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General Equilibrium Impacts of a Federal Clean Energy Standard

Lawrence H. Goulder, Marc A.C. Hafstead, and Roberton C. Williams III

1616 P St. NW
Washington, DC 20036
202-328-5000 www.rff.org

RESOURCES FOR THE FUTURE

General Equilibrium Impacts of a Federal Clean Energy Standard

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Abstract

Economists have tended to view emissions pricing (e.g., cap and trade or a carbon tax) as the most cost-effective approach to reducing greenhouse gas emissions. This paper offers a different view. Employing analytical and numerically solved general equilibrium models, the paper indicates plausible conditions under which a more conventional form of regulation—namely, the use of a clean energy standard (CES)—is more cost-effective. The models reveal that in a realistic economy with prior taxes on factors of production, the CES distorts factor markets less because it is a smaller implicit tax on factors. This advantage more than offsets the disadvantages of the CES when relatively minor reductions in emissions are called for. Numerical simulations indicate that the cost-effectiveness of the CES is sensitive to what is deemed "clean" electricity. To achieve maximal cost-effectiveness, the CES must offer significant credit to electricity generated from natural gas.

Key Words: clean energy standard, intensity standard, emissions pricing, climate

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Lawrence H. Goulder[a, b, c], Marc A.C. Hafstead[b], and Roberton C. Williams III [b, c, d *]

1. Introduction

There is little or no near-term prospect for any pricing of US carbon emissions (a carbon tax or tradable permits) at the federal level. But federal climate policy is advancing on other fronts. One important policy approach under consideration at the federal level is a clean energy standard (CES); such a standard was proposed by former senator Jeff Bingaman (D-NM) in the Clean Energy Standard Act of 2012.[1] A CES establishes a minimum for the share of electricity purchased by electric utilities coming from "clean" sources. The CES thus aims to give a boost to clean electricity generation, such as generation from wind or solar thermal sources.

The CES is an example of an intensity requirement: it focuses on the ratio of inputs of clean electricity to total inputs of electricity to utilities.[2] Intensity standards are also a likely direction for policy actions the US Environmental Protection Agency (EPA) is taking under the

* [a] Stanford University, [b] Resources for the Future, [c] National Bureau of Economic Research, [d] University of Maryland. We are grateful to Lint Barrage, Terry Dinan, Don Fullerton, Stephen Holland, and seminar participants at the NBER Summer Institute on Environmental and Energy Economics, the Northeast Workshop on Energy Policy and Environmental Economics, Resources for the Future, the University of New South Wales, and the University of Ottawa for their helpful comments and suggestions.

[1] Earlier CES proposals were contained in the Clean Energy Act of 2009 proposed by Senator Graham (R-SC) and the Practical Energy and Climate Plan of 2010 proposed by Senator Luger (R-IN). On June 25, 2013, President Obama promised to introduce controls on CO_2 emissions from coal-fired power plants under the authority granted to EPA under the Clean Air Act. Such controls are formally similar to a CES in which natural-gas-fired and nonfossil-generated electricity receive credit and coal-fired electricity does not.

[2] Thus the CES is an *input*-oriented intensity requirement. So is a renewable fuel standard, which requires that the share of refiners' total fuel purchases represented by "green" fuels not fall below some minimum. Intensity requirements can apply to outputs as well; these are often termed "performance standards." Automobile fuel economy standards (floors on the miles per gallon) provide an example.

auspices of the Clean Air Act.[3] Such policies are also being pursued through initiatives by many US states.[4]

Economists recognize some attractions of intensity standards but can offer only faint praise. On the positive side, intensity standards are seen as superior (on cost-effectiveness grounds) to some conventional policy approaches: in contrast to specific technology mandates, intensity standards give firms or facilities the flexibility to choose whatever production method meets the standard at lowest private cost.

But economists generally view intensity standards as less cost-effective than policies that price emissions, as is the case with emissions taxes or systems of tradable emissions allowances. As shown by Holland et al. (2009) and Fullerton and Metcalf (2001), input-based intensity standards are formally identical to the combination of an emissions tax and input subsidy, with the implied revenue loss from the subsidy identical to the revenue gain from the tax. As discussed below, even if the intensity standard leads to the efficient ratio of use of clean to "dirty" (higher-polluting) production inputs, the subsidy component tends to promote inefficiently high demands for inputs in general, which sacrifices cost-effectiveness.[5] Indeed, Holland et al. show that an intensity standard intended to promote the use of cleaner fuels in the gasoline blend can result in an *increase* in emissions from fuels—because it promotes an inefficiently high demand for gasoline in general. This would suggest that, as a policy to reduce carbon dioxide emissions associated with the production of electricity, the CES is much less cost-effective than a cap-and-trade program or carbon-based emissions tax applied to the electricity sector.

This paper challenges that conclusion. It employs analytical and numerical general equilibrium models to assess the costs of achieving given reductions in greenhouse gases (GHGs) under the CES and under cap and trade (C&T). It shows that the cost disadvantage of

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[3] EPA action is called for as a result of the 2006 US Supreme Court decision in *Massachusetts v. EPA*, the Obama administration's subsequent "endangerment finding" that carbon dioxide (and other greenhouse gases) endanger public health and welfare, and the consequent designation in 2010 of carbon dioxide as a pollutant for regulatory purposes under the Clean Air Act both for stationary and mobile sources. The exact form these regulations will take is still an open question, but it seems likely they will be some form of an intensity standard. Indeed, Burtraw et al. (2012) suggest that EPA could use tradable performance standards, which are essentially equivalent to a CES.

[4] Twenty-nine states currently have implemented or committed to some form of a renewable electricity standard or renewable portfolio standard, each of which is a form of an intensity standard.

[5] The CES can suffer a further disadvantage if it fails to provide incentives to utilities to switch optimally between nonfossil-generated, natural-gas-generated, and coal-generated electricity. We consider this issue below.

the CES is much smaller than previously thought. Indeed, in some circumstances, a CES can actually be more efficient than emissions pricing.

This difference arises because of interactions with the tax system.[6] The CES leads to a lower price for electricity than a cap-and-trade system (or carbon tax) that promotes the same emissions reduction, because of the subsidy component of the CES. Apart from tax interactions, this would sacrifice cost-effectiveness, as lower electricity prices limit the extent that emissions are reduced through the channel of lower electricity demand. However, as indicated below, lower electricity prices have a virtue in the presence of tax interactions: they imply a smaller adverse “tax-interaction effect.” This offsetting benefit makes the CES nearly as cost-effective as—or even more cost-effective than—the equivalent emissions price policy.[7]

We first employ an analytical model that compares the costs while taking account of tax interactions as well as other incentive effects not considered in prior theoretical work. This model indicates that the relative cost-effectiveness depends on the nature and extent of prior tax distortions, the stringency of the CES policy, substitutability among various forms of electricity generation, and specifics of the CES policy design. We then apply a numerical general equilibrium model of the United States to obtain quantitative results and arrive at more specific policy conclusions. The numerical model combines details on the US energy system with details on the US tax system, thus permitting an assessment of the tax interactions. The numerical simulations yield quantitative assessments of how the relative costs of the two types of policies depend on the various factors identified by the analytical model.

The rest of the paper is organized as follows. Section 2 describes and applies the analytical model. Section 3 presents the numerical model, and Section 4 examines the data used by that model. Section 5 discusses the policy simulations and the simulation results. The final section offers conclusions.

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[6] Recent work by Parry and Williams (2010) also indicates that the CES might fare considerably better on cost-effectiveness grounds once one accounts for interactions with the tax system, though that paper does not suggest that a CES could outperform emissions taxes.

[7] The smaller price increases from intensity standards can confer another potential attraction of such standards relative to emissions taxes. Environmental regulations can lead to “emissions leakage” when they cause firms to migrate outside of the jurisdiction in which the regulation is imposed or consumers to shift demands toward emissions-intensive goods or services produced outside of that jurisdiction. Holland (2012) points out that the smaller price increases from intensity standards can help limit emissions leakage and thereby reduce costs per reduction in (overall) emissions.

2. An Analytical Model

This section introduces a relatively simple analytical model that illustrates the trade-offs between a CES and C&T (or a carbon tax), along with key factors that determine the relative efficiency of these two instruments.

2.1. The Model

A representative agent consumes two private goods, *X* and *Y*, and a public good, *G*, and supplies capital (*K*) and labor (*L*). The agent's utility function is given by

$$U(X, Y, G, K, L) \tag{1}$$

where *U* is continuous, quasi-concave, and twice-differentiable. This function is increasing in the first three arguments (the two private goods and the public good) and decreasing in the last two. In contrast with the next section's numerical model, which is dynamic and considers capital formation, this analytical model is static and thus ignores the dynamics of capital accumulation. For simplicity, it assumes instead that the provision of capital causes disutility to the agent (in keeping with the disutility of postponing consumption, which cannot be explicitly represented in a static model).[8] Thus in this model, capital is very similar to labor.[9]

The agent's budget constraint is given by

$$X + p_Y Y = (1 - \tau_L) wL + (1 - \tau_K) rK \tag{2}$$

where p_Y is the price of good *Y*; τ_L and τ_K are the tax rates on labor income and capital income; and *w* and *r* are the prices of labor and capital (i.e., the wage and rate of return). Good *X* is the numéraire, so its price is normalized to one.

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[8] Ignoring the dynamics of capital accumulation means that this analytical model misses some of the reasons why capital taxation can be more distortionary than labor taxation. But it can still model the implications of a case in which one factor is subject to a more distortionary tax than the other.

[9] The model's results are identical under several alternative specifications or interpretations. One alternative is to specify capital supply as fixed and treat capital as having nonmarket (i.e., untaxed) uses. In that case, the disutility from supplying capital to the market would represent the cost of reducing the amount of capital devoted to those nonmarket uses. Similarly, the disutility from labor supply could represent disutility from working or could represent the cost of giving up some nonmarket uses of time. A further alternative is to view *K* not as capital, but as a second type of labor. In all of these cases, the main results of the model would remain unchanged.

The agent maximizes utility (1) subject to the budget constraint (2), taking prices, tax rates, and the quantity of the public good as given. This yields the consumer first-order conditions:

$$U_X = \lambda;\ U_Y = p_Y\lambda;\ -U_K = \left(1-\tau_K\right)r\lambda;\ -U_L = \left(1-\tau_L\right)w\lambda \tag{3}$$

where λ is the marginal utility of income.

Goods X and G are nonpolluting. For simplicity, we assume that they have identical production technologies. Thus production of these goods is given by

$$X + G = F_X\left(K_X, L_X\right) \tag{4}$$

where K_X and L_X are the quantities of capital and labor used in production of X and G. The production function for good Y is similar, except that production of good Y generates pollution (Z).[10] Pollution, a joint product, is represented here as an input. Thus the production of Y follows

$$Y = F_Y\left(K_Y, L_Y, Z\right). \tag{5}$$

Both production functions are quasi-concave and twice-differentiable and exhibit constant returns to scale. Pollution is not priced by the free market but is subject to an emissions tax, τ_Z. Production of good Y is also subject to a tax at the rate τ_Y. Both industries are perfectly competitive; hence firms take all prices as given while maximizing profits. This implies the following first-order conditions for production of X and G:

$$\partial F_X/\partial K_X = r;\ \partial F_X/\partial L_X = w \tag{6}$$

and for production of Y:

$$\partial F_Y/\partial K_Y = r\big/\left(p_Y-\tau_Y\right);\ \partial F_Y/\partial L_Y = w\big/\left(p_Y-\tau_Y\right);\ \partial F_Y/\partial Z = \tau_Z\big/\left(p_Y-\tau_Y\right) \tag{7}$$

The market for capital must clear (i.e., capital supplied must equal capital used in production)

[10] The model does not capture the harmful effects of pollution. This has no effect on comparisons between the CES and C&T because in all cases we compare policies that yield the same reductions in emissions.

$$K = K_X + K_Y \tag{8}$$

and the same is true for labor

$$L = L_X + L_Y \tag{9}$$

The government uses tax revenue to finance provision of the public good.[11] The government budget constraint follows

$$\tau_Y Y + \tau_Z Z + \tau_L wL + \tau_K rK = G \tag{10}$$

Taken together, equations (1) through (10) implicitly define utility, all prices, and all quantities as functions of the four tax rates. The CES and C&T can each be represented as a revenue-neutral combination of an increase in the pollution tax (τ_Z) and a reduction in one of the other tax rates. As indicated in the introduction, the CES is equivalent to a pollution tax combined with a negative tax (i.e., a subsidy) on good *Y*. And under the assumption that the permits are auctioned and the revenue is used to reduce taxes on capital and/or labor income, C&T is equivalent to a pollution tax combined with a reduction in τ_K and/or τ_L.

Taking a total derivative of utility (1) with respect to τ_Z, substituting in the consumer first-order conditions (3), subtracting total derivatives of the production functions (4) and (5) with respect to τ_Z, substituting in the firm first-order conditions (6) and (7), substituting in total derivatives of the factor-market clearing conditions (8) and (9) and the government budget constraint (10) with respect to τ_Z, and rearranging yield the following equation for the marginal change in welfare for a marginal change in either the CES or C&T:

$$\frac{1}{\lambda}\frac{dU}{d\tau_Z} = \tau_Z \frac{dZ}{d\tau_Z} + \tau_Y \frac{dY}{d\tau_Z} + \tau_K \frac{d(rk)}{d\tau_Z} + \tau_L \frac{d(wL)}{d\tau_Z} \tag{11}$$

This equation shows that the money-equivalent change in utility is equal to the sum of four terms, each of which represents the effect of a particular distortion. Each of these terms is equal to the size of the distortion (i.e., the tax rate) times the change in quantity in the distorted market. In each case, the tax puts a wedge between the marginal social cost and marginal social

[11] The model's results would be identical if government revenue (or a portion of that revenue) were instead spent on a transfer to the representative agent, as long as the real purchasing power of that transfer is held constant.

benefit for the taxed good, and thus any change in quantity has a corresponding effect on welfare.

