American Economic Journal: Economic Policy 2016, 8(2): 186–218
http://dx.doi.org/10.1257/pol.20140011

General Equilibrium Impacts of a Federal Clean Energy Standard[†]

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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, it provides 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 the CES distorts factor markets less because it is a smaller implicit tax on factors of production. This advantage more than offsets the disadvantages of the CES when minor emissions reductions are involved. (*JEL* H23, Q42, Q48, Q54, Q58)

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 climate policy in the United States is advancing, often through a different type of instrument: intensity standards.

At present, 29 states and the District of Colombia seek to control carbon emissions through a renewable portfolio standard (RPS), a form of intensity standard. An RPS imposes a floor on the share of electricity purchased by electric utilities that comes from sources deemed renewable (for example, electricity from wind farms or solar panels). It thus aims to give a boost to renewable-sourced electricity.

Federal-level programs involving intensity standards have been proposed as well. Former senator Jeff Bingaman (D-NM) sponsored the Clean Energy Standard Act of 2012, which called for a nationwide Clean Energy Standard (CES). A CES is similar to an RPS, establishing a floor for the ratio of "clean" electricity (electricity whose production involves relatively low emissions) to total electricity. Typically the CES promotes a wider range of electricity sources by incorporating nuclear-generated

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[†]Go to http://dx.doi.org/10.1257/pol.20140011 to visit the article page for additional materials and author disclosure statement(s) or to comment in the online discussion forum.

electricity, which usually receives no favorable treatment (i.e., is not deemed "renewable") under an RPS. Also, an intensity standard is at the heart of the Clean Power Plan that President Obama proposed in June 2014 to reduce emissions from existing fossil-based electric power plants. Under the Plan's default option, by 2030 each state's emissions rate—the ratio of the state's CO2 emissions from its fossil-based power plants to the state's electricity generation from those plants—must not exceed the target rate assigned to each state.

Economists recognize some attractions of such standards but generally 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 the lowest private cost. And many intensity standards (including the RPS and CES) allow credit trading, which equalizes marginal abatement costs across heterogeneous firms.

But economists generally view intensity standards as less cost-effective than emissions-pricing policies such as emissions taxes or systems of tradable emissions allowances. As shown by Holland, Hughes, and Knittel (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 an 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. Indeed, Holland, Hughes, and Knittel 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 the generality of 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). The models show that because of interactions with the tax system, the cost disadvantage of the CES is much smaller than previously thought. Indeed, in some plausible circumstances, the CES emerges as more cost-effective than emissions pricing, and this can occur even when the revenues from emissions pricing are used to cut other taxes.[1]

The relative cost-effectiveness reflects two opposing economic impacts stemming from differences in the policies' impacts on electricity prices. On the one hand, the CES's subsidy component implies that the CES will lead to a lower price for

[1] Earlier 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 when emissions tax revenues are recycled through cuts in other taxes.

electricity than a cap-and-trade system (or carbon tax) that promotes the same emissions reduction. 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. On the other hand, lower electricity prices have a virtue associated with tax interactions. Because it gives rise to a less pronounced increase in electricity prices, the CES leads to smaller reductions in real factor returns and thereby exacerbates by a smaller amount the preexisting factor-market distortions caused by the tax system. Our models indicate that this offsetting benefit makes the CES nearly as cost-effective as—and in some cases more cost-effective than—the equivalent emissions price policy.

We first employ an analytical model that offers general predications as to how the relative cost-effectiveness depends on the nature and extent of prior tax distortions, the stringency of the emissions-reduction target, and other factors. We then assess the relative costs using a numerical general equilibrium model of the United States. This model enables us to obtain quantitative results because it contains greater detail on energy supplies and demands and associated CO_2 emissions, as well as on elements of the US tax system.

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

I. An Analytical Model

This section introduces a relatively simple analytical model that illustrates the key elements that determine the relative cost-effectiveness of a CES and C&T (or a carbon tax). The model reveals that the policies interact in different ways with preexisting tax distortions in the labor and capital markets, and shows how these differing interactions importantly influence the absolute and relative costs of the policies.

A. *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.[2]

[2] This analytical model is static and ignores the dynamics of capital accumulation. In particular, the first-order condition for capital (equation (3)) does not include the future discounted marginal utility of consumption. Instead, it assumes for simplicity that providing capital causes disutility to the agent. Thus, the analytical model can represent the steady state of the full dynamic problem but not the transition to that steady state. In contrast, the numerical model in Section II is dynamic and can be used to examine the transition dynamics.

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.

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:

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

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

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

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). 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. Pollution, a joint product, is represented here as an input. Thus, the production of Y follows

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

Both production functions are quasi-concave and twice-differentiable and exhibit constant returns to scale. Pollution 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:

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

and for production of Y:

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

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

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

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. 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.

B. *Effects of Cap and Trade*

Here we exploit the fact that a cap-and-trade system, by putting a price on emissions, is formally equivalent to a pollution tax in a model without uncertainty. We assume that the system's emissions allowances (permits) are auctioned, with revenue used to reduce the tax rate on capital and/or labor. This revenue-neutral cap-and-trade program is represented as a pollution tax τ_Z combined with a reduction in τ_K and/or τ_L. The total derivatives here (i.e., the $d/d\tau_Z$ terms) will include the combined effect of the change in τ_Z and the effects of the associated changes in τ_K and/or τ_L. There is no need to consider a tax on or subsidy to Y since cap and trade does not involve these elements. Under the assumption that X and Y are separable in utility from K and L, the marginal cost of emissions reductions under cap-and-trade can be expressed (see online Appendix B for derivation) as

$$MC_{CT} \equiv \frac{1}{\lambda}\frac{dU}{d\tau_Z}\Big/\frac{dZ}{d\tau_Z} = \tau_Z + (\eta_R - 1)\left(\frac{Z + \tau_Z dZ/d\tau_Z}{dZ/d\tau_Z}\right) - \eta_R \mu_{IZ}\frac{Z}{dZ/d\tau_Z}. \tag{11}$$

The first term on the right-hand side of (11) is the direct cost of the policy: the cost that comes from the effect on emissions. At the margin, this is equal to the emissions price.

