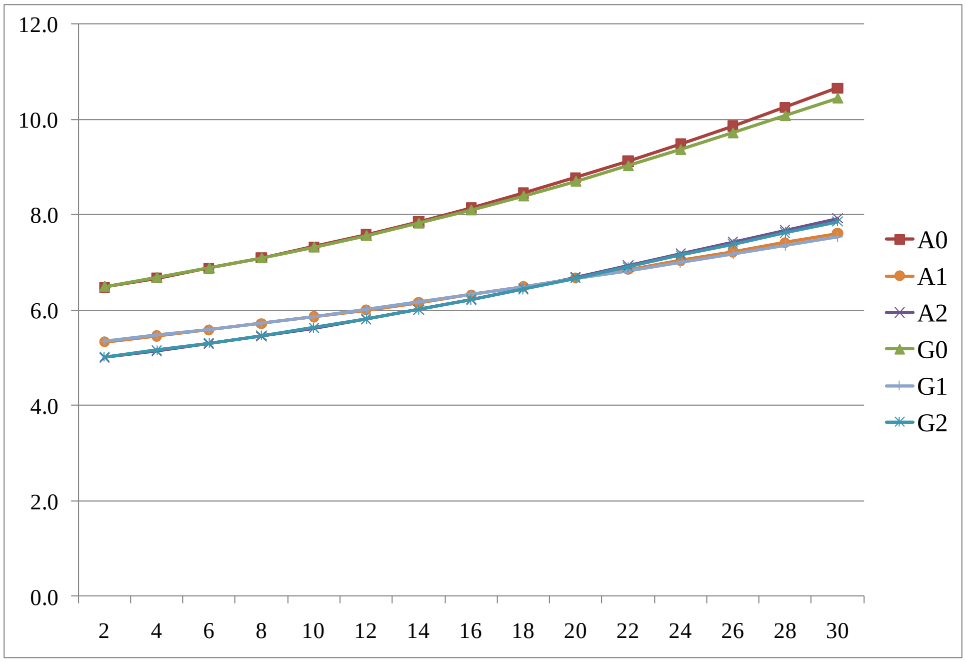


Figure 5. Sensitivity of Carbon Price to Policy Stringency and Scenario (USD per ton CO2)