2.2. Effects of Cap and Trade

Here we exploit the fact that cap and trade is equivalent to a pollution tax combined with a reduction in τ_K and/or τ_L. In this case, the $\frac{d}{d\tau_Z}$ terms will include the effect of the change in τ_Z and the effects of the changes in τ_K and/or τ_L. Under cap and trade, there is no tax or subsidy on *Y*. Thus for this policy, (11) can be rewritten as

$$\begin{aligned}\frac{1}{\lambda}\frac{dU}{d\tau_Z} &= \tau_Z\frac{dZ}{d\tau_Z} + \tau_K\frac{\partial(rk)}{\partial\tau_Z} + \tau_L\frac{\partial(wL)}{\partial\tau_Z} + \frac{d\tau_K}{d\tau_Z}\left[\tau_K\frac{\partial(rK)}{\partial\tau_K} + \tau_L\frac{\partial(wL)}{\partial\tau_K}\right] \\ &+ \frac{d\tau_L}{d\tau_Z}\left[\tau_K\frac{\partial(rK)}{\partial\tau_L} + \tau_L\frac{\partial(wL)}{\partial\tau_L}\right]\end{aligned} \tag{12}$$

The first term on the right-hand side of (12) is the direct cost of the policy: the cost that comes from the effect on emissions (which is the same as the first term in (11)). The next two terms are what Goulder (1995) referred to as the "tax-interaction" effect: the welfare effect that arises when environmental policy distorts factor markets by altering real returns to these factors. The final two terms are the "revenue-recycling" effect: the welfare effect of using revenue from environmental policy to finance tax rate cuts for distortionary taxes.

To aid in interpretation of equation (12), it is useful to define the marginal cost of public funds (MCPF) for the taxes on capital and labor. The MCPF for a given tax is the marginal welfare cost per dollar of incremental revenue raised using a given tax. The MCPF for the capital and labor tax are

$$\eta_K = \frac{rK}{rK + \tau_K\frac{\partial(rK)}{\partial\tau_K} + \tau_L\frac{\partial(wL)}{\partial\tau_K}} \tag{13}$$

and

$$\eta_L = \frac{wL}{wL + \tau_K\frac{\partial(rK)}{\partial\tau_L} + \tau_L\frac{\partial(wL)}{\partial\tau_L}} \tag{14}$$

respectively. In each of these expressions, the numerator is the cost to the representative agent of a marginal increase in the tax, while the denominator is the marginal revenue from that tax increase. Thus the ratio is the MCPF.[12]

Using the MCPF and assuming that *X* and *Y* are separable in utility from *K* and *L* allows (12) to be rewritten (see Appendix A for derivation) as

$$\frac{1}{\lambda}\frac{dU}{d\tau_Z} = \tau_Z\frac{dZ}{d\tau_Z} - \eta_R\mu_{IZ}Z + \left(\eta_R - 1\right)\left(Z + \tau_Z\frac{dZ}{d\tau_Z}\right) \tag{15}$$

where η_R is the MCPF for the mix of tax cuts enabled by the pollution tax revenue. This provides a measure of how large a welfare gain those tax cuts will generate (i.e., how large the gain from the revenue-recycling effect will be). This is a weighted average of the MCPFs of the capital and labor taxes; it is given by

$$\eta_R = \alpha_K\eta_K + \alpha_L\eta_L \tag{16}$$

where α_K and α_L are the shares of marginal revenue devoted to cutting capital and labor taxes, respectively (note that we assume all revenue is used for cutting one tax or the other, implying that $\alpha_K + \alpha_L = 1$).

Similarly, μ_{IZ} is a measure of the distortions from the capital and labor taxes that determine the magnitude of the tax interaction effect. It is given by

$$\mu_{IZ} = \gamma_{ZK}\left(\frac{\eta_K - 1}{\eta_K}\right) + \gamma_{ZL}\left(\frac{\eta_L - 1}{\eta_L}\right) \tag{17}$$

where γ_{ZK} and γ_{ZL} are the shares of the burden of τ_Z that fall on capital and labor, respectively (and where $\gamma_{ZK} + \gamma_{ZL} = 1$). To understand the expression for μ_{IZ}, recognize that $\eta - 1$ is the excess burden per dollar of revenue from a given tax (η is the burden per dollar of revenue, and subtracting 1 leaves the excess burden). Then $(\eta - 1)/\eta$ is the excess burden per dollar of

[12] Each expression is a “nonenvironmental” MCPF, one that ignores any welfare effects stemming directly from policy-induced changes in emissions or environmental quality.

burden from that tax. μ_{IZ} thus measures the loss from the tax-interaction effect per dollar of burden of the carbon tax.

The underlying effects that determine the relative magnitudes of γ_{ZK} and γ_{ZL} are the same as the effects that determine the relative incidence on capital and labor of a pollution tax, a problem previously studied by Fullerton and Heutel (2007).[13] Most notably, γ_{ZK} tends to be higher if capital is more complementary to pollution than labor is (i.e., when reducing pollution per unit of output implies a shift toward more labor-intensive production) or if the polluting good is relatively capital-intensive. In those cases, the burden of the pollution tax tends to fall more on capital (as shown by Fullerton and Heutel), and thus the tax-interaction effect here is also skewed more toward capital.

Equation (15) shows the three effects that determine the overall cost of emissions pricing. The first term, the direct cost of reducing emissions, is straightforward: it equals firms' marginal abatement cost (τ_Z, because firms will abate emissions up to the point where their marginal cost of abatement equals the tax rate) times the marginal change in emissions caused by the policy.

The second term, the tax-interaction effect, depends on the quantity of pollution (the greater the quantity of pollution, the more of a burden a given pollution tax will have) and on μ_{IZ} (to the extent that the pollution tax burden falls on highly distorted factors of production, the welfare loss from the tax-interaction effect will be larger). Perhaps surprisingly, it also depends on η_R: the tax-interaction effect implies a loss of government revenue (discouraging the supply of capital and/or labor causes a drop in the revenue from taxes on those factors), and thus implies that the rates of those other taxes cannot be cut by as much.

The third term, the revenue-recycling effect, is equal to the MCPF for the mix of taxes that are cut (η_R) times the marginal revenue from the pollution tax. This is intuitive: the more revenue the pollution tax raises or the more distortionary the taxes that are cut, the bigger the gain.

As will be shown in the next section, these effects also determine the cost of the CES and thus the difference in costs between policies. The CES has a higher direct cost and raises no

[13] The exact expressions for the γ terms differ slightly from the results in Fullerton and Heutel's model, because that paper's model assumed that both capital and labor supply are fixed, whereas this model allows both to vary. But the underlying effects are identical.

revenue (thus generating no beneficial revenue-recycling effect), but because it generates a smaller tax-interaction effect, it can still be more cost-effective. As we indicate below, the difference in costs between the two policies will depend on magnitudes of the differences in the direct cost and tax-interaction terms between the two policies and on the size of the revenue-recycling term.

2.3. Effects of a Clean Energy Standard

Here we exploit the fact that the clean energy standard is equivalent to a pollution tax combined with a negative tax on (i.e., a subsidy to) good *Y*.[14] In this case, the $\frac{d}{d\tau_Z}$ terms will include the effect of the increase in τ_Z and the decrease in τ_Y. In addition, these terms will also include the effects of changes in τ_K and/or τ_L. This might at first seem strange, as the CES does not raise any revenue. But there still may be changes in the tax rates on capital and labor in this case because the CES may affect the quantities of capital and labor, which indirectly affects revenue and requires offsetting tax rate changes in order to keep total government revenue constant. In light of this, starting from (11), expanding the total derivatives, and making the same simplifying assumption as in the C&T case (that *X* and *Y* are separable in utility from *K* and *L*) provide an expression for the cost of the CES (see Appendix A for derivation):

$$\frac{1}{\lambda}\frac{dU}{d\tau_Z} = \tau_Z \frac{dZ}{d\tau_Z} + \tau_Y \frac{dY}{d\tau_Z} - \eta_R \mu_{IZ} Z - \eta_R \mu_{IY} Y \frac{d\tau_Y}{d\tau_Z} \qquad (18)$$

where μ_{IY} is analogous to μ_{IZ}, but with the weights depending on the shares of the burden of τ_Y rather than τ_Z. Just as in the C&T case, the effects that determine those relative weights are the same as those that determine the relative incidence of the environmental policy on capital and labor.[15] Note that the weights underlying μ_{IY} are determined not by the total incidence of the

[14] One implication of this is that if the use of revenue from a pollution tax can be optimized over a sufficiently broad range of different recycling options, then a pollution tax (or auctioned cap and trade) will always be at least as efficient as a CES. The reason is simple: imposing a pollution tax and recycling the revenue to subsidize the polluting good (*Y*) is equivalent to a CES. Hence if revenue recycling is optimized over a set of possible recycling options that includes a subsidy to *Y*, the outcome must be at least as efficient as a CES. In this section, however, we are examining the effect of a range of different recycling options that are not necessarily optimal. Arguably, what we consider are more realistic and relevant to policy discussions.

[15] In this case, the relevant prior paper on these effects is Fullerton and Heutel (2010), which focuses on the incidence of environmental mandates such as the CES.

CES on capital and labor, but rather by the incidence of the subsidy component of the CES (the incidence of the tax component of the CES is reflected in the weights that determine μ_{IZ}). Thus for μ_{IY}, the weights depend primarily on the relative factor intensity in production of the polluting good (the relative complementarity with pollution, which was important for the weights in μ_{IZ}, is not important for μ_{IY}).

Expression (18) parallels expression (15) for the C&T case. The first two terms on the right-hand side are the direct welfare effect of the CES, which comes from how the CES affects pollution emissions and the quantity of the polluting good. The third and fourth terms (i.e., the rest of the right-hand side) are the tax-interaction effect.

This tax-interaction effect has two components, corresponding to the effect of the emissions-tax component of the CES (the third term) and the effect of the output-subsidy component (the fourth term). The expression for the first (emissions-tax) component of the CES is the same as the one for the tax-interaction effect in the C&T case. The expression for the second (output-subsidy) component is analogous, though it will typically have the opposite sign, implying a welfare gain, not a loss, because it is caused by a subsidy, not a tax. As a result, the tax-interaction effect is generally more positive (i.e., a smaller welfare loss or larger gain) for the CES than for C&T. However, in contrast with the C&T case, the CES does not produce any gain from the revenue-recycling effect.

These expressions show the effects that will determine the relative cost of the two policies. C&T has a lower direct cost and gains from the revenue-recycling effect. But the CES typically benefits from a smaller loss due to the tax-interaction effect. The relative cost-effectiveness of the two policies thus depends on the relative magnitudes of these effects. The next subsection explores that comparison in more detail.

2.4. Comparing Marginal Costs under the Two Policies

In order to compare the costs under the two policies, it is useful first to convert the expressions for marginal welfare changes into expressions for the marginal cost per unit of emissions reductions. In each case, this is accomplished by dividing through by $\frac{dZ}{d\tau_Z}$. For the C&T case (starting from equation (15)), this gives

$$MC_{CT} = \tau_Z - \eta_R \mu_{IZ} \frac{Z}{dZ/d\tau_Z} + \left(\eta_R - 1\right)\left(\frac{Z + \tau_Z \, dZ/d\tau_Z}{dZ/d\tau_Z}\right) \tag{19}$$

and for the CES case (starting from equation (18)), it gives

$$MC_{CES} = \tau_Z + \tau_Y \frac{dY}{d\tau_Z} \frac{dY/d\tau_Z}{dZ/d\tau_Z} - \eta_R \mu_{IZ} \frac{Z}{dZ/d\tau_Z} - \eta_R \mu_{IY} \frac{Yd\tau_Y/d\tau_Z}{dZ/d\tau_Z} \tag{20}$$

We can then use these expressions to look at key determinants of the relative marginal costs of cap and trade versus a clean electricity standard.

2.4.1. Policy Stringency

There are two main ways in which the stringency of the policy (i.e., the amount of emissions reductions achieved) will affect the relative costs of the policies. Both tend to favor C&T as the policy becomes more stringent. The first is well known from prior work that ignores general-equilibrium effects: the direct costs tend to be higher under CES, because the CES does much less to reduce consumption of the polluting good, and the magnitude of that disadvantage grows as the policy becomes more stringent. Thus the sum of the first two terms in (20) will be larger than the first term in (19), and that difference will tend to grow as the policies become more stringent.

The second reason is that as policy becomes more stringent, the direct-cost terms become more important relative to the general-equilibrium terms (the tax-interaction and revenue-recycling effects). This is clear from examining (19) and (20): the direct-cost terms are proportional to τ_Z and τ_Y, which are initially zero and increase as the policies become more stringent. In contrast, the general-equilibrium terms depend on *Z* and *Y*, which will tend to shrink as the policies become more stringent. This means that increasing stringency will favor whichever policy fares worse with these general-equilibrium terms. In general, that could be either policy. But for cases in which the overall costs of the two policies are similar, that will be C&T: because C&T has lower direct costs, if the overall costs are similar between the two policies, then it must be because the general-equilibrium terms are more favorable to CES. Thus a more stringent policy, by making those terms relatively less important, will tend to favor C&T.

2.4.2. Level of Preexisting Taxes

Higher preexisting tax rates will tend to increase all of the η and μ terms, thus magnifying the importance of the general-equilibrium terms. Thus higher preexisting taxes will tend to favor whichever policy fares better with those general-equilibrium terms. Again, in general this could be either policy, but for cases in which the overall costs of the two policies are similar, the CES must fare better with the general-equilibrium terms. Thus in those cases, higher preexisting tax rates will tend to favor the CES.

2.4.3. Average MCPF of the Taxes That Are Reduced Using C&T Revenue

C&T will tend to fare better when the revenue it generates is used to cut a more distortionary tax than when it is used to cut a less distortionary tax. This is evident in equation (19): a higher η_R boosts the magnitude of the revenue-recycling term relative to the tax-interaction term. The intuition here is obvious: cutting a more distortionary tax provides a bigger efficiency gain than cutting a less distortionary tax. No such effect shows up for the CES, which doesn't raise revenue.

2.4.4. MCPF for the Factor That Is More Intensively Used in Production of the Polluting Good

A CES will tend to fare better when the tax on the factor that is more intensively used in production of the polluting good is more distortionary (more generally, if $\gamma_{YK} > \gamma_{YL}$, then a higher η_K relative to η_L will tend to favor the CES, but relative factor intensity is the most important determinant of the γ terms). This is evident from examining the last term in (20): that term lowers the cost of the CES, and a larger μ_{IY} will increase the magnitude of that term relative to other terms. The CES's implicit subsidy for the polluting good tends to lower the cost from the tax-interaction effect, and that becomes more important when the tax on the factor more tightly linked to that polluting good is particularly distortionary.