The second term is the "revenue-recycling" effect: the welfare effect of using revenue from environmental policy to finance rate cuts for distortionary taxes. This effect is a function of the marginal cost of public funds (MCPF) from capital and labor taxes, that is, the marginal welfare cost per dollar of marginal revenue from these factors. It is useful to define η_R, the MCPF for the mix of changes in capital and labor taxes that will be used to balance the government budget. η_R is a weighted average of the MCPFs for those changes in taxes:

$$\eta_R \equiv \alpha_K \eta_K + \alpha_L \eta_L, \tag{12}$$

where η_K and η_L are the MCPFs for the capital and labor taxes, and α_K and α_L are the policymaker's chosen shares of marginal revenue devoted to cutting those taxes. (See online Appendix B for expressions for η_K and η_L.) Holding the government budget fixed implies that $\alpha_K + \alpha_L = 1$. The revenue-recycling term is then equal to

the excess burden per dollar of marginal revenue times the marginal revenue from the environmental policy per unit of emissions reduced.

The third term on the right-hand-side of (11) is the "tax-interaction" effect: the welfare effect that arises when environmental policy distorts factor markets by altering real returns to these factors. This term depends on the quantity of pollution (the greater the quantity of pollution, the greater the burden from a given pollution tax) and the extent of prior distortions in the markets for the factors that bear the burden of that tax. The latter is measured by

$$\mu_{IZ} \equiv \gamma_{ZK}\left(\frac{\eta_K - 1}{\eta_K}\right) + \gamma_{ZL}\left(\frac{\eta_L - 1}{\eta_L}\right), \tag{13}$$

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). Hence, $(\eta - 1)/\eta$ is the excess burden per dollar of burden from that 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), though the expressions for the γ terms differ slightly from that study's results; that study assumed that both capital and labor supply are fixed, whereas we allow both to vary. But the underlying effects are identical. Most notably, γ_{ZK} tends to be higher if the polluting good is relatively capital-intensive or 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). 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.[3]

As will be shown in the next subsection, the three effects shown in expression (11) 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 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.

C. *Effects of a Clean Energy Standard*

Here we exploit the fact that the clean energy standard is equivalent to a pollution tax and a negative tax on (i.e., subsidy to) good *Y*, with the revenue from

[3] At first it might seem odd to be considering the factor incidence of the pollution tax—the extent to which the tax is borne by capital and labor—when evaluating net welfare effects. Economists often separate incidence questions from efficiency questions. But the efficiency effects here depend on the extent to which the policy exacerbates or ameliorates preexisting capital and labor tax distortions, and those in turn depend on how the policy affects returns to capital and labor.

the pollution tax exactly equal to the cost of the output subsidy.[4] However, while the CES itself does not raise any revenue, it may still cause changes in revenue by inducing changes in the quantities of capital and labor and thereby altering the revenue yield from taxes on these factors. As in the case of cap and trade, we assume for the CES that tax rates on capital and labor are adjusted to keep total revenue constant. Thus, in this case, the $d/d\tau_Z$ terms will include the effect of the increase in τ_Z and the decrease in τ_Y that make up the CES, as well as the effects of changes in τ_K and/or τ_L that keep total revenue constant. Taking a similar approach to that used to derive equation (11) provides an expression for the cost of the CES (see online Appendix B for derivation):

$$(14)\quad MC_{CES} = \tau_Z + \tau_Y \frac{dY}{d\tau_Z}\frac{dY/d\tau_Z}{dZ/d\tau_Z} - \eta_R \mu_{IZ}\frac{Z}{dZ/d\tau_Z} - \eta_R \mu_{IY}\frac{Yd\tau_Y/d\tau_Z}{dZ/d\tau_Z}.$$

Expression (14) parallels expression (11) for the C&T case. The first two terms on the right-hand side represent 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. The first component (third right-hand-side term) is the emissions-tax component of the CES. This expression for this component is the same as the one for the tax-interaction effect in the C&T case. The second component (fourth right-hand-side term) captures the effect of the output-subsidy element of the CES. The expression for this component parallels that for the first term. It depends on μ_{IY}, which is analogous to μ_{IZ}, but with the weights depending on the shares of τ_Y's burden falling on K and L rather than the shares of τ_Z's burden falling on these factors (see Fullerton and Heutel 2010 for a full discussion of the incidence of policies like the CES). Note that the weights underlying μ_{IY} are determined not by the total incidence of the 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}).

This second component of the tax-interaction effect will typically have the opposite sign from the first, 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,

[4] See the Appendix for a proof of this equivalence. One implication of the equivalence 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 a cap-and-trade system in which allowances are auctioned) will always be at least as cost-effective 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, CES can be seen as a special case of pollution taxes or cap and trade with revenue recycling. However, real-world cap-and-trade systems generally do not include a subsidy to Y, let alone an optimal subsidy. The CES and C&T programs considered in policy discussions are in fact quite different. This paper considers these differences in analyzing the policies.

in contrast with the C&T case, the CES does not produce any gain from the revenue-recycling effect.