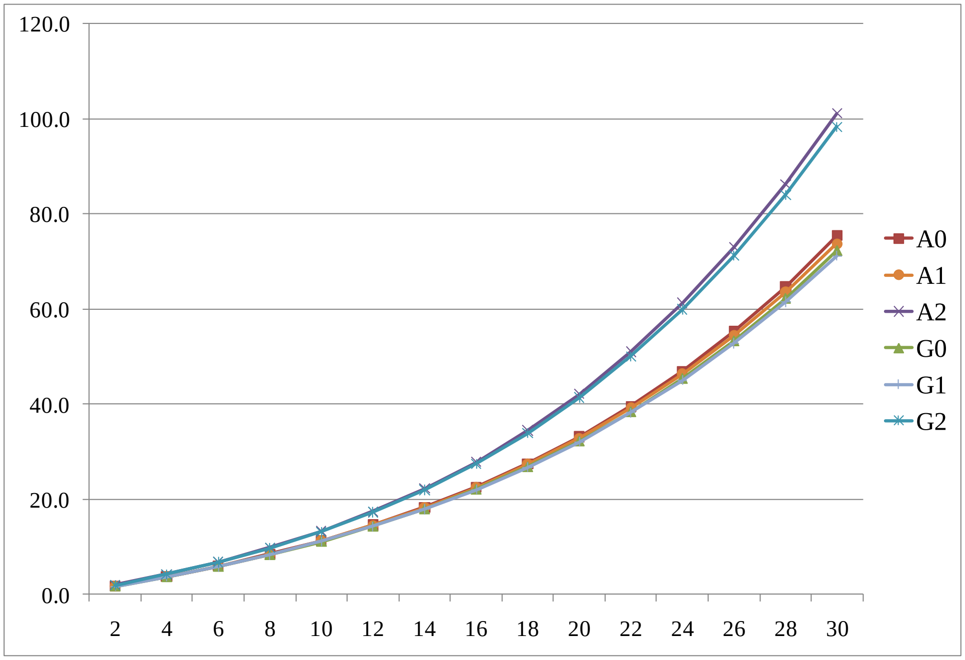
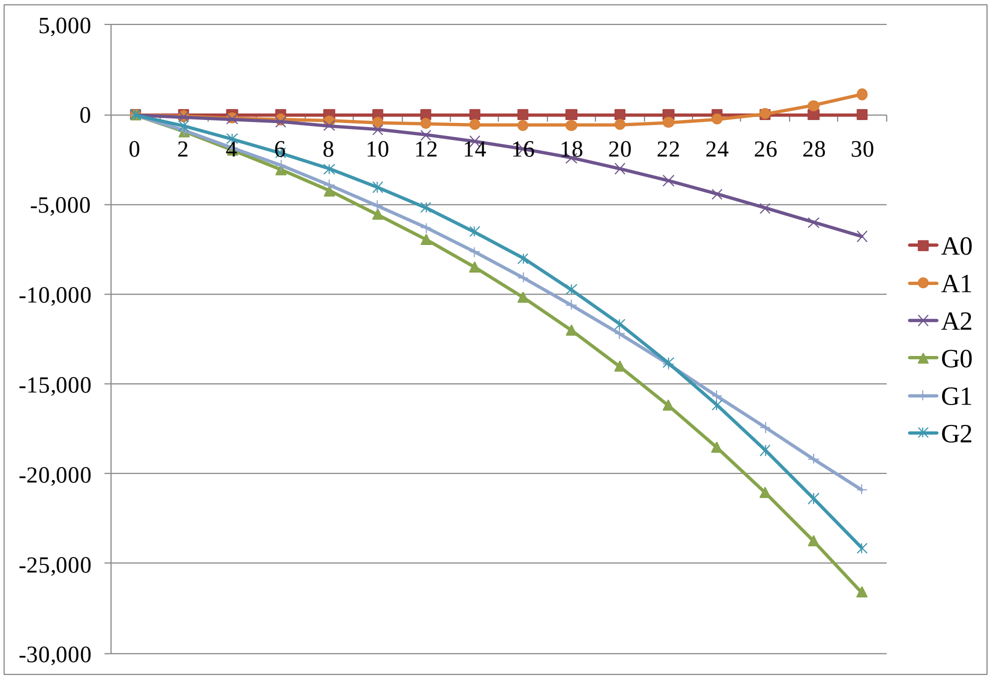


Figure 6. Sensitivity of Global Net Welfare Changes to Stringency of Emissions Reduction Target, Compared to Auctioned Comprehensive Cap (Millions of 2004 USD)



Incomplete Domestic Coverage

We consider a second set of scenarios in which the emissions cap-and-trade program is applied in a manner similar to the EU ETS, in which only energy-intensive sectors are covered (i.e., electricity, refining, and the EITE sectors). A 20 percent reduction target is applied for these covered sectors alone. The result is a system in which permit prices are lower by half, revealing that emissions reductions are more expensive in non–energy–intensive sectors.

Qualitatively, though, the results are similar to those of the comprehensive coverage scenarios. The percentage changes in key economic indicators are presented in Table 5. When auctioning and revenue recycling is the default use of the revenues, A1 generates the smallest welfare loss, while A0 is least disruptive to most other economic variables. The exception is changes in production; with limited coverage, A2 limits more of the overall production quantity losses. When grandfathering is the default use of revenues, G2 is the least disruptive to the real wage, employment, and production, and the economic welfare consequences are smaller than with G1 or G0.

Table 5. Percentage Change in Summary Economic Indicators for the United States with Coverage Limited to Energy-Intensive Sectors

	A0	A1	A2	G0	G1	G2
Welfare (equivalent variation, excluding emissions values)	-0.069	-0.051	-0.080	-0.117	-0.085	-0.083
Production	-0.200	-0.202	-0.161	-0.316	-0.286	-0.169
Employment	0.05	0.03	-0.03	-0.13	-0.10	-0.04
Real wage	0.16	0.09	-0.15	-0.55	-0.42	-0.20
Labor tax change (percentage points)	-0.96%	-0.67%	0.02%	0.26%	0.20%	0.10%
Permit price (\$/metric ton CO_2)	\$17.24	\$17.78	\$22.67	\$17.10	\$17.68	\$22.66