2.4.5. Factor Intensity in Production of the Polluting Good for the More Distorted Factor

The CES will also tend to fare better when the polluting good is more tightly connected to the factor subject to the more distortionary tax (e.g., if $\eta_K > \eta_L$, then a higher γ_{YK} will tend to favor CES). This arises for the same reason as the previous result: this tends to magnify the tax-interaction-effect advantage of the CES by boosting μ_{IY}. One highly important influence on γ_{YK} and γ_{YL} is the factor intensity in production of *Y*: the more capital-intensive *Y* is, the higher γ_{YK} will be, while the more labor-intensive *Y* is, the higher γ_{YL} will be.

2.4.6. Relative Importance of Reductions in Consumption of Polluting Goods versus Reductions in Emissions per Unit of Polluting Goods Produced

The CES will fare worse in cases where reducing consumption of polluting goods represents a relatively important channel for emissions reductions. As noted previously, the CES does not provide the right incentives to reduce consumption of polluting goods (the price increase for polluting goods is relatively small under the CES). Thus, to the extent that those reductions are an important channel for emissions reductions, the direct-cost disadvantage of the CES will be relatively large. This will occur, for example, in cases where the demand for polluting goods is relatively elastic.

Conversely, the CES will fare better in cases where reducing emissions per unit of polluting goods produced is a relatively important channel. In these cases, reducing consumption of polluting goods is relatively less important, which diminishes the direct-cost disadvantage of the CES. This will occur, for example, in cases with a high elasticity of substitution in production between polluting and nonpolluting inputs.

We have employed this analytical model to qualitatively demonstrate the key factors affecting the relative costs between CES and C&T. We now turn to a quantitative assessment using a detailed numerical model of the US economy. In particular, we will show that due to large preexisting tax distortions, especially on capital, the high capital intensity of electricity sectors, and the importance of fuel switching for achieving emissions reductions, the direct-cost disadvantages of CES are small. As a result, we find that the CES is *more* cost-effective than equivalent C&T policies when the overall stringency is low and/or the C&T revenue is used inefficiently.

3. A Numerical Model

Here we describe the structure and simulation results of an intertemporal general equilibrium model of the US economy with international trade. The model generates paths of equilibrium prices, outputs, and incomes for the United States and the rest of the world under specified policy scenarios. The key agents are producers of various goods and services, a representative household, and the government. The model captures interactions among these agents, whose actions generate supplies and demands for various commodities and productive factors. It solves for all variables at yearly intervals beginning in the benchmark year 2010.[16]

The model combines a detailed US tax system with a detailed representation of energy production and demand. The detail on taxes is key to capturing the interactions of environmental initiatives (like the CES or emissions pricing) and the tax system, as well as the significance of

[16] In the model, agents face infinite planning horizons. To derive the necessary long-term information, under each policy experiment we first calculate steady-state (terminal) conditions and then employ those conditions in performing simulations over an interval of 100 years, by which time the economic path has converged very close to the steady-state (balanced) growth path.

alternative ways to "recycle" any potential policy-generated revenues. Below we offer a brief description of the model. A detailed description is provided in Goulder and Hafstead (2013) .

3.1. Producer Behavior

The model divides US production into the 24 industry categories listed in Table 1. This division gives particular attention to energy-related industries, as it identifies separately oil and natural gas extraction, coal mining, electric power, petroleum refining, and natural gas distribution. The specification of energy supply incorporates the nonrenewable nature of crude petroleum and natural gas and the transitions from conventional to backstop fuels. The electricity sector includes three types of generators, distinguishing coal-fired electricity generation, other fossil electricity generation, and nonfossil electricity generation.[17] It also includes electric utilities that purchase electricity from the generators on the wholesale market and are responsible for transmission and distribution of electricity.

General Specifications. In each industry, a nested production structure is employed with constant elasticity of substitution functional forms at each nest.[18] In all industries except the oil and natural gas extraction industry, production exhibits constant returns to scale. Each industry is modeled via a representative firm. Every industry produces a distinct output (*X)*, which is a function of the inputs of capital (*K*), labor (*L*), an energy composite (*E*), a nonenergy (or materials) composite (*M*), and the level of investment (*I*)[19]:

$$X = f\,(K, g(L, h(E, M))) \;-\; \phi\,(I \,/\, K\,) \bullet I \tag{21}$$

The energy composite is made up of the outputs of the energy industries, while the materials composite consists of the outputs of the other industries:

$$E = E\left(\bar{x}_{1a} + \bar{x}_{1b},\ \bar{x}_2, ...,\ \bar{x}_8\right) \tag{22}$$

[17] Noncoal fossil fuel generators primarily consist of natural gas–fired generators. Nonfossil generators include nuclear, hydro, solar, and wind generators.

[18] This nesting structure rules out the possibility that labor and capital differ in their degree of complementarity with pollution. This eliminates one effect that influences the relative weights on capital and labor in the tax-interaction effect. While that effect could significantly influence the overall cost of both CES and C&T, it does not importantly affect the cost difference between the policies.

[19] In each industry, capital (*K*) is a constant-elasticity-of-substitution aggregate of structures and equipment.

$$M = M\left(\bar{x}_9, ..., \bar{x}_{24}\right) \tag{23}$$

where $\bar{x}_i$ is a composite of the good produced by domestic industry i and its foreign counterpart.[20] Industry indices correspond to those in Table 1.[21]

In the model, the nonrenewable nature of oil and gas stocks is captured by the specification of a reserve of the domestic oil and gas resource. This reserve is reduced according to the amount of production (extraction) each year. Productivity in the oil and gas industry is a decreasing function of the remaining reserve; hence extraction becomes more costly as reserves are depleted. In making profit-maximizing extraction decisions, oil and gas producers account for the effect of current production on future production costs. The domestic price of oil and gas is given by the exogenously specified world price of oil gross of tariffs. The model includes a "backstop fuels industry" that provides a perfect substitute for oil and gas. We assume that the technology for producing backstop fuels on a commercial scale becomes known only in the year 2020. We assume that backstop fuels have the same carbon content as oil and gas.[22]

The model incorporates technological change exogenously for each industry in the form of Harrod-neutral (labor-embodied) technological progress at the rate of 1 percent per year.[23]

Investment. In each industry, managers choose the level of investment to maximize the value of the firm. The investment decision takes account of the adjustment (or installation) costs represented by $\phi(I / K) \cdot I$ in equation (23). ϕ is a convex function of the rate of investment, *I/K*,

$$\phi(I / K) = \frac{(\xi / 2)(I / K - \delta)^2}{I / K} \tag{24}$$

[20] The functions *f, g*, and *h*, and the aggregation functions for the composites *E*, *M*, and $\bar{x}_i$, are CES and exhibit constant returns to scale.

[21] Indices 1a and 1b represent the oil and gas and synfuels industries, respectively. Synfuels are a "backstop technology"—a perfect substitute for oil and gas. Only the oil and gas industry is shown in Table 1 because synfuels production does not begin until 2020.

[22] In reality, some potential backstops (e.g., shale oil) have higher carbon content than others (e.g., biofuels).

[23] There is no explicit modeling of the invention of relatively new and evolving technologies such as carbon capture and storage. Such technologies may have important long-run consequences. However, they are unlikely to affect the relative costs of the CES and C&T, which is our focus here.

where δ is the rate of economic depreciation of the capital stock and ξ is the marginal adjustment cost.[24]

The attention to adjustment costs distinguishes this model from most other economy-wide general equilibrium models. These costs imply that capital is imperfectly mobile across sectors. This allows the model to capture the different impacts of policy interventions on the profits of various industries. The law of motion for capital stocks for each industry is given by $K_{s+1} = (1-\delta)K_s + I_s$.

Profits and the Value of the Firm. For a firm in a given industry and given period of time, profits can be written as

$$\begin{aligned}\pi = (1-\tau_a)[\bar{p}X - w(1+\tau_L)L - EMCOST - rDEBT - TPROP] \\ + \tau_a(DEPL + DEPR)\end{aligned} \tag{25}$$

where τ_a is the corporate tax rate (or tax rate on profits), $\bar{p}$ is the per-unit output price net of output taxes, w is the wage rate net of indirect labor taxes, τ_L is rate of the indirect tax on labor, *EMCOST* is the cost to the firm of energy and materials inputs, r is the gross-of-tax interest rate paid by the firm, *DEBT* is the firm's current debt, *TPROP* is property tax payments, *DEPL* is the current gross depletion allowance, and *DEPR* is the current gross depreciation allowance.

Based on the cash-flow identity linking sources and uses of the firm's revenues, one can derive the following expression for the value of the firm (V):

$$V_t = \sum_{s=t}^{\infty}\left[\frac{1-\tau_e}{1-\tau_v}DIV_s - VN_s\right]\mu_t(s) \tag{26}$$

This equation expresses the equity value of the firm as the discounted sum of after-tax dividends (*DIV*) net of new share issues (*VN*), where τ_e is the tax rate on dividend income and τ_v is the tax rate on capital gains. The discount factor is $\mu_t(s) \equiv \prod_{u=t}^{s}\left[1+\frac{(1-\tau_b)r_u}{1-\tau_v}\right]^{-1}$, where τ_b is the tax rate

[24] The variable ϕ captures the notion that there is an output loss associated with installing new capital as inputs are diverted to install the new capital.

on interest income. In each period, managers choose investment levels as well as cost-minimizing inputs of labor and intermediate inputs to maximize this equity value.

3.2. Household Behavior

Household decisions are made by an infinitely lived representative agent that chooses consumption, leisure, and savings in each period to maximize its intertemporal utility subject to an intertemporal budget constraint. The representative household has constant-relative-risk-aversion utility over "full consumption" *C*, which is a constant-elasticity-of-substitution composite of consumption of goods and services ($\tilde{C}$) and leisure (ℓ). $\tilde{C}$ is a Cobb-Douglas composite of 17 consumer goods, $\overline{C}_i$.[25] In turn, each consumer good $\overline{C}_i$ is a constant-elasticity-of-substitution composite of domestically and foreign produced goods. At each nest in the household's demand system, the household allocates its expenditure to obtain the composite associated with that nest at minimum cost.

3.3. The Government Sector

The public sector is represented by a single agent representing all levels of government. The government collects taxes, distributes transfers, purchases goods and services, and hires labor. Overall government expenditure is exogenous and increases at a constant rate, *g*, equal to the steady-state growth rate of the model. In the benchmark year, 2010, the government deficit is 2.6 percent of GDP. In the reference (status quo) simulation, the deficit-GDP ratio is approximately constant.

In the policy experiments in this paper, we require that the real deficit and real government spending follow the same path as in the reference case. Thus the time profile of the government's real tax receipts in the CES and C&T policy cases must be the same as in the reference case. Revenue neutrality is accomplished through lump-sum adjustments (i.e., rebating C&T auction revenue via dividend checks) or through adjustments to the marginal tax rates applying to individual income (wages, interest income, dividends, and capital gains) or corporate profits.

[25] Consumer goods are produced by combining industry outputs in fixed proportions.

3.4. Foreign Trade

Except for oil and gas imports, which are perfect substitutes for domestically produced oil and gas, imported intermediate inputs and consumer goods are imperfect substitutes for their domestic counterparts. Import prices are exogenous in foreign currency, but the domestic currency price changes with changes in the exchange rate. Export demands are modeled as functions of the foreign price of US exports and the level of foreign income (in foreign currency). The foreign price is the price in US dollars plus tariffs or subsidies, converted to foreign currency through the exchange rate. We impose the assumption of zero trade balance at each period of time. An exchange rate adjusts in each period to achieve balanced trade.

3.5. Modeling the CES and C&T

The model offers a flexible treatment of both the CES and C&T, allowing for alternative specifications as to the time profile of the regulations and the industries covered.

CES. The CES policy applies to electric utilities, affecting their demands for electricity from the three types of generators (coal-fired, other-fossil, and nonfossil).

Let $\bar{M}_t$ denote the standard in period *t*. This constraint can be expressed by

$$\frac{\sum_i a_i m_i x_{it}}{\sum_i m_i x_{it}} \geq \bar{M}_t \qquad (27)$$

The left-hand side is the ratio of "clean" electricity to total electricity demanded by the utility. The product $m_i x_{it}$ in the numerator and denominator is the quantity of electricity purchased in period *t* from generator *i* by the electric transmission and distribution industry, where x_{it} is the quantity of fuel *i* used at time *t* (in units of the model's data), and m_i is a scaling coefficient that converts these units into megawatt hours. The symbol a_i in the numerator is an indicator variable, equal to 1 if the generator type qualifies for the standard and zero otherwise.[26] Since $0 < \bar{M}_t < 1$, electricity from qualifying generators is subsidized while power from nonqualifying generators is taxed.[27]

[26] If we allow for partial credits in the policy, then $a_i \in [0,1]$. President Obama's Clean Energy Standard proposal would give a half credit to electricity from natural-gas-fired power plants.

[27] If $a_i \in [0,1]$, then a generator is taxed if $a_i < \bar{M}_t$.

Producers minimize the cost of variable inputs subject to the constraint in (27). As shown in Appendix B the constrained cost minimization problem can be replicated with an unconstrained cost minimization problem with the introduction of a revenue-neutral tax and subsidy scheme, where the utility receives a subsidy for the input of qualifying electricity and pays a tax on the input of nonqualifying electricity. Specifically, the tax on electricity from generator *i* is given by

$$\tau_{it} = p_t^{ces} m_i(\bar{M}_t - a_i) \tag{28}$$

where $p_t^{ces} \geq 0$ is the unique "price" that satisfies $\sum_i \tau_{it} x_{it} = 0$, thus making the tax-subsidy combination revenue neutral.

C&T. Cap-and-trade programs can vary along several dimensions, including the point of regulation, the nature of allowance allocation, and the presence or absence of provisions for allowance banking, borrowing, or offsets. To make a clean comparison between the cost-effectiveness of the CES and C&T programs, we introduce C&T policies that match the point of regulation of the CES. Thus we consider C&T applied only to the electric utility sector. Additionally, to simplify the analysis, we focus primarily on policies with 100 percent auctioning without banking and borrowing or offset provisions.[28]

E_t, total emissions from electricity generation in period *t*, is expressed by

$$E_t = \sum_i e_{it} x_{it} \tag{29}$$

where x_{it} again is the input (in model units) of generator i in period *t*, and e_{it} is the carbon intensity of generator *i* in period *t*. Let A_t represent the cap on total emissions from electricity generation in period *t*. The CO_2 allowance price p_t^c adjusts to equate aggregate emissions from electricity generation to the supply or cap.