D. *Comparing Marginal Costs under the Two Policies*

Here we use (11) and (14) to explore key determinants of the relative marginal costs of the two policies.

Policy Stringency.—Policy stringency (the amount of emissions reductions to be achieved) will raise the costs of the CES relative to C&T. The main reason is that greater stringency increases the direct-cost disadvantage of the CES. This direct-cost disadvantage arises because the CES introduces an implicit subsidy to output. From an efficiency point of view, this implies that the incentive to abate emissions by reducing output is weak relative to reducing emissions per unit of output. When the CES is barely binding, the implicit subsidy is very small and the distortion associated with the weak output-related incentive is relatively minor. But as the policy becomes more stringent the magnitude of the implicit subsidy rises and the associated distortion increases. Thus, when the policies are weakly binding the sum of the first two terms in (14) will be only slightly larger than the first term in (11). That difference will grow as the policies become more stringent.

Even in the case where the general-equilibrium terms (the tax-interaction and revenue-recycling effects) favor the CES, those terms become less important relative to the direct-cost terms as the policies become more stringent. This is clear from examining (11) and (14): 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. Thus, even if the general-equilibrium terms provide an advantage for the CES, its direct-cost disadvantage will dominate as the policies become more stringent.

Level of Preexisting Taxes.—Higher preexisting tax rates tend to increase all of the η and μ terms, thus magnifying the importance of the general-equilibrium terms. Higher preexisting taxes will therefore tend to favor whichever policy fares better with those general-equilibrium terms.

Average MCPF of the Taxes That Are Reduced Using C&T Revenue.—The costs of C&T are reduced to the extent that 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 (11): a higher η_R enlarges the revenue-recycling term by more than it affects the magnitude of 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. Moreover, a higher η_R will tend to raise the cost of the CES because this policy actually lowers revenue slightly—it doesn't directly raise any revenue, and the TI effect implies a small reduction in revenue from capital and labor taxes—and the lower revenue must be made up by increasing tax rates.

MCPF for the Factor That Is More Intensively Used in Production of the Polluting Good.—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 (14). 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.

Factor Intensity in Production of the Polluting Good for the More Distorted Factor.—The CES will tend to fare better to the extent that the factor subject to the more distortionary tax bears more of the burden of a tax on Y. (For example, if $\eta_K > \eta_L$, then a higher γ_{YK} will tend to favor CES.) This arises for the same reason as the one behind the previous result: this tends to magnify the tax-interaction-effect advantage of the CES by boosting η_{IY}. One highly important influence on γ_{YK} and γ_{YL} is the factor intensity in production of Y: γ_{YK} increases with the capital intensity of Y, while γ_{YL} increases with Y's labor intensity.

Relative Importance of Reductions in Consumption of Polluting Goods versus Reductions in Emissions per Unit of Polluting Goods Produced.—The relative cost of the CES will be higher to the extent that reducing consumption of the polluting good represents a relatively important channel for emissions reductions. As noted previously, because the price increase for polluting goods under the CES is too small from an efficiency point of view, the CES does not provide efficient incentives to reduce consumption of these goods. 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.

In contrast, the relative cost of CES will be lower to the extent that reducing the emissions intensity of polluting goods produced is a relatively important channel. In this case, reducing consumption of polluting goods is relatively less important, which diminishes the direct-cost disadvantage of the CES. This will occur, for example, when the elasticity of substitution in production between polluting and nonpolluting inputs is high.

This analytical model demonstrates qualitatively the key factors affecting the relative costs between the CES and C&T. We now turn to a numerical model that yields a quantitative assessment. We will show that because of large preexisting tax distortions (especially on capital) and the high capital intensity of electricity sectors, the tax-interaction advantage of the CES can be substantial. And because of the importance of fuel-switching (relative to reducing electricity use) for achieving emissions reductions, the direct-cost disadvantage of the CES is 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.

II. A Numerical Model

Here we present the structure of and simulation results from 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.

The model combines a detailed US tax system with a detailed representation of energy production and demand. Tax detail 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 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).

A. *Producer Behavior*

The model divides US production into the 25 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 as well as 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.[5] 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. 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):

$$X = f(K, g(L, h(E, M))) - \phi\,(I/K) \cdot I. \tag{15}$$

[5] Non-coal fossil fuel generators primarily consist of natural gas-fired generators. Nonfossil generators include nuclear, hydro, solar, and wind generators.

Table 1—Output in 2010 by Industry in Reference Case

Industry	Output	Pct. of total output
1. Oil and gas extraction	198.6	0.9
2. Electric utilities	326.2	1.5
3. Coal fired electricity generation	67.6	0.3
4. Other fossil electricity generation	52.3	0.2
5. Nonfossil electricity generation	37.9	0.2
6. Coal mining	54.4	0.2
7. Natural gas distribution	123.9	0.6
8. Petroleum refining	468.0	2.1
9. Mining services	37.9	0.2
10. Agriculture and forestry	433.4	2.0
11. Non-coal mining	63.8	0.3
12. Water utilities	42.0	0.2
13 Construction	1,445.5	6.6
14. Food, tobacco, and beverages	804.7	3.7
15. Textiles	165.2	0.8
16. Wood and paper products	344.8	1.6
17. Chemicals and misc. nonmetal products	1,151.2	5.3
18. Primary metals	271.7	1.2
19. Machinery	1,867.9	8.5
20. Motor vehicle production	487.1	2.2
21. Transportation	724.3	3.3
22. Railroads	86.0	0.4
23. Information and communication	827.0	3.8
24. Services	9,879.8	45.2
25. Owner occupied housing	1,908.6	8.7

Note: Output in billions of 2010 dollars.