Table 6 presents the results in terms of leakage indicators. With incomplete coverage, “leakage” must consider not only foreign leakage, but also emissions changes among uncovered sectors in the United States. Overall leakage—including changes in uncovered sectors—is significantly smaller than with complete coverage because with few exceptions, the domestic uncovered sectors reduce their emissions as well. However, leakage from EITE sectors remains similar to the full coverage scenarios, only somewhat less (22 percent rather than 28 percent) due to the lower carbon price. As a result, A1 and G1 lead to the lowest levels of overall leakage. By extending OBA to ELE, A2 and G2 yield the least leakage from foreign sources but at a cost of lessening reductions among domestic uncovered sources.

Table 6. Leakage Rates by Policy Scenario with Coverage Limited to Energy-Intensive Sectors

	A0	A1	A2	G0	G1	G2
EITE leakage rate	22.4%	8.4%	7.1%	22.4%	8.5%	7.1%
Overall uncovered/covered	2.9%	0.8%	1.9%	2.4%	0.5%	1.9%
Overall foreign/domestic	6.9%	4.9%	4.4%	6.9%	4.9%	4.4%

We find some additional interesting results looking at some of the sector-specific effects behind these tables. While one might expect the higher permit price in the A2 and G2 scenarios and the resulting higher costs of refined petroleum products to drive greater reductions among the transportation sector, we find fewer reductions in transportation than with OBA to the EITE sectors alone; the reason is the much smaller contraction in production overall, which is complementary to transportation.

Figure 7. Sensitivity of U.S. Welfare Changes to Stringency of Emissions Reduction Target, Compared to Auctioned Cap on Energy-Intensive Sectors (Millions of 2004 USD)

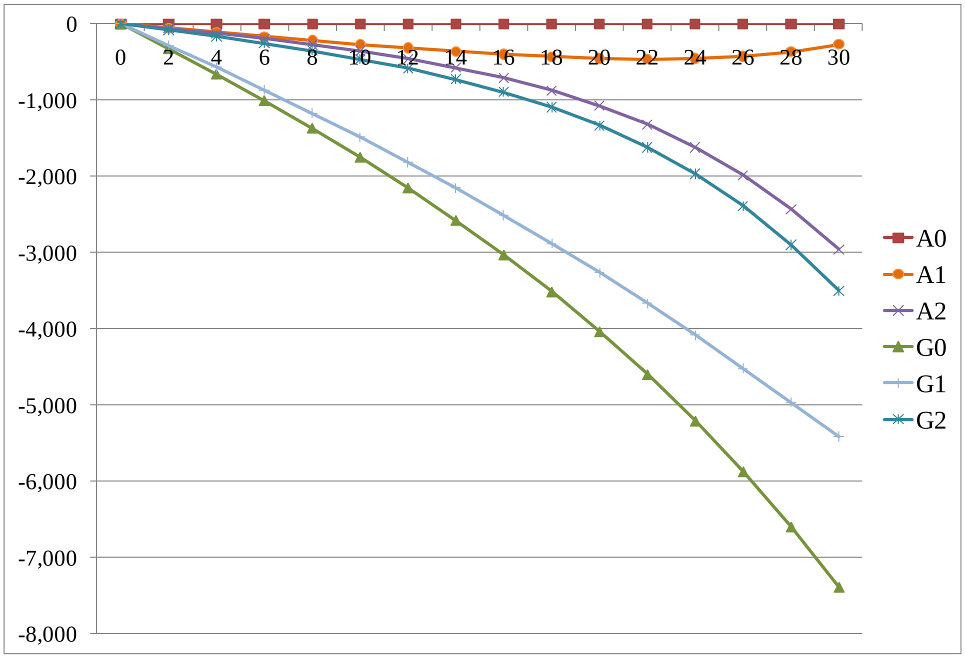


Figure 8. Sensitivity of Global Welfare Changes to Stringency of Emissions Reduction Target, Compared to Auctioned Cap on Energy-Intensive Sectors (Millions of 2004 USD)