Under a C&T program implemented for the electric utility sector, the utility must hold and submit emissions allowances corresponding to the emissions generated by the production of the electricity it purchases. Let p_{iu} denote the price to the utility of electricity produced by

[28] See Goulder et al. (2010) for an analysis of the trade-offs of auctioning versus free allocation and a discussion on the cost-effectiveness of alternative policy designs such as banking and borrowing and carbon offsets.

generator *i*, inclusive of the cost of emissions allowances associated with a unit of electricity. Then p_{iu} can be expressed as

$$p_{iu} = p_i + p^c e_i \tag{30}$$

where p_i is production cost excluding the allowance cost. By affecting the p_{iu}'s associated with electricity from each type of generator, C&T influences the utilities' demands for electricity from the various generators.[29]

3.6. Equilibrium

In each period, the requirements of equilibrium are that (1) labor supply equals its demand, (2) savings equals investment, and (3) government expenditure equals tax revenue less the exogenously specified government deficit. Under simulations of C&T policies, an additional equilibrium condition is that the aggregate demand for emissions allowances equals the aggregate supply (or cap).

In each period, market clearing is achieved through adjustments in output prices, the market interest rate, and lump-sum taxes or tax rates.[30] In simulations of C&T policies, the allowance price adjusts such that the aggregate demand for allowances (given by aggregate emissions from covered sectors) equals the aggregate supply each period. We impose perfect foresight on all agents' expectations.[31]

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[29] C&T also can affect the generators' production methods. The demand by utilities for electricity from generator *i* is a function of p_{iu}, which in turn is a function of the emissions associated with generator *i*'s production. To the extent that a generator recognizes this connection, it has an incentive to reduce these associated emissions. For example, coal-fired generators will have an incentive to reduce the amount of coal needed to generate a unit of electricity. In our simulations, we assume that generators are aware of this connection. Under these circumstances, a C&T program applied to utilities according to the emissions embodied in the electricity they purchase is equivalent to a C&T program imposed directly on the emissions from the generators. In our simulations of C&T, the cap is applied directly to the generators.

[30] By Walras's Law, the required number of equilibrating variables is one less than the number of equilibrium conditions. The numéraire is the nominal wage.

[31] To solve for the equilibrium, we apply a two-step algorithm similar to that of Fair and Taylor (Fair and Taylor, 1983). First we solve the model in each period for the market clearing prices, interest rates, and taxes given a set of expectations. We then iterate until we find expectations consistent with the intertemporal equilibrium condition of perfect foresight.

4. Data and Parameters

Here we sketch some main components of the data and parameter inputs to the numerical model and their sources. Detailed documentation on the 2010 dataset used for this analysis is provided in Goulder and Hafstead (2013).

4.1. Data

Industry input and output flows were obtained primarily from the 2010 input–output tables from the US Department of Commerce's Bureau of Economic Analysis (BEA). These tables were also the source for consumption, investment, government spending, employment, import, and export values by industry. Data on capital stocks by industry derive from BEA tables on the net stock of structures and equipment for each industry. Data on inputs, outputs, and capital are not available at a disaggregated level for the four electric power industries. To disaggregate the electric power industry, we must use a number of assumptions. We assume that nonfuel variable inputs are distributed across the four sectors according to revenue shares derived from the 2007 US Census of Manufacturing. We distribute overall labor input across the generators based on the labor shares derived from the 2007 US Census of Manufacturing, and distribute fixed capital based on total overnight installation costs by generator type from the US Energy Information Administration (2011).

4.2. Parameters

4.2.1. Production Parameters

The model employs production function elasticities of substitution derived from estimates by Jorgenson and Wilcoxen (1996). We translate the Jorgenson-Wilcoxen estimates of parameters for translog cost functions into elasticities of substitution parameters to make them compatible with the constant-elasticity-of-substitution function form of our model. The capital adjustment cost parameters are based on Summers (1981). For the retail sector that purchases electricity from the three generators, in our central case we employ a value of 3 for the elasticity of substitution across electricity from the different generator types. Although electricity from different sources is highly substitutable, we assume less than perfect substitutability to account for regional capacity constraints. In the sensitivity analysis in Section 5.2, we employ other values for this important parameter.

4.2.2. Household Parameters

The elasticity of substitution in consumption between goods and leisure, υ, is set to yield a compensated elasticity of labor supply of 0.4.[32] The intertemporal elasticity of substitution in consumption, σ, equals 0.5.[33] The intensity parameter α_C is set to generate a ratio of labor time to the total time endowment equal to 0.44. These parameters imply a value of 0.19 for the interest elasticity of savings between the current period and the next.

4.2.3. Emissions Parameters

Carbon dioxide emissions coefficients are set to match the distribution of emissions from energy consumption by source in 2010 (EIA 2011). Coefficients convert the input of coal and oil into emissions.[34]

5. Results

5.1. Reference Case

All simulations begin in the year 2010. We first perform a reference case simulation that assumes business-as-usual conditions and forms the reference path against which we measure the effects of policy shocks. Table 1 shows the levels of real output of each industry in the reference case in 2010, in billions of 2010 dollars.

Of key relevance to the CES and C&T policies are the emissions levels and intensities of the various electricity generators. Table 2 provides this information. The emissions indicated are based on the carbon content of the fuels combusted in the generation process. As shown in the table, coal-fired generation has by far the highest emissions intensity and represents the largest share of emissions among the generators. We attribute zero emissions to the nonfossil generators.

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[32] This lies midway in the range of estimates displayed in the survey by Russek (1996).

[33] This value falls between the lower estimates from time-series analyses (e.g., Hall (1988) and the higher ones from cross-sectional studies (e.g., Lawrance (1991).

[34] The aggregation of reported emissions sources (electric power, transportation, commercial, residential, and transportation) differs from the model industry aggregation. To match emissions by source, we make the following assumptions: (1) the coal coefficient for all industries except coal-fired electricity generators is equal and (2) the oil coefficient for all industries except petroleum refining, other-fossil electricity generation, and natural gas distribution is equal.

5.2. Policy Results

5.2.1. CES and Cap-and-Trade Policies: Central Case Simulations

We start with a focus on CES policies that are similar to those in the Obama-Bingaman proposal in terms of what qualifies as "clean" electricity. As in those proposals, nonfossil-generated electricity is given full credit and natural-gas-fired electricity is given half credit. (Coal-fired generation is considered "dirty" and receives zero credit.) Later we consider alternative specifications where we vary the credit level received by natural-gas-fired generators.

We will use the term "CES ratio" to refer to the required minimal ratio of clean generation (in megawatt hours) to total generation. In our simulations, the CES ratio begins with the business-as-usual ratio in 2013 and increases through time, ultimately settling at some target value in the year 2035.

Figure 1 shows the three CES time profiles on which we focus. The policies are designed to achieve 20, 30, and 40 percent cumulative emissions reductions in the time period from 2013 to 2035. In 2035 and afterward, the ratios of clean to total electricity under these policies are 59.4, 68.4, and 77.7 percent, respectively.[35]

Figure 2 displays the time profile of CO_2 emissions in the reference case and under the three CES policies. The kink at year 2035 reflects the fact that the ratios remain constant starting in that year. As a result, emissions no longer decline but instead increase with the growth rate of the economy.

As mentioned in Section 3.5 above, the CES is equivalent to a revenue-neutral tax and subsidy program, where the utility's electricity purchase involves either a tax or subsidy depending on whether the electricity is produced through "clean" generation. Figure 3 displays the shadow tax and subsidy rates applying to the electricity from the three generators. For each generator *i*, these correspond to τ_{it} in equation (30) above. From 2013 through 2035, the shadow tax on electricity from coal-fired generators tends to rise. This reflects the increasing stringency of the CES over time and the associated need to induce greater substitution away from coal-fired electricity. Starting in 2035, the CES ratio is held constant, and the shadow tax no longer increases. Indeed, it falls. The pattern for nonfossil-generated electricity is the opposite of that

[35] The most stringent policy is closest to the Obama-Bingaman proposal, which aimed to achieve a ratio of 80 percent by 2035.

for coal-fired electricity. Because nonfossil generation is deemed clean, it receives a subsidy. The subsidy is initially high and decreases over the medium term before increasing again through 2035. The shift from a decreasing subsidy to an increasing one tends to correspond to the shift of “other-fossil” electricity (principally natural gas fired) from a subsidy to a tax. In the central case simulations considered here, “other-fossil” generators receive partial credit. In the initial years of the policy, the required CES ratio $\bar{M}_t$ is less than the partial credit, which from equation (30) implies that other-fossil-generated electricity receives a subsidy. Over time, the CES ratio $\bar{M}_t$ is increased. It eventually exceeds the credit, and the subsidy becomes a tax.

To allow for a clean comparison of the CES and C&T policies, the emissions caps for the electricity sector for each year are set to match the emissions that result from that sector under the CES policies.[36] In these initial comparisons, the C&T policy involves auctioning 100 percent of the emissions allowances, with revenues recycled through cuts in the marginal income tax rates. (Below we will assess how alternative methods of revenue recycling affect the costs of the C&T policy, absolutely and relative to the costs under the CES.)

Figure 4 compares the CES and C&T policies in terms of their impacts on the present value of GDP over the interval 2013–2035. Except in the case with the least stringent CES, the GDP costs of the CES are greater than those of C&T, although the disadvantage is small when the policies are not stringent. Figure 5 also displays the relative costs of the two policies, in this case in terms of the equivalent variation welfare measure. Again the relative costs depend on stringency. Under the equivalent variation welfare measure, the CES is less costly at low levels of stringency. The results in both figures reflect the cost trade-off between the two policies and how those trade-offs vary with stringency. The CES has a direct cost disadvantage because it doesn’t raise electricity prices as much as C&T and thus provides less incentive to reduce consumption of electricity. And because it doesn’t raise revenue, it gets no benefit from the revenue-recycling effect. However, it also produces a smaller tax-interaction effect, and that advantage dominates at low levels of stringency. But as the policy becomes more stringent, the direct-cost disadvantage of the CES grows relative to its tax-interaction advantage, and thus for higher levels of stringency, C&T has lower costs.

[36] An alternative is to match economy-wide emissions each year under the two types of policies. We find that the results for the relative costs of CES and C&T are similar when we adopt this alternative.

Figure 6 contrasts the impacts of the CES and C&T policies on the demand for electricity. Because electricity prices are higher under C&T than CES, the quantity of electricity demanded is lower in the C&T case. In the long run, the demand reduction is nearly 3.5 times as large as in the C&T policy in the 20 percent emissions reduction policy, and about 1.9 times larger in the 40 percent reduction policy.

Figure 7 displays the effects of the CES and C&T policies on the price of the consumption bundle as the percent change in price relative to the reference case for 2013–2110.[37] Because C&T raises electricity prices more, it has a more pronounced effect on the price level than the equivalent CES policy. The difference in the price increases is relatively small in the early years of the policy, but the difference is increasing over time as the policies become more stringent. These differing impacts in prices underlie the differences indicated earlier in the costs of the two policies. Cap and trade's larger price impacts imply a larger tax-interaction effect. In Figure 7, the deviation in percentage increases in prices is largest for the most stringent policy, although the ratio of these percentage increases declines with stringency.

5.2.2. Isolating the Tax-Interaction Effect

We now examine results from counterfactual simulations in which we have altered the level of preexisting taxes. This enables us to isolate and assess the impact of the tax-interaction effect, as the magnitude of the tax-interaction effect is positively related to the levels of such taxes.

Figure 8a compares the welfare costs of CES and C&T under the scenarios that differ in terms of the preexisting individual income taxes (taxes on wages, interest, and dividends). The comparisons are for policies involving intermediate stringency (30 percent cumulative emissions reductions over the interval 2013–2035). The CES policy offers other-fossil-generated electricity a half credit, as in the Obama-Bingaman proposal, and the C&T policy involves auctioning of the emissions allowances, with revenues recycled lump-sum to households.[38] Figure 8b

[37] The percent change in other aggregate prices, such as the price of the producer price index, displays a time profile and pattern similar to those of the percent change in the price of the consumption bundle.

[38] For simplicity, in the simulations shown in Figure 8, revenue neutrality is achieved through lump-sum recycling of the policy-generated revenues. As a result, the benefit associated with each dollar returned to the private sector is the same (one dollar), regardless of the level of preexisting taxes. If instead the recycling were in the form of cuts in existing income tax rates, the value of the recycling would depend on the preexisting marginal rates. This added dimension would unnecessarily complicate the analysis.

compares the same policies across scenarios differing in terms of preexisting individual income taxes and corporate income tax rates.

As predicted by the analytical model, the level of welfare costs for both the CES and C&T policies are increasing in the level of preexisting taxes. Additionally, the ratio of the CES policy's welfare cost to that of the C&T policy is decreasing in the size of preexisting taxes. This confirms the relative advantage of the CES in terms of a smaller tax-interaction effect. These results are particularly magnified when corporate income taxes are included in Figure 8b, as corporate income taxes are more distortionary than personal income taxes in our model.

5.2.3. Factor Intensities of the Electricity Sector

The analytical model predicted that the CES will fare better when the polluting good is tightly tied to the factor subject to the more distortionary tax. In our model, capital is subject to the more distortionary tax, as taxes on individual and corporate capital income have a higher marginal excess burden than taxes on labor income. Thus the analytical model predicts that the ratio of the cost of the CES to that of C&T will increase to the extent that the capital intensity of the electric utility sector is reduced. To test this prediction, we run counterfactual simulations in which we reduce the capital intensity of the electric utility sector.[39] Figure 9 shows that the welfare costs of both CES and C&T are declining in the capital intensity of the utility sector. As predicted by the analytical model, the welfare costs of C&T decline relatively more than the welfare costs of the corresponding CES policies, because the tax on capital (through individual capital income and corporate income taxes) is more distortionary than the tax on labor.

5.2.4. Alternative Cap-and-Trade Specifications

In most of the C&T policies considered above, emissions allowances were auctioned and the revenues were recycled through cuts in the marginal rates of personal income taxes. However, the method of revenue recycling can affect the relative costs of C&T and the CES. Figure 10 compares costs of C&T and the CES under a range of revenue-recycling specifications for the C&T policy. The case labeled "C&T, Auctioning, Net MTR LK" is the case we focused on earlier. "C&T, Auctioning, Net MTR C" recycles revenues through cuts in corporate income taxes. "C&T, Auctioning, Net LS" refers to the case where net revenues are returned to

[39] To do this, we shift $200 billion or $400 billion from K to L in the 2010 dataset.

households via lump-sum rebates. “C&T, Free Allocation” refers to the case where all of the allowances are distributed free to generators.