In each industry, K is a constant-elasticity-of-substitution aggregate of structures and equipment. 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:

$$E = E\left(\overline{x}_{1a} + \overline{x}_{1b}, \overline{x}_2, \ldots, \overline{x}_8\right) \tag{16}$$

$$M = M\left(\overline{x}_9, \ldots, \overline{x}_{24}\right), \tag{17}$$

where $\overline{x}_i$ is a composite of the good produced by domestic industry i and its foreign counterpart.[6] Industry indices correspond to those in Table 1.[7]

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

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

[7] 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.

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, and that backstop fuels have the same carbon content as oil and gas.

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.

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 (15). ϕ is a convex function of the rate of investment, I/K,

$$\phi(I/K) = \frac{(\xi/2)(I/K - \delta)^2}{I/K}, \tag{18}$$

where δ is the rate of economic depreciation of the capital stock and ξ is the marginal adjustment cost. 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. The law of motion for capital stocks for each industry is given by $K_{s+1} = I_s + (1 - \delta)K_s$.

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.

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

$$\begin{aligned} \pi \;=\; & (1 - \tau_a)[\overline{p}X - w(1 + \tau_P)L - EMCOST - rDEBT - TPROP] \\ & +\; \tau_a(DEPL + DEPR), \end{aligned} \tag{19}$$

where τ_a is the corporate tax rate (or tax rate on profits), $\overline{p}$ is the per-unit output price net of output taxes, w is the wage rate net of indirect labor taxes, τ_P is rate of the indirect tax on labor (payroll tax), *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. In each period, firms issue new debt to maintain debt as a fixed ratio of debt to the value of its capital stock. The new debt is financed by households.

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):

$$V_t \;=\; \sum_{s=t}^{\infty} \left[\frac{1 - \tau_e}{1 - \tau_v}\, DIV_s - VN_s\right] \mu_t(s). \tag{20}$$

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 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. The tax rates τ_a, τ_e, τ_b, and τ_v are all taxes on capital income and thus account for both corporate and personal taxes on income derived from the ownership of capital.

B. *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, $\overline{C}_j(j = 1,\ldots,17)$. Each consumer good $\overline{C}_j$ is a constant-elasticity-of-substitution composite of domestically and foreign produced goods of type j. 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. The household receives the after-tax wage rate $(1-\tau_L)w$ in exchange for its labor.

C. *The Government Sector*

A single agent represents 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. The domestic household owns the bonds and a portion of its savings are used to buy new government bonds.

In our policy experiments we specify paths for the real deficit and real government spending that match those of the reference case. Hence to satisfy the government's budget constraint, 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. We describe below how this revenue-neutrality condition is met.

D. *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 these prices change in domestic currency 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. The exchange rate adjusts in each period to achieve balanced trade.

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

$$\frac{\sum_i a_i m_i x_{it}}{\sum_i m_i x_{it}} \geq \overline{M}_t. \tag{21}$$

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 one if the generator type qualifies for the standard and zero otherwise. Partial credit to generator i is modeled by setting a_i at a value between zero and one. Since $0 < \bar{M}_t < 1$, electricity from qualifying generators is subsidized while power from nonqualifying generators is taxed.

Producers minimize the cost of variable inputs subject to the constraint in (21). As shown in the Appendix, the constrained cost minimization problem can be replicated with an unconstrained cost minimization problem involving a tax and subsidy scheme in which the utility receives a subsidy for the input of qualifying electricity and pays a tax on the input of nonqualifying electricity, with the revenue from the tax exactly covering the cost of the subsidy. Specifically, the tax on electricity from generator i is given by

$$\tau_{it} = p_t^{ces} m_i (\overline{M}_t - a_i), \tag{22}$$

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. This is how the model represents the CES.

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 C&T here applies only to the electric utility sector. Additionally, to simplify the analysis, we focus primarily on policies with 100 percent auctioning and no banking, borrowing or offset provisions.[8]

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

$$Z_t = \sum_i z_{it} x_{it}, \tag{23}$$

where x_{it} again is the input (in model units) of generator i in period t and z_{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 τ_z 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 generator i, inclusive of the cost of emissions allowances associated with a unit of electricity. Then p_{iu} can be expressed as

$$p_{iu} = p_i + \tau_z z_i, \tag{24}$$

where p_i is production cost excluding the allowance cost. By affecting the prices p_{iu} associated with electricity from each type of generator, C&T influences the utilities' demands for electricity from the various generators.[9]

F. *Equilibrium*

In each period, the requirements of equilibrium are that (i) labor supply equals its demand, (ii) the supply of loanable funds (private savings) equals private and public borrowing, and (iii) 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).

Market clearing is achieved each period through adjustments in output prices, the market interest rate, and lump-sum taxes or tax rates. 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.

[8] See Goulder, Hafstead, and Dworsky (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.

[9] 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. Our simulations incorporate the assumption 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. We exploit this equivalence by modeling C&T as a cap applied directly to generators.

All agents face infinite planning horizons and represented as having perfect foresight. 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. We solve for the transition path using an approach similar to that of Fair and Taylor (Fair and Taylor 1983). This involves solving for prices, interest rates, and tax adjustments in each period conditional on a set of expectations, and iterating over expectations until they are consistent with perfect foresight.