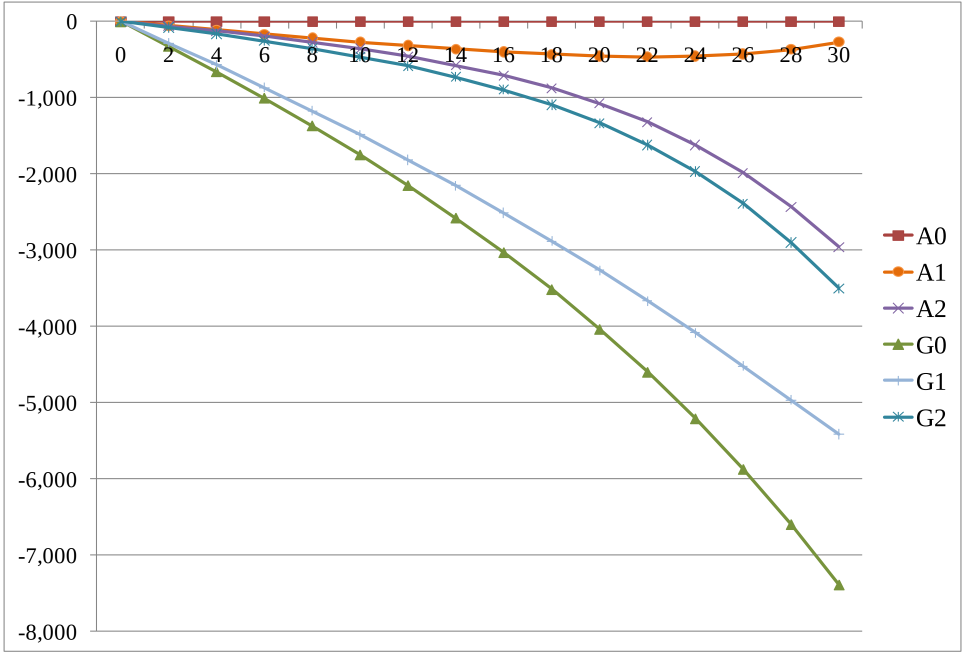


Figure 7 and Figure 8 present the welfare changes for the United States and world, respectively, given the same global emissions reductions as a given stringency of A0. As in the comprehensive coverage case, when remaining revenues are recycled, the United States prefers A1 while the world prefers A0 (at least until the cap gets more stringent than this range). Furthermore, when remaining revenues are grandfathered, both find G0 the most costly. With limited coverage, however, we see a much smaller difference between A2 and G2; the United States sees little difference between these and full auctioning, while G2 eliminates half of the global welfare loss from grandfathering, due in large part to the smaller tax interaction effect.

In an additional scenario not fully reported here, we find that with partial auctioning—e.g., grandfathering to all industry but revenue recycling of allowances for final demand—OBA to both EITE and ELE can be the preferred policy for the United States, as the higher permit prices raise revenue that when recycled helps maintain real wages. Thus, the extent of revenue recycling can affect the relative attractiveness of the different OBA policies.

Conclusion

Simple economic models have produced a clear preference for using tradable emissions permits and auctioning the revenues to reduce labor taxes. However, this preference generally has not translated into the policy sphere, where emissions permits have for the most part been given away, as in the U.S. SO_2 trading program, the legislative proposals for carbon trading in the 111th Congress, and in the evolving EU ETS, which actually imposed limits on auctioning in the early phases. An exception is the U.S. Northeast Regional Greenhouse Gas Trading Initiative, in which the participating states chose to auction roughly 90 percent of allowances. Furthermore, all these programs limit their coverage to a select group of major emitters, leaving others uncovered by the regulation.

Contrary to the simple models, the actual policy situation is rarely simple. Competition through international trade, carbon leakage, and administrative issues likely hold more sway than tax interaction problems. In the case of such multiple problems, the allocation of emissions permits can have even more important efficiency effects. While auctioning with revenue recycling effectively addresses tax interactions, it does not address the problem of emissions leakage. Grandfathering, of course, has even more costly effects in terms of welfare, tax interaction, competitiveness, and leakage, though some agents will receive a windfall.