The results in this figure reveal circumstances where the CES is less costly than C&T. As prior studies have emphasized,[40] the costs of C&T increase when auction revenues are returned lump-sum (rather than via marginal rate cuts) or when allowances are given out for free. As shown in these figures, when C&T has either of these two features, it is always more costly than the CES, even when the policy is not very stringent.

As shown in the analytical section, C&T will tend to fare better when the revenue it generates is used to cut a more distortionary tax than when the revenue is used to cut a less distortionary tax. The MCPF of individual income taxes is \$1.17 and of corporate income taxes is \$1.77; therefore, C&T will be less costly when corporate income taxes are reduced than when personal income taxes are reduced. Figure 10 shows that C&T always performs better than CES when revenues are used to cut corporate tax rates.

5.2.5. Alternative CES Specifications: Partial Credit for Natural Gas

Figure 11 shows the ratio of welfare costs (CES/C&T) under a range of credits to natural gas.[41] As the credit received by natural-gas-generated electricity increases, the relative cost of CES decreases. If natural-gas-fired electricity receives zero credit, the CES will not induce efficient substitution between the two carbon-based electricity generators. If natural-gas-fired electricity receives a full credit, the CES will not induce efficient substitution between natural-gas-fired electricity and renewables. In contrast, a C&T system that charges a uniform price for CO_2 emissions will promote the generator-switching pattern that minimizes direct costs. A CES would provide similar incentives if it credits gas generation based on its relative emissions intensity; this would imply gas generation receiving 0.58 times credit.[42] However, Figure 11 shows that the relative cost is minimized on the chart at a credit of about 0.8, implying that costs are minimized by giving gas more credit than its emissions intensity would suggest. This suggests that favoring gas generation tends to reduce the general-equilibrium components of the

[40] See, for example, Parry and Oates (2000) and Goulder et al. (1999).

[41] In each of the simulations here, revenues are recycled through cuts in personal income tax rates.

[42] Using 2010 emissions, the ratio of emissions per megawatt hour of other-fossil electricity to coal-fired electricity is 0.42.

CES cost.[43] Currently, EPA is developing rules for limiting CO_2 emissions through Section 111(d) of the Clean Air Act. Our results on partial credits for natural gas suggest the most cost-effective rules will be ones that give slightly more credit to gas than emissions ratios would suggest (though still not full credit). Rules that simply limit the amount of emissions per unit of electricity by fuel type, such as the rules that were proposed for new sources, would not promote efficient fuel switching.

5.2.6. Further Sensitivity Analysis

Figure 12 displays the welfare costs under alternative elasticities of labor supply. The lower elasticity is 0.3 and the higher elasticity is 0.5. The welfare cost of achieving a given level of emissions reductions is increasing in the level of the elasticity of labor supply.[44] However, the relative welfare cost of the CES policy to the C&T policy is approximately constant across varying elasticities of labor supply.

Figure 13 displays the welfare costs under alternative elasticities of substitution across generators in the utilities' production function. In our central case, the value of this elasticity is 3. Here we consider values of 2 and 4 as well. As expected, both the level of welfare costs and the relative cost of CES to cap and trade is decreasing in the elasticity of substitution across generators. When the elasticity is high, it is easy for electric utilities to substitute between generators, and therefore the aggregate price increases and welfare losses will be reduced. As discussed, the CES relies more heavily on this substitution than C&T, which makes more efficient use of the channel of reduced overall demand for electricity. Because of the greater weight attached to substitution under the CES, greater substitutability enhances the relative attractiveness of the CES policy. Symmetrically, lower substitutability reduces the relative attractiveness of CES.

6. Conclusions

In a realistic economy with prior taxes on factors of production, the CES has a potential attraction relative to an electricity-sector C&T program: it produces a smaller tax-interaction

[43] This result is similar to Lemoine's (2013) result that welfare-maximizing intensity ratings do not always reflect actual emissions intensities due to market interactions, though that paper does not consider interactions with tax distortions.

[44] The CES target in 2035 is varied across alternative labor supply elasticities such that the level of emissions reductions is constant across policies.

effect. This raises the possibility that the CES might not suffer a disadvantage relative to cap and trade on cost-effectiveness grounds.

This paper has employed analytical and numerical general equilibrium models to assess the relative cost-effectiveness of the CES and an electricity-sector C&T program. Numerical simulations indicate that a well-designed CES is more cost-effective than C&T (even when C&T revenue is recycled to cut marginal tax rates) when relatively minor reductions in emissions are called for. To achieve maximal cost-effectiveness, the CES needs to offer partial credit to natural-gas-fired electricity. The CES can more easily overtake C&T in terms of cost-effectiveness when the C&T program involves free allowance allocation or when revenues from auctioned allowances are rebated lump-sum.

Although emissions pricing remains an exceptionally attractive vehicle for reducing greenhouse gas emissions, these results demonstrate that the advantage of such pricing in terms of cost-effectiveness is less clear once interactions with the tax system are taken into account. As climate change policy continues to evolve at the state and federal levels in the United States, reducing emissions from coal-fired power plants is likely to remain a priority. States may increasingly rely on renewable portfolio standards (the state-level equivalent to a federal CES), and federal policy discussions may continue to consider the CES as well as emissions-pricing policies such as a federal carbon tax. In assessing these policy options, it is important to consider the interactions with the tax system because, as indicated here, such interactions significantly affect their relative costs.

Appendix A. Analytical Derivations

Derivation of Equation (15)

The first step in going from equation (12) to equation (15) is to derive expressions for $d\tau_K / d\tau_Z$ and $d\tau_L / d\tau_Z$. Taking a total derivative of the government budget constraint (10) and substituting in $dG = 0$ and $\tau_Y = 0$ yields

$$\left(Z + \tau_Z \frac{dZ}{d\tau_Z} + \tau_L \frac{\partial(wL)}{\partial \tau_Z} + \tau_K \frac{\partial(rK)}{\partial \tau_Z} \right) d\tau_Z + \left(rK + \tau_L \frac{\partial(wL)}{\partial \tau_K} + \tau_K \frac{\partial(rK)}{\partial \tau_K} \right) d\tau_K + \left(wL + \tau_L \frac{\partial(wL)}{\partial \tau_L} + \tau_K \frac{\partial(rK)}{\partial \tau_L} \right) d\tau_L = 0 \tag{A.31}$$

The share α_K of marginal revenue from the carbon tax (the first term in (A.31) is used to reduce the capital tax and the share α_L is used to reduce the labor tax. Together with (A.31), these imply

$$\frac{d\tau_K}{d\tau_Z} = -\alpha_K \frac{Z + \tau_Z \frac{dZ}{d\tau_Z} + \tau_L \frac{\partial(wL)}{\partial \tau_Z} + \tau_K \frac{\partial(rK)}{\partial \tau_Z}}{rK + \tau_L \frac{\partial(wL)}{\partial \tau_K} + \tau_K \frac{\partial(rK)}{\partial \tau_K}} \tag{A.32}$$

and

$$\frac{d\tau_L}{d\tau_Z} = -\alpha_L \frac{Z + \tau_Z \frac{dZ}{d\tau_Z} + \tau_L \frac{\partial(wL)}{\partial \tau_Z} + \tau_K \frac{\partial(rK)}{\partial \tau_Z}}{wL + \tau_L \frac{\partial(wL)}{\partial \tau_L} + \tau_K \frac{\partial(rK)}{\partial \tau_L}} \tag{A.33}$$

Substituting (A.32) and (A.33) into (12) and rearranging, using (13), (14), and (16) yields

$$\frac{1}{\lambda} \frac{dU}{d\tau_Z} = \tau_Z \frac{dZ}{d\tau_Z} + \eta_R \left[\tau_K \frac{\partial(rk)}{\partial \tau_Z} + \tau_L \frac{\partial(wL)}{\partial \tau_Z} \right] + (\eta_R - 1) \left(Z + \tau_Z \frac{dZ}{d\tau_Z} \right) \tag{A.34}$$

The last remaining step is to expand the tax-interaction term (the second term on the right-hand side of (A.34)). To do this, recognize that the marginal burden of τ_Z is *Z*, and the marginal burden of τ_K is *rK*. So having γ_{ZK} share of the burden fall on capital implies that portion of the tax-interaction effect is equivalent to an increase in τ_K of $\gamma_{ZK} Z / rK$. Following the analogous step for τ_L lets us express the tax-interaction term as

$$\eta_R\left[\tau_K\frac{\partial(rk)}{\partial\tau_Z}+\tau_L\frac{\partial(wL)}{\partial\tau_Z}\right]= \\ \eta_R Z\left[\frac{\gamma_{ZK}}{rK}\left(\tau_K\frac{\partial(rk)}{\partial\tau_K}+\tau_L\frac{\partial(wL)}{\partial\tau_K}\right)+\frac{\gamma_{ZL}}{wL}\left(\tau_K\frac{\partial(rk)}{\partial\tau_L}+\tau_L\frac{\partial(wL)}{\partial\tau_L}\right)\right] \tag{A.35}$$

Rearranging (A.35), using (13) and (14) yields

$$\eta_R\left[\tau_K\frac{\partial(rk)}{\partial\tau_Z}+\tau_L\frac{\partial(wL)}{\partial\tau_Z}\right]=\eta_R Z\left[\gamma_{ZK}\frac{1-\eta_K}{\eta_K}+\gamma_{ZL}\frac{1-\eta_K}{\eta_K}\right] \tag{A.36}$$

Substituting (A.36) and (17) into (A.34) yields (15).

Derivation of Equation (18)

Expanding the total derivatives from (11) yields

$$\frac{1}{\lambda}\frac{dU}{d\tau_Z}=\tau_Z\frac{dZ}{d\tau_Z}+\tau_Y\frac{dY}{d\tau_Z}+\tau_K\frac{\partial(rk)}{\partial\tau_Z}+\tau_L\frac{\partial(wL)}{\partial\tau_Z} \\ +\frac{d\tau_Y}{d\tau_Z}\left[\tau_K\frac{\partial(rk)}{\partial\tau_Y}+\tau_L\frac{\partial(wL)}{\partial\tau_Y}\right]+\frac{d\tau_K}{d\tau_Z}\left[\tau_K\frac{\partial(rK)}{\partial\tau_K}+\tau_L\frac{\partial(wL)}{\partial\tau_K}\right] \\ +\frac{d\tau_L}{d\tau_Z}\left[\tau_K\frac{\partial(rK)}{\partial\tau_L}+\tau_L\frac{\partial(wL)}{\partial\tau_L}\right] \tag{A.37}$$

The CES is equivalent to a revenue-neutral combination of τ_Y and τ_Z. This implies that

$$\frac{d\tau_Y}{d\tau_Z}=-\frac{Z+\tau_Z\dfrac{dZ}{d\tau_Z}}{Y+\tau_Y\dfrac{dY}{d\tau_Z}} \tag{A.38}$$

Note however, that because the CES still affects the revenue from other taxes, it still implies a change in τ_K and τ_L. Following a similar set of steps to those that gave (A.32) and (A.33) yields

$$\frac{d\tau_K}{d\tau_Z} = -\alpha_K \frac{\tau_L \frac{\partial(wL)}{\partial\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z} + \frac{d\tau_Y}{d\tau_Z}\left[\tau_L \frac{\partial(wL)}{\partial\tau_Y} + \tau_K \frac{\partial(rK)}{\partial\tau_Y}\right]}{rK + \tau_L \frac{\partial(wL)}{\partial\tau_K} + \tau_K \frac{\partial(rK)}{\partial\tau_K}} \tag{A.39}$$

and

$$\frac{d\tau_L}{d\tau_Z} = -\alpha_L \frac{\tau_L \frac{\partial(wL)}{\partial\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z} + \frac{d\tau_Y}{d\tau_Z}\left[\tau_L \frac{\partial(wL)}{\partial\tau_Y} + \tau_K \frac{\partial(rK)}{\partial\tau_Y}\right]}{wL + \tau_L \frac{\partial(wL)}{\partial\tau_L} + \tau_K \frac{\partial(rK)}{\partial\tau_L}} \tag{A.40}$$

Substituting (A.39) and (A.40) into (A.37) and rearranging, using (13), (14), and (16) yields

$$\begin{aligned} &\frac{1}{\lambda}\frac{dU}{d\tau_Z} = \tau_Z \frac{dZ}{d\tau_Z} + \tau_Y \frac{dY}{d\tau_Z} \\ &+\eta_R \left\{\tau_K \frac{\partial(rk)}{\partial\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} + \frac{d\tau_Y}{d\tau_Z}\left[\tau_K \frac{\partial(rk)}{\partial\tau_Y} + \tau_L \frac{\partial(wL)}{\partial\tau_Y}\right]\right\} \end{aligned} \tag{A.41}$$

which is analogous to (A.34). Then to get from (A.41) to (18), follow the same steps that led from (A.34) to (15).

Appendix B. Constant-Elasticity-of-Substitution Cost Minimization

A clean energy standard is a constraint on the optimal input decision making process made by an electric utility that buys wholesale electricity from multiple generators. The purpose of this appendix is to show that the constrained cost minimization problem imposed by the clean energy standard can be replicated by an unconstrained cost minimization problem with taxes and subsidies when the utility aggregates electricity from multiple generators using a constant-elasticity-of-substitution aggregation function.

B.1 Constrained Cost Minimization

A producer uses *N* intermediate inputs in production, x_i for $i = 1,...,N$. The intermediate inputs are combined into a composite intermediate with a constant-elasticity-of-substitution aggregation function,

$$X = \gamma\left[\sum_{i=1}^{N}\alpha_i x_i^{\rho}\right]^{\frac{1}{\rho}} \tag{B.1}$$

Each intermediate input *i* has unit price p_i. The problem of the producer is to obtain the composite good *X* at the lowest cost subject to a constraint. The constraint is to use a minimum amount of a given intermediate input. Without loss of generality, assume the constraint is on good *N* such that

$$\frac{\beta_N x_N}{\sum_{i=1}^{N}\beta_i x_i} \geq \overline{a} \tag{B.2}$$

where β_i is a scalar (used to transform measures of input, if necessary) and $\overline{a}$ is the minimum utilization of good *N*. The Lagrangian for this problem can be written as

$$L = \sum_{i=1}^{N} p_i x_i + \lambda\left\{\gamma\left[\sum_{i=1}^{N}\alpha_i x_i^{\rho}\right]^{\frac{1}{\rho}} - X\right\} + \mu\left[\beta_N X_N - \overline{a}\sum_{i=1}^{N}\beta_i x_i\right] \tag{B.3}$$

where μ is the Lagrange multiplier on the input constraint. The FOC for input $i \in [1,...,N-1]$ is

$$p_i = \lambda \left[\gamma \left[\sum_{i=1}^{N} \alpha_i x_i^{\rho} \right]^{\frac{1}{\rho}-1} \alpha_i x_i^{\rho-1} \right] - \mu \bar{a} \beta_i$$

and the FOC for good N is

$$p_N = \lambda \left[\gamma \left[\sum_{i=1}^{N} \alpha_i x_i^{\rho} \right]^{\frac{1}{\rho}-1} \alpha_N x_N^{\rho-1} \right] + \mu(1-\bar{a})\beta_N$$

The optimal input equates marginal cost to the marginal benefit plus an adjustment for whether a marginal increase in the input helps or hurts the producer meet the constraint.