III. Data and Parameters

We sketch here 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).

A. *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 values for consumption, investment, government spending, employment, imports, and exports 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. First, we assign fuel inputs to the relevant generators: coal input is assigned to coal-fired generation and oil&gas and petroleum refining (heating oil) are assigned as inputs to other-fossil generators. To disaggregate the electric power industry, 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). As this is a general equilibrium model, prices are determined endogenously. The one exception is the world oil price, which is exogenous in real terms and assumed to increase by 2.41 percent per year, following projections of the Energy Information Administration. For all goods and factors, units are defined from the input-output tables so that initial prices are equal to one.

B. *Parameters*

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.

As discussed in the analytical section, reducing emissions per unit of the polluting good is particularly important under the CES, and the relative ease of

reducing emissions through that channel compared to reducing the quantity of the polluting good plays a key role in determining the relative cost-effectiveness of the CES versus C&T. In the numerical model, the ease of reducing emissions per unit of electricity is determined primarily by the elasticity of substitution across different generator types (though capital adjustment costs also have a significant effect). The Jorgenson-Wilcoxen data do not distinguish different types of generators and thus they do not provide this substitution elasticity. In our central case we employ a value of three for this elasticity. This high but finite value acknowledges the significant degree of substitutability among different forms of electricity while recognizing that because of regional capacity constraints the substitutability is less than perfect. Alternative values are considered as part of the sensitivity analysis in subsection IVD.

There remains considerable uncertainty as to nature and magnitudes of capital adjustment costs faced by firms, though recent studies suggest that these costs are a fairly small fraction of firms' overall production costs.[10] In keeping with these findings, in our central case we use a value of three for the adjustment cost parameter ξ. In subsection IVD's sensitivity analysis we consider alternative values.

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. This value is higher than estimates for married men, but lower than values for women (see, for example, Blundell and MaCurdy 1999). The intertemporal elasticity of substitution in consumption, σ, equals 0.5, a value between the lower estimates from time-series analyses (e.g., Hall 1988) and the higher ones from cross-sectional studies (e.g., Lawrance 1991). 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.

Emissions Parameters.—Carbon dioxide emissions coefficients are set to match the distribution of emissions from energy consumption by source in 2010 (US Energy Information Administration (EIA) 2011). Coefficients convert the input of coal and oil into emissions.

IV. Results

A. *Reference Case*

All simulations begin in the year 2010. We first perform a reference case or business-as-usual simulation that forms a baseline 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

[10] See, for example, Hall (2004) and Cooper and Haltiwanger (2006).

Table 2—Emissions and Emissions Intensities by Generator

Generator	Billions MWh (2010)	Emissions	Emissions per MWh (2010)
Coal-fired	1.84	1.83	0.99
Other fossil	1.04	0.43	0.42
Non-fossil	1.24	0.00	0.00

Note: Emissions in billions of metric tons CO_2.

Source: EIA

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.

B. *Policy Specifications*

We focus on CES policies resembling the Bingaman proposal referred to in the introduction in terms of what qualifies as "clean" electricity. As in that proposal, 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).[11] As part of a sensitivity analysis below, we consider alternative specifications where we vary the credit level received by natural-gas-fired generators.

We use the term "CES ratio" to refer to the required minimal ratio of clean generation (in megawatt hours) to total generation. We consider three CES policies that differ according to the required increase in the CES ratio over time. The specified time profiles for the paths of these ratios are displayed in Figure 1. In each case, the CES begins with the business-as-usual ratio of 42 percent in 2013. The ratio rises over time, ultimately arriving at values of 60, 70, and 80 percent in 2035 and remaining at those values afterward.

The three CES policies are compared with three C&T policies that are equivalently scaled in that the emissions caps are set in each year to constrain emissions in the electricity sector to the same levels as those resulting from the CES policies. 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.

Under the C&T policies, all of the emissions allowances are auctioned out. As indicated in prior studies,[12] auctioning the allowances is conducive to cost-effectiveness because it yields revenues that potentially can be used to finance cuts in preexisting distortionary taxes. The sensitivity analysis considers C&T policies in which allowances are given out free.

[11] We include hydro and nuclear electricity within the general classification, nonfossil electricity. In our analysis, all electricity generation within this classification qualifies as clean. As a result, our specification of the CES differs from the Bingaman proposal, which did not include hydro and nuclear within the clean category. Our analysis also differs from the Bingaman proposal in that we do not include the proposal's provision enabling utilities to pay a fine rather than meet the CES requirement.