Output-based allocation may then emerge as a reasonable option to combine gratis allocation with incentives that mitigate impacts on consumers and trade. Indeed, economies including New Zealand, Australia, and California are actively pursuing these mechanisms. We have shown that in theory and application, targeted rebating to energy-intensive, trade-exposed sectors can improve welfare, as well as a range of economic indicators important in domestic policymaking. Of course, some of these domestic gains come from improvements in the terms of trade, while the world as a whole would be more often better off if the United States chose 100 percent auctioning with revenue recycling. However, if the allowance values would otherwise be grandfathered, targeted OBA can even improve global welfare by reducing both tax interactions and emissions leakage.

That said, we note several aspects of OBA programs ignored in this analysis that have the potential to raise concerns. First of all, our CGE model does not allow for substitution effects among production inputs other than energy; therefore, we do not capture options like using less steel in a finished product and the efficiency losses of undoing the price signal to do so. Second, the key EITE sectors of interest in our model are too highly aggregated than is comfortable for detailed policy analysis. Third, we do not include the EU ETS and other existing and emerging emissions trading systems in the rest of the world that can affect leakage outcomes. All these issues are a focus for extended research.

Finally, this analysis does not capture the significant practical challenges in implementing OBA, from determining the sectors to defining the units of production and the relevant benchmarks for sector average allocations. To the extent that products are more narrowly defined, especially based on production method (e.g., steel from blast furnaces as opposed to electric arc furnaces), such tailored rebates can undo the incentives within a sector to shift to cleaner products. On the other hand, benchmarks that are too broadly defined (such as for chemicals with widely different values) can result in implicit subsidies out of whack with reasonable values. Attributing benchmarks to divergent products that are jointly produced is another challenge. Although we have established that in a second-best world, OBA can improve climate policy outcomes, the political process may not lead to the most appropriate set of sectors and definitions, and a poorly designed program of rebating can certainly be worse than none, especially if auctioning with revenue recycling is a real alternative.

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Appendix

In this Appendix, we derive the results presented in the Theoretical Background. Let us define the following variables:

Table A-7 Specification of Variables

		Quantities			*Prices*
Q_1	=	Production in the regulated sector	q_1	=	Producer prices in the regulated sector
Q_2	=	Production in the unregulated sector	q_2	=	Producer prices in the unregulated sector
L_1	=	Labor demand in the regulated sector			
L_2	=	Labor demand in the unregulated sector			
L	=	Labor supply	w	=	Labor wage (numéraire)
l	=	Leisure = 1–L	t_L	=	Tax on labor
C_1	=	Demand for good produced in the regulated sector	p_1	=	Consumer prices in the regulated sector
C_2	=	Demand for good produced in the unregulated sector	p_2	=	Consumer prices in the unregulated sector
E_1	=	Emissions of pollutant in the regulated sector	τ_1	=	Emissions price in the regulated sector
E_2	=	Emissions of pollutant in the unregulated sector	τ_2	=	Emissions price in the unregulated sector (0)
A_1	=	Allocations of grandfathered permits	s_1	=	Subsidy to regulated commodity

The household sector consists of a representative consumer, for whom utility is a function of consumption of goods and leisure: $U = U(C_1, C_2, 1-L)$. Households also suffer disutility as a function of total emissions: $D = D(E_1 + E_2)$. These utility and disutility functions enter the welfare function separably:

$$W = U - D = U(C_1, C_2, 1-L) - D(E_1 + E_2).$$

Consumer Problem. Taking pollution externalities as given, the representative household maximizes utility with respect to consumption and leisure, subject to a budget constraint:

$$\max_{C_1, C_2, L} \; U(C_1, C_2, 1-L) - \lambda\left(p_1 C_1 + p_2 C_2 - (1-t_L)L - A_1\right),$$

yielding the following first-order conditions:

$$(C_1)\ \frac{\partial U}{\partial C_1} = p_1\lambda; \qquad (C_2)\ \frac{\partial U}{\partial C_2} = p_2\lambda; \qquad (L)\ \frac{\partial U}{\partial l} = \lambda(1-t_L).$$

Producer Problems. Production in each sector (*i* = 1, 2) is a function of labor and emissions: $Q_i = f_i(L_i, E_i)$. Equivalently, labor in each sector can be specified as a function of output and emissions: $L_i = L_i(Q_i, E_i)$. The representative firm in each sector *i* chooses output and emissions to maximize profits, given the prevailing product and emissions prices:

$$\pi_i = q_i Q_i - L_i(Q_i, E_i) - \tau_i E_i \,,$$

from which we obtain

$$(Q_i) \;\; q_i = \frac{\partial L_i}{\partial Q_i}; \qquad (E_i) \;\; -\frac{\partial L_i}{\partial E_i} = \tau_i .$$

The first expression implies that the output price equals the marginal cost (or, with some rearranging, that the value of the marginal product of labor equals the wage rate). The second means that the labor cost savings from using more emissions equal the tax.