By combining the FOC, the relative demand for any two inputs can be written as

$$\frac{x_i}{x_j} = \left[\frac{\alpha_i}{\alpha_j} \frac{\hat{p}_j}{\hat{p}_i} \right]^{\sigma} \tag{B.4}$$

where $\hat{p}_i = p_i + \mu \bar{a} \beta_i$ for $i \in [1,...,N-1]$ and $\hat{p}_N = p_N - \mu(1-\bar{a})\beta_N$. Given the optimal constrained unit price P^C,

$$P^C = \gamma^{\frac{\sigma}{\sigma-1}} \left[\sum_{i=1}^{N} \alpha_i^{\sigma} \hat{p}_i^{-\sigma} p_i \right]^{\frac{1}{1-\sigma}} \tag{B.5}$$

the optimal input intensity for a given input can be written as

$$\frac{x_j}{X} = \left[\frac{\alpha_j}{\gamma} \right]^{\sigma} \left[\frac{\hat{p}_j}{P^C} \right]^{-\sigma} \tag{B.6}$$

The constrained minimization problem is completed when the value of μ is found such that the inequality constraint is exactly binding. Assuming a binding equality constraint, the constraint can be rewritten as

$$\sum_{i=1}^{N-1} \frac{\beta_i}{\beta_N} \frac{x_i}{x_N} = \frac{1-\bar{a}}{\bar{a}} \tag{B.7}$$

Substituting into Equation (B.4),

$$\sum_{i=1}^{N-1} \frac{\beta_i}{\beta_N} \left[\frac{\alpha_i}{\alpha_N} \frac{p_N - \mu(1-\bar{a})\beta_N}{p_i + \mu\bar{a}\beta_i} \right]^{\sigma} = \frac{1-\bar{a}}{\bar{a}} \tag{B.8}$$

The shadow value μ is the unique value that satisfies Equation (B.8).

B.2 Tax/Subsidy Cost Minimization

Let τ_i represent a per unit input tax (subsidy if $\tau_i < 0$) for input *i*. The Lagrangian for the producer problem is

$$L = \sum_{i=1}^{N} (p_i + \tau_i) x_i + \lambda \left\{ \gamma \left[\sum_{i=1}^{N} \alpha_i x_i^{\rho} \right]^{\frac{1}{\rho}} - X \right\} \tag{B.9}$$

and the corresponding FOC are given by

$$p_i + \tau_i = \lambda \left[\gamma \left[\sum_{i=1}^{N} \alpha_i x_i^{\rho} \right]^{\frac{1}{\rho}-1} \alpha_i x_i^{\rho-1} \right]$$

Again, the FOC can be combined and the relative demand for inputs is

$$\frac{x_i}{x_j} = \left[\frac{\alpha_i}{\alpha_j} \frac{\tilde{p}_j}{\tilde{p}_i} \right]^{\sigma} \tag{B.10}$$

where $\tilde{p} = p_i + \tau_i$. Given the optimal unconstrained unit price P^U,

$$P^U = \gamma^{\frac{\sigma}{\sigma-1}} \left[\sum_{i=1}^{N} \alpha_i^{\sigma} \tilde{p}_i^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \tag{B.11}$$

the optimal input intensity in the tax/subsidy unconstrained minimization problem is

$$\frac{x_j}{X} = \left[\frac{\alpha_j}{\gamma} \right]^{\sigma} \left[\frac{\tilde{p}_j}{P^U} \right]^{-\sigma} \tag{B.12}$$

B.3 Equating Constrained and Tax/Subsidy Minimization Problems

This section will show that a revenue neutral combination of taxes and subsidies on inputs can replicate the constrained cost minimization problem.

Proposition 1: Let $\tau_i = p^{CES}\bar{a}\beta_i$ for $i \in (1,\dots,N-1)$ and $\tau_N = -p^{CES}(1-\bar{a})\beta_N$ denote the taxes and subsidies on the inputs. The unique value of p^{CES} such that $\sum_{i=1}^{N}\tau_i x_i = 0$ is exactly equal to the shadow value μ from the constrained problem with constraint $\beta_N X_N - \bar{a}\sum_{i=1}^{N}\beta_i x_i \geq 0$.

Proof: Substituting the tax/subsidies into the revenue neutral constraint $\sum_{i=1}^{N}\tau_i x_i = 0$ yields

$$\sum_{i=1}^{N-1} p^{CES}\bar{a}\beta_i x_i = p^{CES}(1-\bar{a})\beta_N x_N$$

Dropping p^{CES} from both sides and rearranging,

$$\sum_{i=1}^{N-1}\frac{\beta_i}{\beta_N}\frac{x_i}{x_N} = \frac{1-\bar{a}}{\bar{a}}$$

Using Equation (B.10),

$$\sum_{i=1}^{N-1}\frac{\beta_i}{\beta_N}\left[\frac{\alpha_i}{\alpha_N}\frac{p_N - p^{CES}(1-\bar{a})\beta_N}{p_i + p^{CES}\bar{a}\beta_i}\right]^{\sigma} = \frac{1-\bar{a}}{\bar{a}} \tag{B.13}$$

Equation (B.13) is the exact same equation as Equation (B.8) from the constrained minimization problem. Therefore, $p^{CES} = \mu$ when $\tau_i = p^{CES}\bar{a}\beta_i$ for $i \in (1,\dots,N-1)$, $\tau_N = -p^{CES}(1-\bar{a})\beta_N$, and $\sum_{i=1}^{N}\tau_i x_i = 0$.

Proposition 2: If $\tau_i = p^{CES}\bar{a}\beta_i$ for $i \in (1,\dots,N-1)$, $\tau_N = -p^{CES}(1-\bar{a})\beta_N$, and $\sum_{i=1}^{N}\tau_i x_i = 0$, then $P^C = P^U$, where P^C is the unit price from the constrained minimization problem with constraint $\beta_N X_N - \bar{a}\sum_{i=1}^{N}\beta_i x_i \geq 0$.

Proof: Given that $P^U X$ is by definition equal to the sum of the costs of individual inputs,

$$P^U X = \sum_{i=1}^{N} (p_i + \tau_i) x_i = \sum_{i=1}^{N} p_i x_i$$

where the second equality holds if and only if $\sum_{i=1}^{N} \tau_i x_i = 0$. Using Equation (B.12) and rearranging,

$$P^U = \gamma^{\frac{\sigma}{\sigma-1}} \left[\sum_{i=1}^{N} \alpha_i^{\sigma} (p_i + \tau_i)^{-\sigma} p_i \right]^{\frac{1}{1-\sigma}} \tag{B.14}$$

Using proposition 1, $\tau_i = p^{CES} \bar{a} \beta_i = \mu \bar{a} \beta_i$ for $i \in (1,...,N-1)$ and $\tau_N = -p^{CES}(1-\bar{a})\beta_N = -\mu(1-\bar{a})\beta_N$; therefore $p_i + \tau_i = \hat{p}_i$ for all *i* and therefore by Equations (B.5) and (B.14), $P^C = P^U$.

Proposition 3: If $\tau_i = p^{CES} \bar{a} \beta_i$ for $i \in (1,...,N-1)$, $\tau_N = -p^{CES}(1-\bar{a})\beta_N$, and $\sum_{i=1}^{N} \tau_i x_i = 0$, then the optimal input intensities from the unconstrained tax/subsidy problem are equal to optimal input intensities from the constrained minimization problem with constraint $\beta_N X_N - \bar{a} \sum_{i=1}^{N} \beta_i x_i \geq 0$.

Proof: Recall that the optimal input intensity from the constrained problem is

$$\frac{x_j}{X} = \left[\frac{\alpha_j}{\gamma} \right]^{\sigma} \left[\frac{\hat{p}_j}{P^C} \right]^{-\sigma}$$

where $\hat{p}_i = p_i + \mu \bar{a} \beta_i$ for $i \in [1,...,N-1]$ and $\hat{p}_N = p_N - \mu(1-\bar{a})\beta_N$. Also recall that the optimal input intensity from the unconstrained problem is

$$\frac{x_j}{X} = \left[\frac{\alpha_j}{\gamma} \right]^{\sigma} \left[\frac{\tilde{p}_j}{P^U} \right]^{-\sigma}$$

where $\tilde{p}_i = p_i + p^{CES} \bar{a} \beta_i$ for $i \in [1,...,N-1]$ and $\tilde{p}_N = p_N - p^{CES}(1-\bar{a})\beta_N$. It should be clear by Proposition 1 that $\tilde{p}_i = \hat{p}_i$ for all *i* when $\tau_i = p^{CES} \bar{a} \beta_i$ for $i \in (1,...,N-1)$, $\tau_N = -p^{CES}(1-\bar{a})\beta_N$, and $\sum_{i=1}^{N} \tau_i x_i = 0$. Given $P^C = P^U$ by Proposition 2, the revenue-neutral tax/subsidy scheme with taxes and subsidies equal to the marginal cost of the constraint replicates the optimal input intensities of the constrained cost minimization problem.

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Figures and Tables

See following pages.

Table 1. Output[1] in 2010 by Industry in Reference Case

Industry	**Output**	**Pct. of Total Output**
1a. Oil and Gas Extraction	272.2	0.7
2. Electric Utilities	441.0	1.2
3. Coal-Fired Electricity Generation	100.1	0.3
4. Other Fossil Electricity Generation	57.8	0.2
5. Nonfossil Electricity Generation	64.2	0.2
6. Coal Mining	79.5	0.2
7. Natural Gas Distribution	144.9	0.4
8. Petroleum Refining	573.4	1.5
9. Agriculture and Forestry	506.9	1.4
10. Noncoal Mining	69.6	0.2
11. Water Utilities	48.6	0.1
12. Construction	5,325.4	14.4
13. Food, Tobacco, and Beverages	970.2	2.6
14. Textiles	186.7	0.5
15. Wood and Paper Products	456.4	1.2
16. Chemicals and Misc. Nonmetal Products	1,527.5	4.1
17. Primary Metals	311.7	0.8
18. Machinery	2,247.2	6.1
19. Motor Vehicle Production	719.9	1.9
20. Transportation	803.8	2.2
21. Railroads	143.1	0.4
22. Information and Communication	1,109.2	3.0
23. Services	15,973.5	43.1
24. Owner-Occupied Housing	4,918.1	13.3

[1] In billions of 2010 dollars.

Table 2. Emissions and Emissions Intensities by Generator

Generator	Billions MWh (2010)	Emissions[1]	Emissions Per MWh (2010)
Coal-Fired	1.84	1.83	0.99
Other Fossil	1.04	0.43	0.42
Nonfossil	1.24	0.00	0.00

[1] In billions metric tons CO_2.