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

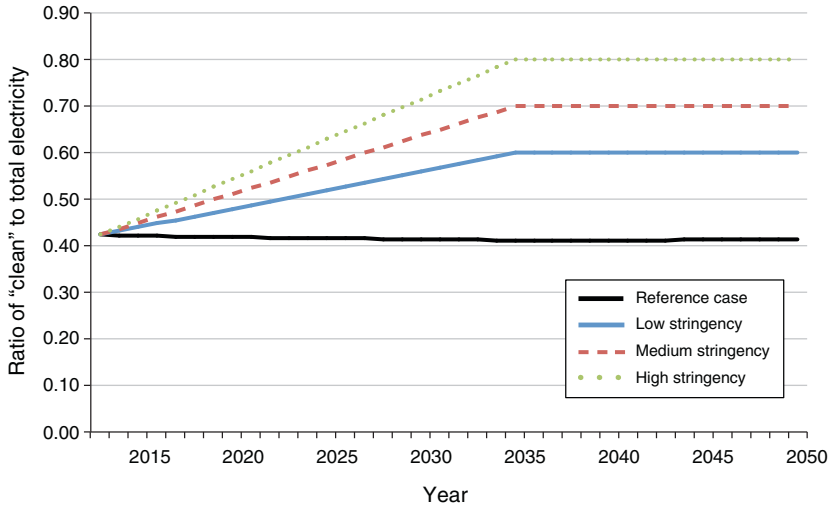

FIGURE 1. CES RATIO BY TIME AND STRINGENCY, 2013–2050

All policies are revenue-neutral. In our central case policy simulations, any revenue that the policy would yield or lose (from adverse impacts on the tax base) is offset through adjustments to the marginal tax rates applying to individual income (wages, interest income, dividends, and capital gains). As part of subsection IVD's sensitivity analysis, we consider achieving revenue-neutrality through lump-sum reductions in income taxes, as would apply if revenues were recycled to households in the form of rebate checks.

C. *Results*

Emissions, Shadow Taxes, and Shadow Subsidies.—Figure 2 displays the time profile of CO_2 emissions in the reference case and under the three CES policies of differing stringency. The low, medium, and high stringency cases are where the CES ratio is increased to 60, 70, and 80 percent, respectively, in the long run. The kink at year 2035 reflects the fact that beginning in that year the ratios no longer increase but instead remain constant. Correspondingly, emissions no longer decline but instead increase with the growth rate of the economy.

As mentioned in subsection IIE 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.[13] Figure 3 displays the shadow tax and subsidy rates applying to the

[13] The policy is revenue-neutral in the sense that the gross revenues from the tax component are matched by the revenues paid out for the subsidy component. It should be noted that the CES itself is not revenue-neutral in a broader sense. The CES imposes costs on the economy and causes a reduction in incomes, which reduces the tax base and implies a decrease in the revenues generated by the tax system. In order to make the CES policy revenue-neutral overall (and assure comparability with the C&T policy), the policy is accompanied by revenue-preserving increments to personal income tax rates.

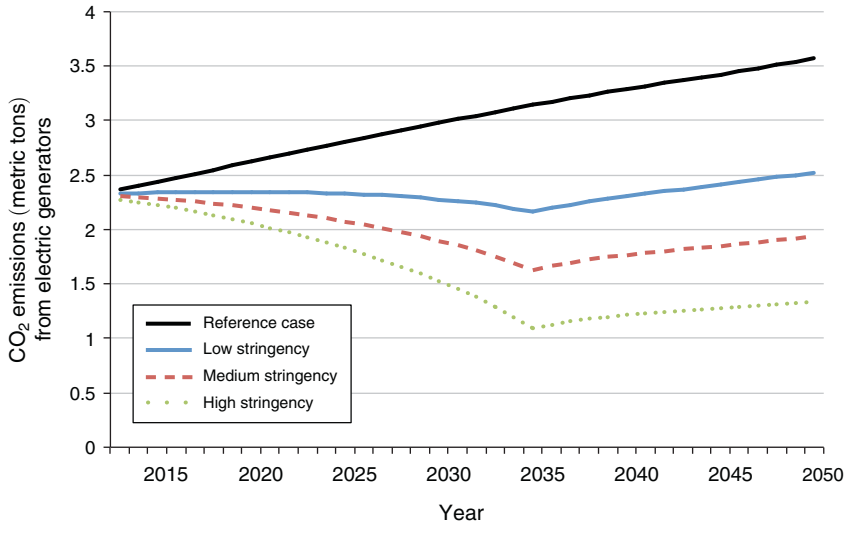

FIGURE 2. EMISSIONS FROM ELECTRICITY GENERATION, 2013–2050

electricity from the three generators. For each generator i, these correspond to τ_{it} in equation (22) above.

From 2013 through 2035 the shadow tax on electricity from coal-fired generators tends to rise, reflecting 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 mirror image of the one for coal-fired electricity generation. Because nonfossil generation is deemed clean, the shadow tax is negative; that is, it receives a subsidy. The subsidy expands over the medium term before contracting starting in 2035. In the central case simulations considered here, "other-fossil" generators receive partial credit. In the initial years of the policy, the required CES ratio $\overline{M}_t$ is slightly less than the partial credit, which from equation (22) implies that other-fossil-generated electricity receives a subsidy. Over time, the CES ratio $\overline{M}_t$ is increased and eventually exceeds the credit. Correspondingly, the subsidy becomes a tax.

Impacts on Prices.—As indicated in Section I, the potential advantage of the CES over a C&T policy is that it yields smaller increases in electricity prices and the price level and thus produces a smaller tax-interaction effect. Figure 4 compares the two policies in terms of their impacts on electricity prices and demands. Greater stringency implies larger increases in prices and correspondingly larger reductions in demand. In all of the stringency cases, the reduction in demand for electricity is greater at every point in time under C&T than under the CES policy, in keeping with the fact that electricity prices increase by a larger amount under C&T. Under the CES policy, the reductions in electricity demand are about two and a half times larger in the high stringency case than in the low stringency case. Under the C&T