Totally differentiating the emissions first-order condition, we further observe that, given any E_1, anything that increases output will raise the emissions price:

$$d\tau_1 = -\frac{\partial^2 L_1(Q_1, E_1)}{\partial E_1 \partial Q_1} dQ > 0.$$

Government Revenue. The government collects revenue from auctioning emissions allowances for the regulated sector 1, net of any subsidies given, and a tax on labor must make up any shortfall:

$$G = \tau_1(E_1 - A_1) + t_L L - s_1 C_1 .$$

Market Equilibrium. In equilibrium, we have

$$C_1 = Q_1; \quad C_2 = Q_2; \quad L_1(Q_1, E_1) + L_2(Q_2, E_2) + G = L \,,$$

$q_i = p_i + s_i$, and the revenue and emissions constraints are met.

With well-behaved utility and production functions, consumption of each good is decreasing in its own costs, which include output and emissions taxes. As a result, $dC_i / ds_i > 0$ (and $dC_i / d\tau_i < 0$). Let us define the goods as substitutes if $dC_i / ds_j < 0$ and complements if $dC_i / ds_j > 0$. These cross-price effects depend not only on the signs of the cross-partials in the utility function but also on the general equilibrium. Overall labor supply is increasing in the marginal utility of consumption.

Planner Problem. Suppose the government has made a commitment to cap emissions in the regulated sector at a certain level. However, the unregulated sector does not face a cap, emissions tax, or even a production tax ($\tau_2 = s_2 = 0$). In this case, can subsidizing production in the regulated sector raise welfare?

The essence of the problem can be seen by totally differentiating welfare, recalling that with the cap, $dE_1 = 0$:

$$\frac{dW}{ds_1} = \frac{\partial U}{\partial C_1}\frac{dC_1}{ds_1} + \frac{\partial U}{\partial C_2}\frac{dC_2}{ds_1} - \frac{\partial U}{\partial l}\frac{dL}{ds_1} - \frac{\partial D}{\partial E}\frac{dE_2}{ds_1}.$$

From the first-order conditions from the consumer problem, $\partial U / \partial C_i = p_i \lambda$, and $\partial U / \partial l = \lambda(1-t_L)$, so this equation simplifies to

$$\frac{dW}{ds_1} / \lambda = p_1 \frac{dC_1}{ds_1} + p_2 \frac{dC_2}{ds_1} - (1-t_L)\frac{dL}{ds_1} - \frac{D'}{\lambda}\left(\frac{dE_2}{ds_1}\right).$$

Furthermore, the change in total labor supplied is $dL = dL_1 + dL_2$, and totally differentiating the production function gives us $dL_i = \frac{\partial L_i}{\partial Q_i} dQ_i + \frac{\partial L_i}{\partial E_i} dE_i$. Using the producer first-order conditions ($\partial L_i / \partial Q_i = q_i, -\partial L_i / \partial E_i = \tau_i$) and market equilibrium conditions, this implies that $dL_i = q_i dC_i$ because for sector 1, $dE_i = 0$, while for sector 2, $\tau_i = 0$. Furthermore, emissions in the unregulated sector, which lacks any incentive to change emissions intensity, are proportional to output: $dE_2 = m_2 dC_2$, where m is the marginal emissions rate. Substituting, we get the marginal welfare impacts of a change in the subsidy rate (relative to the marginal utility of consumption), as presented in the main text:

$$\frac{dW}{ds_1} / \lambda = -s_1 \frac{dC_1}{ds_1} - \left(\frac{D'}{\lambda}\right) m_2 \frac{dC_2}{ds_1} + t_L \frac{dL}{ds_1}.$$