Figure 1. CES Ratio by Time and Stringency, 2013-2050

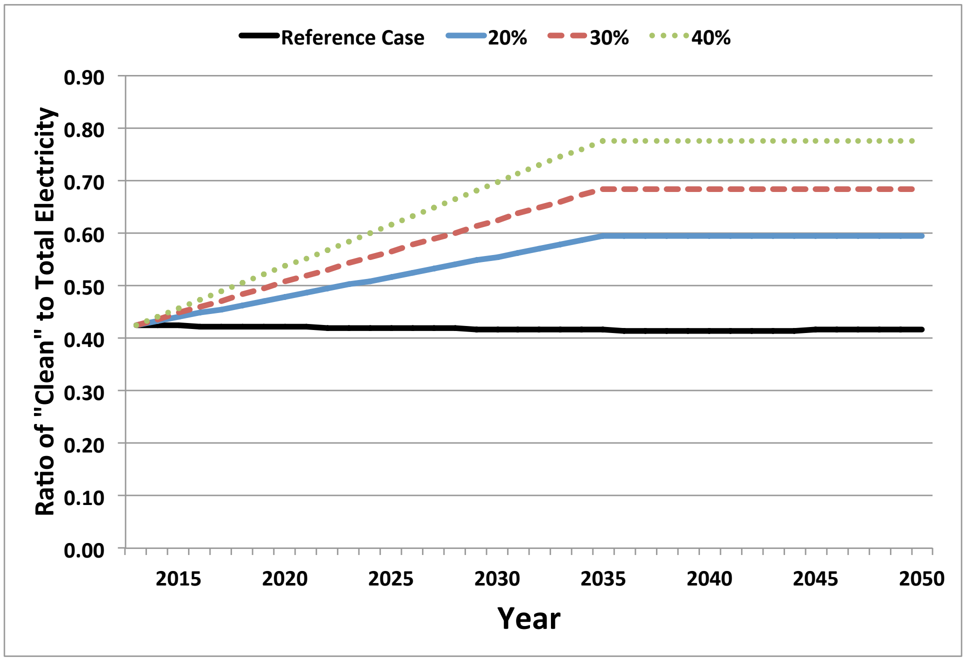


Figure 2. Emissions from Electricity Generation, 2013-2050

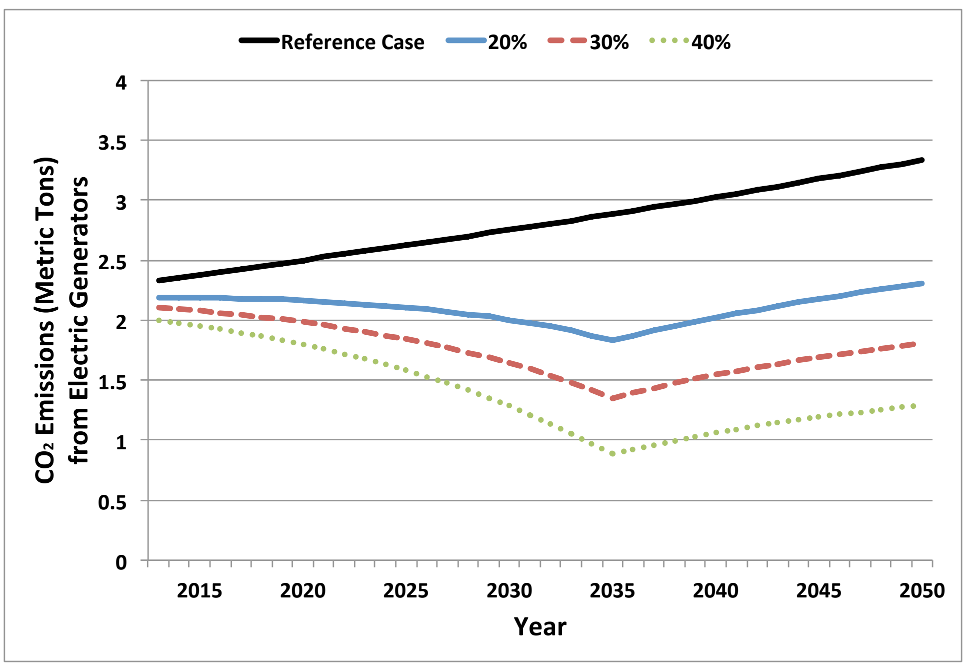
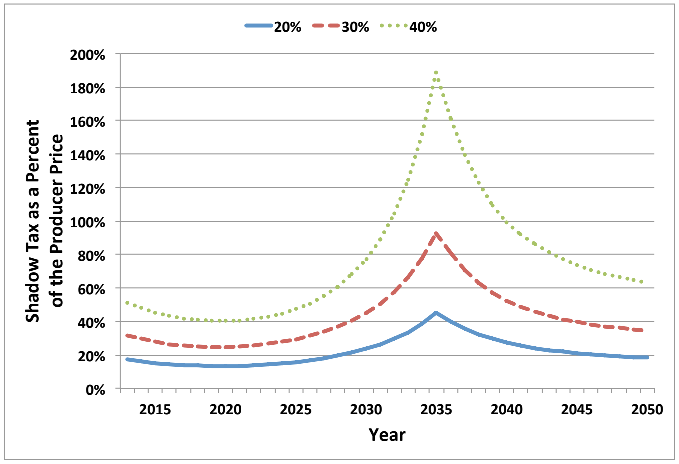
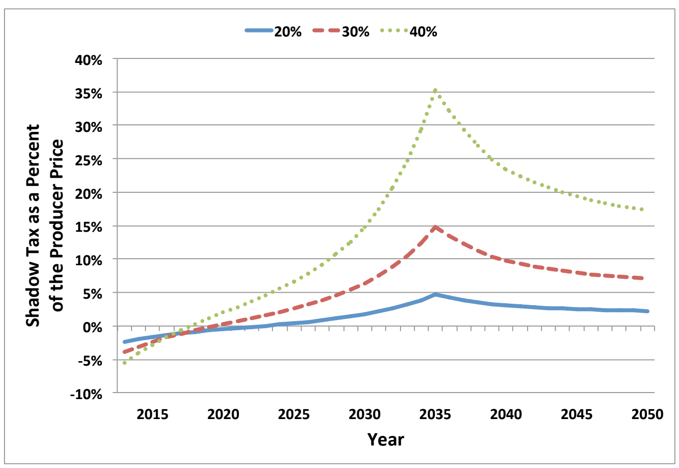


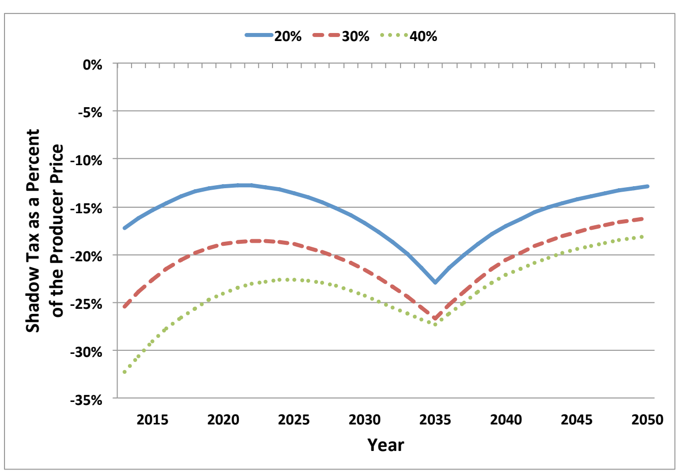
Figure 3. Shadow Tax/Subsidy on Electricity Generators



(a) **Coal-Fired Generators**



(b) **Other-Fossil Generators**



(c) **Nonfossil Generators**

Figure 4. GDP Costs of CES and Cap and Trade

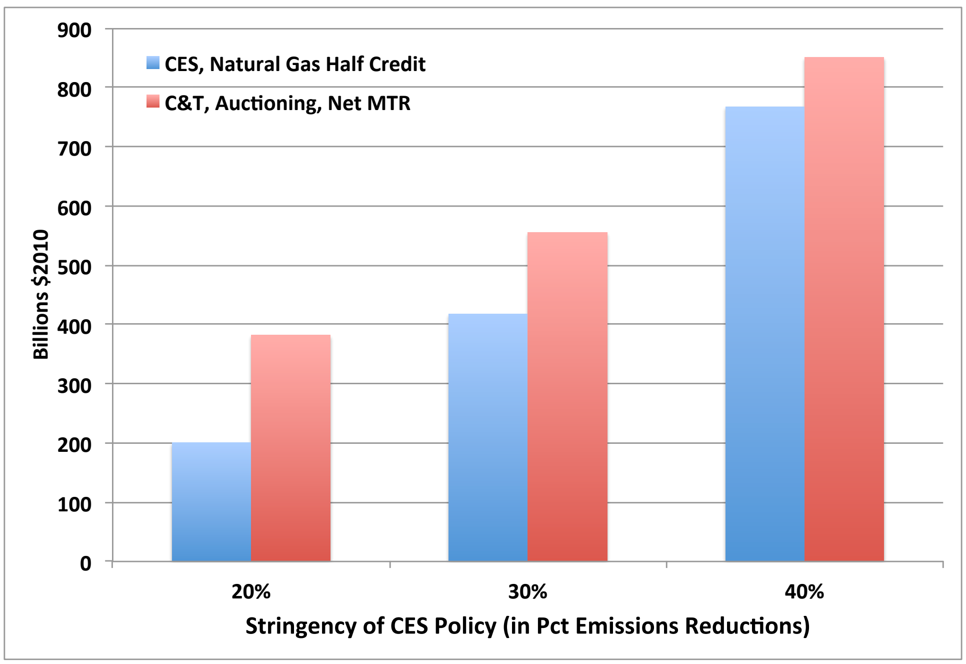


Figure 5. Welfare Costs of CES and Cap and Trade
(Equivalent Variation Measure)

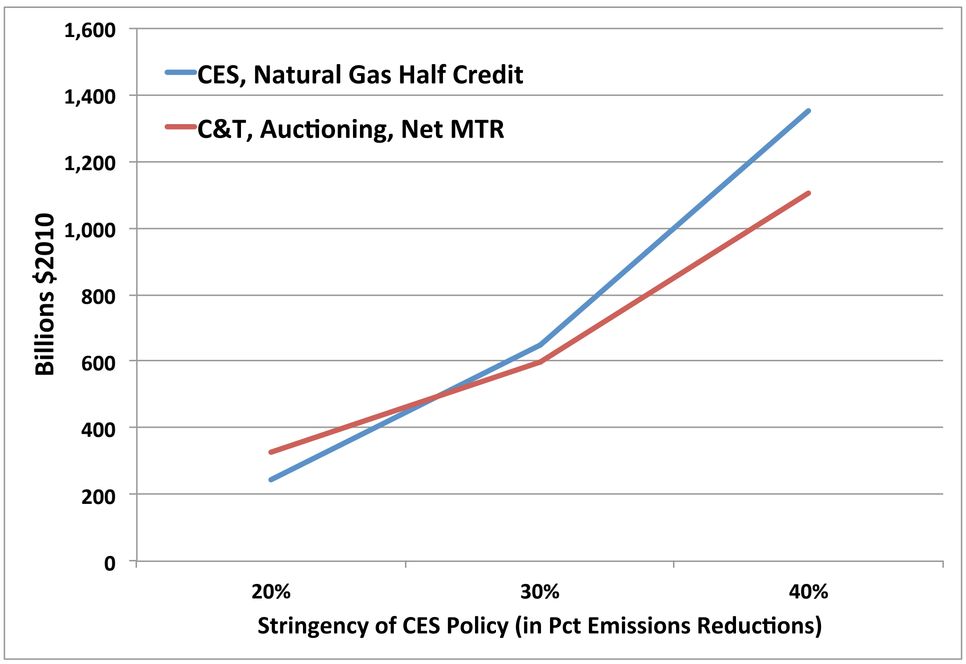
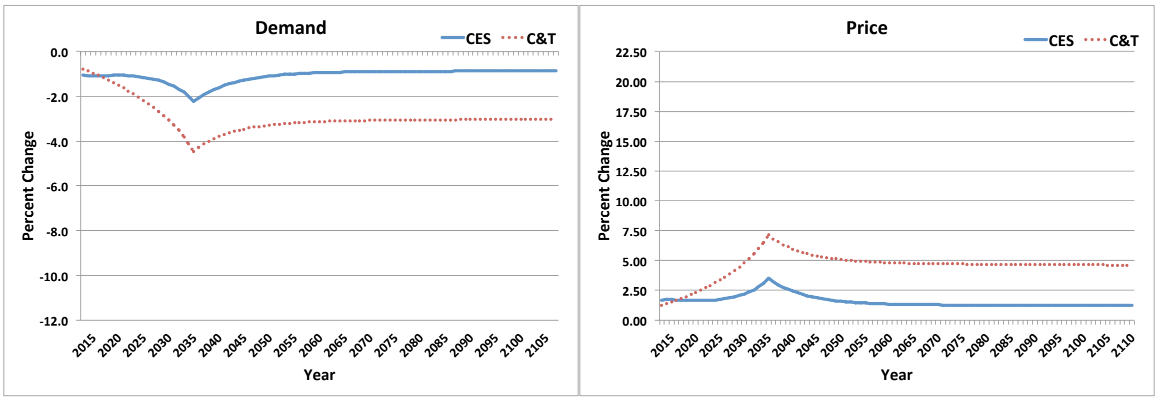
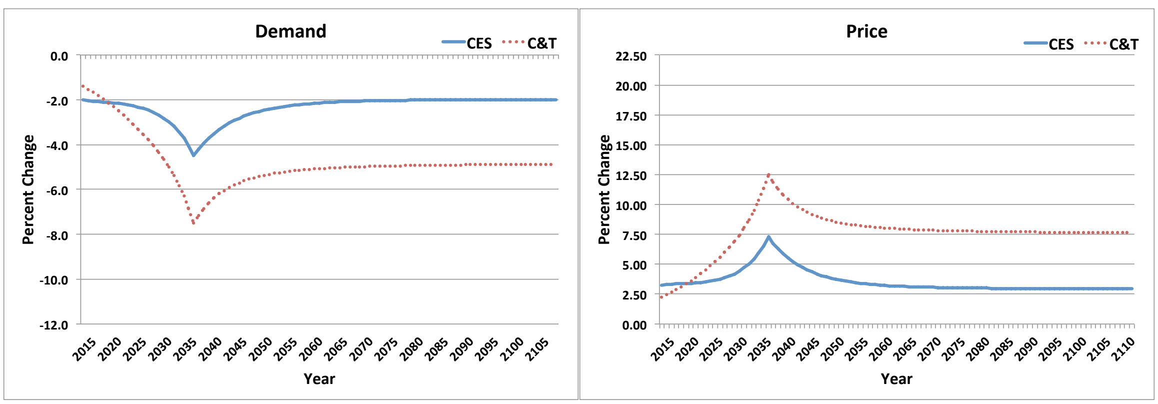


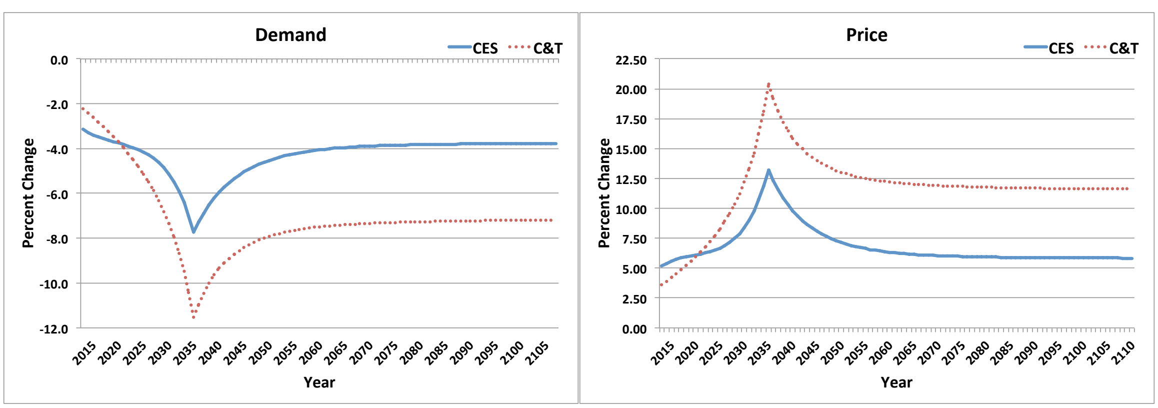
Figure 6. Percent Change in Demand for and Price of Retail Electricity



(a) **20% Long-Run Reductions**

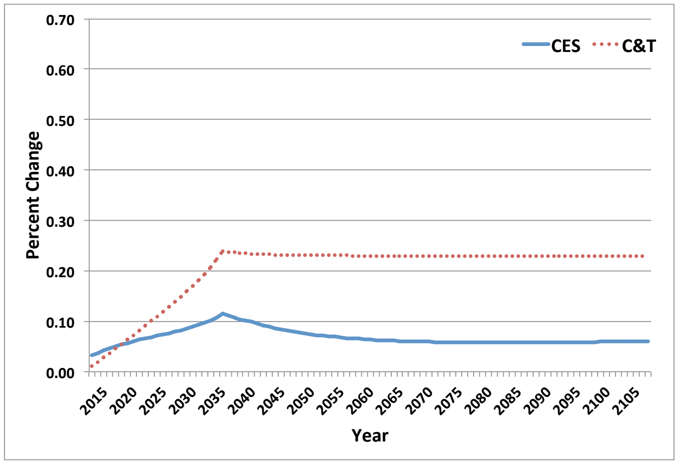


(b) **30% Long-Run Reductions**

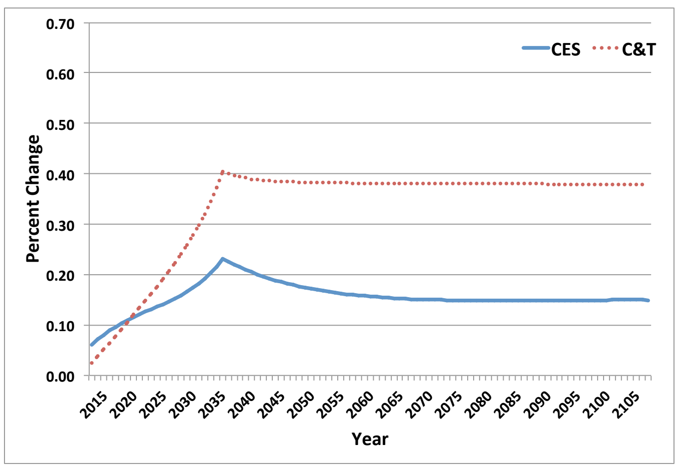


(c) **40% Long-Run Reductions**

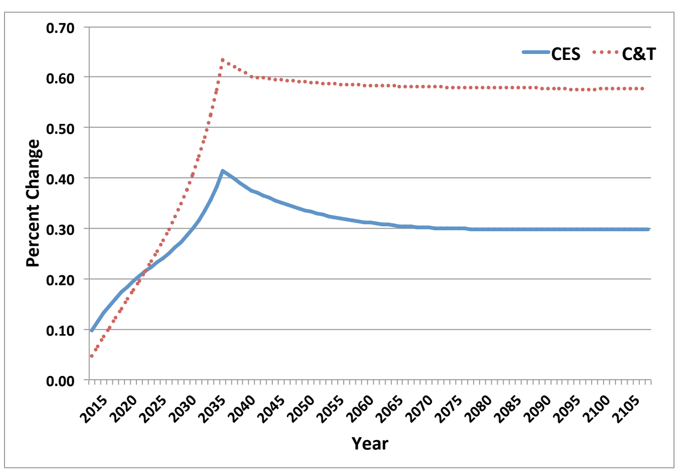
Figure 7. Percent Change in Price of Consumption Bundle



(a) **20% Long-Run Reductions**

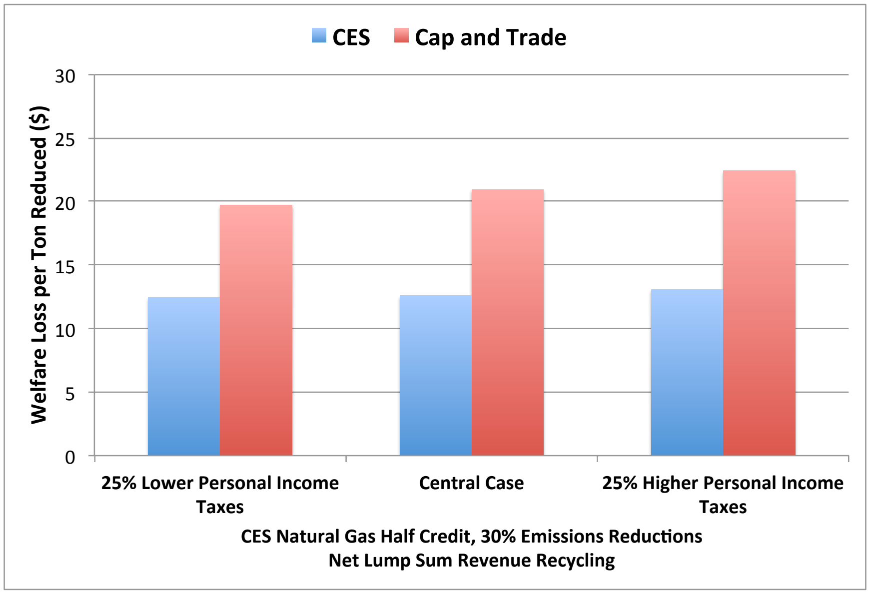


(b) **30% Long-Run Reductions**

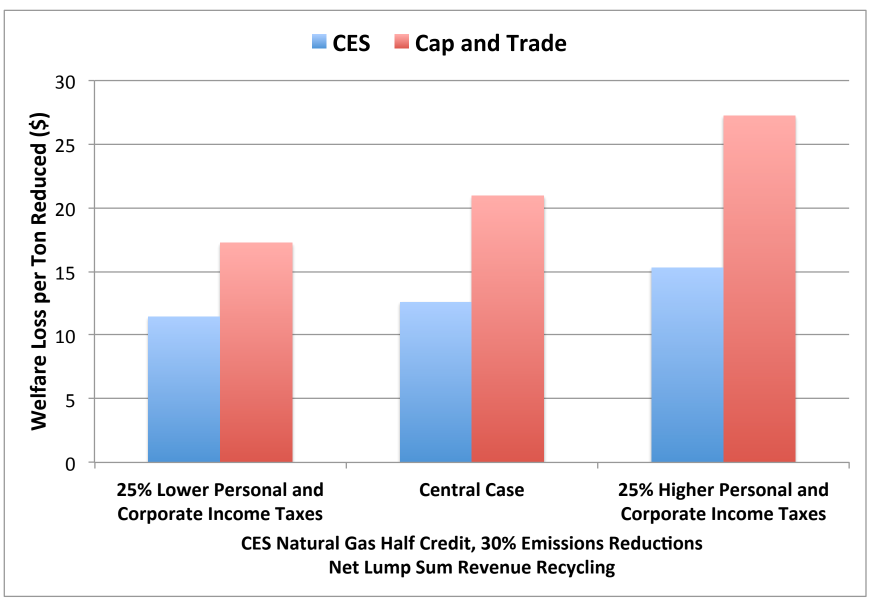


(c) **40% Long-Run Reductions**

Figure 8. Welfare Loss by Preexisting Tax Distortions



(a) **Personal Income Taxes**



(b) **Personal and Corporate Income Taxes**

Figure 9. Welfare Loss by Capital Intensity of Utilities

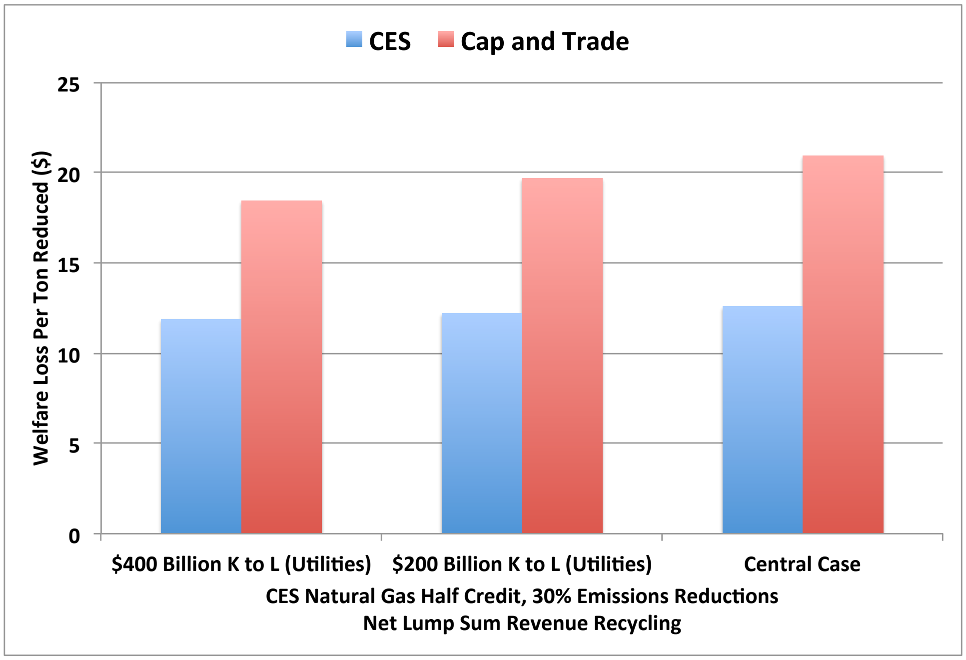


Figure 10. Welfare Cost by Revenue Recycling

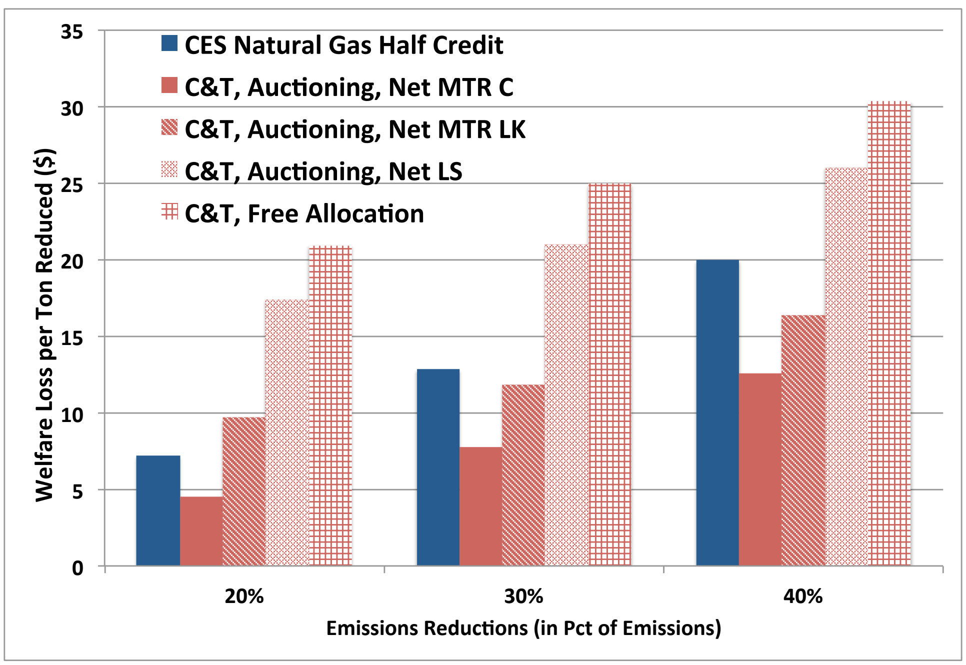


Figure 11. Relative Welfare Cost by Natural Gas Credit and Stringency

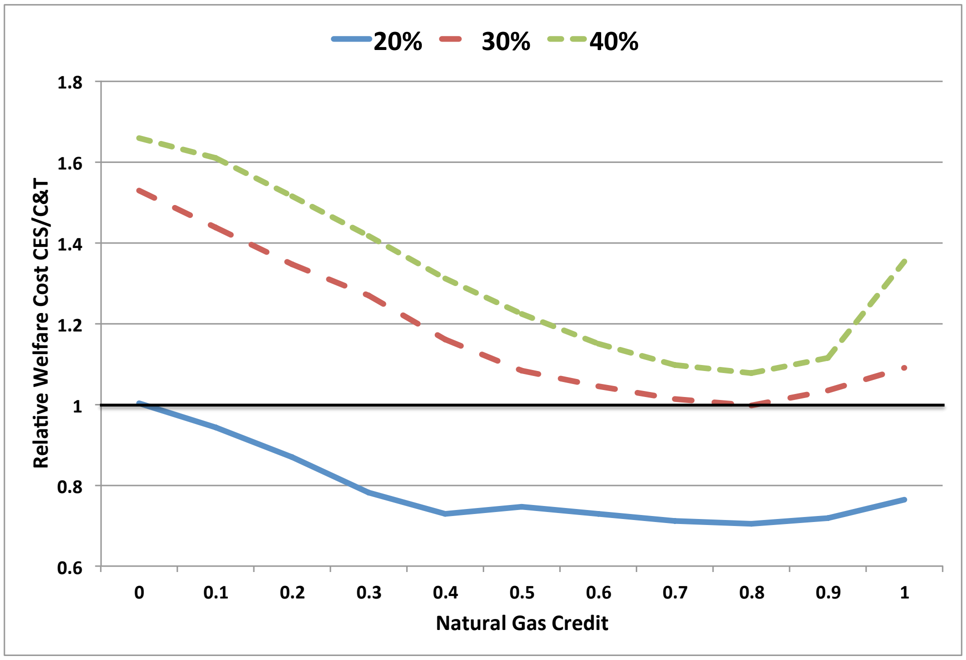


Figure 12. Welfare Costs by Elasticity of Labor Supply

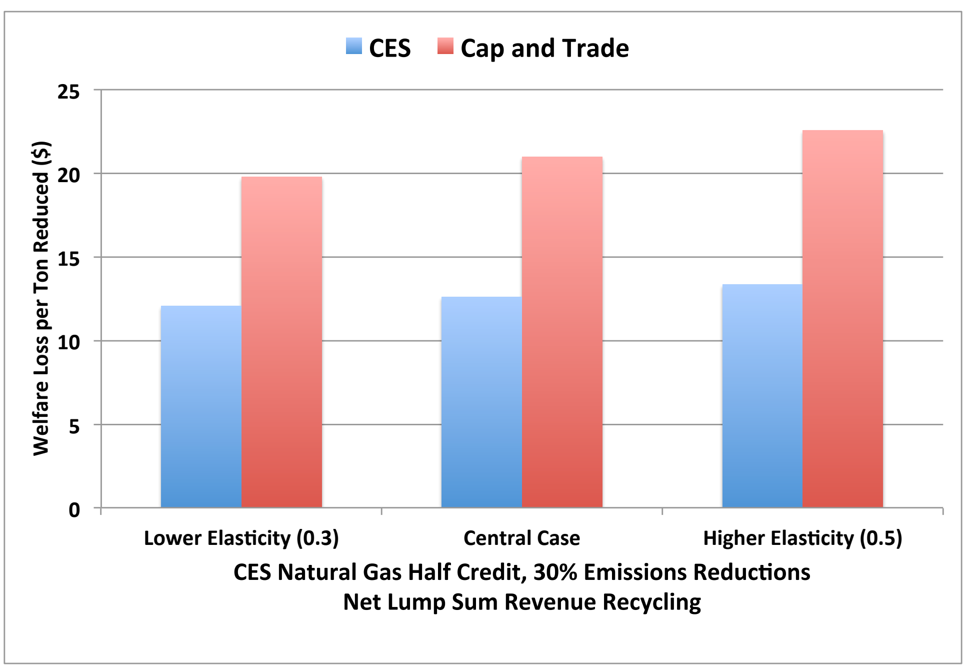


Figure 13. Welfare Costs by Elasticity of Substitution Between Generators