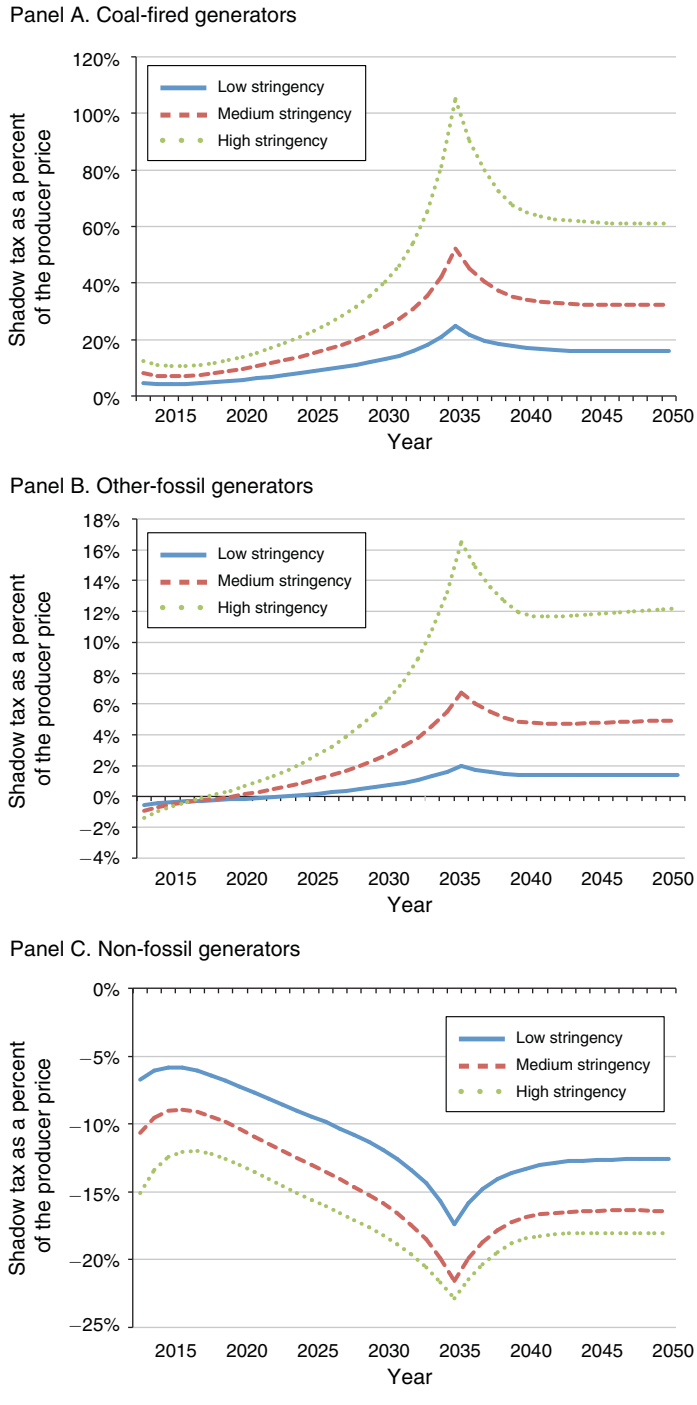

FIGURE 3. SHADOW TAX/SUBSIDY ON ELECTRICITY GENERATORS

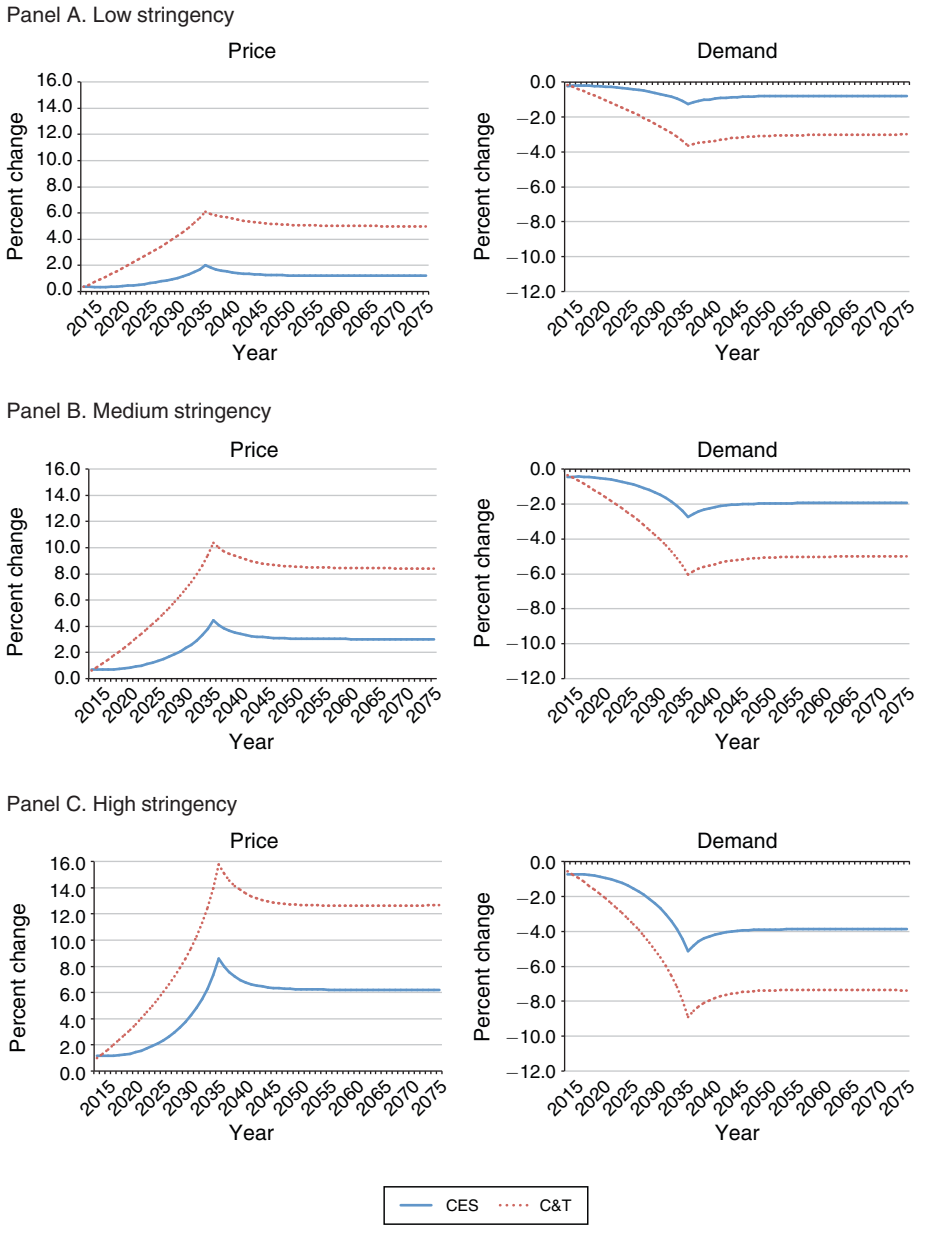

FIGURE 4. PERCENT CHANGE IN PRICE OF AND DEMAND FOR RETAIL ELECTRICITY

policy, the demand reductions are about four times larger under high stringency than under low stringency.

Figure 5 displays the effects of the CES and C&T policies on the price index for a Cobb-Douglas composite of consumption goods, which we term the "consumption bundle." It shows, for the interval 2013–2110, the percentage change in this price relative to its value in the reference case. The percent change in other aggregate

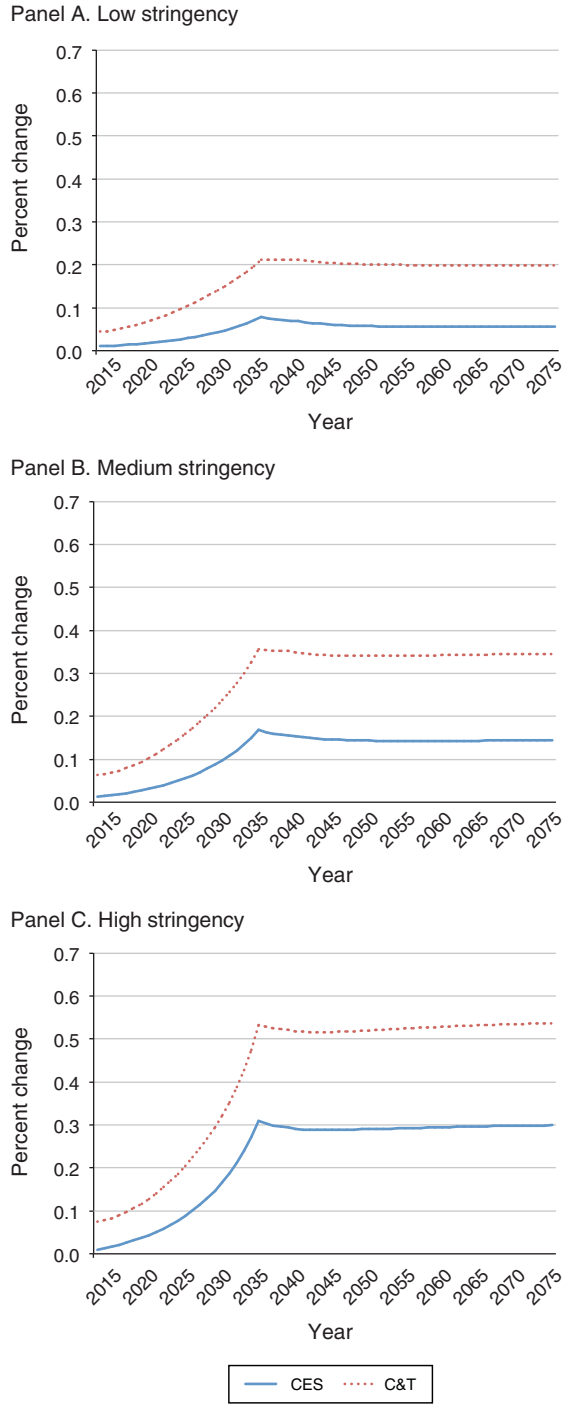

FIGURE 5. PERCENT CHANGE IN PRICE OF CONSUMPTION BUNDLE

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. Because C&T boosts electricity prices more, it has a more pronounced effect on the price level than the equivalent CES policy. The difference in the price increase across the two policies is relatively small in the early years of the policy, but the difference expands over time as the policies become more stringent. In Figure 5 the deviation in the percentage increases in prices is largest for the most stringent policy, although the ratio of these percentage increases declines with stringency.

Welfare Impacts.—Figure 6 displays the relative costs of the CES and C&T policies in terms of the equivalent variation welfare measure. Here we add a "very low stringency" case that requires the C&S ratio to reach 50 percent by 2035.

Figure 6 panel A displays the costs of the two policies, taking into account the transition path as well as the ultimate steady state. The relative costs depend on stringency. When the costs over the entire time horizon are taken into account, the CES is less costly when the policy is relatively lax, but its cost-advantage declines with increased levels of stringency. At very low levels of stringency, the CES's advantage in terms of producing a smaller tax-interaction effect more than offsets its disadvantage in terms of its inability to elicit efficient ratios of coal-fired, other-fossil-, and nonfossil-generated electricity. But as the analytical model suggested, that disadvantage grows with stringency, and becomes more important relative to the tax-interaction effect. Here, that is enough to reverse the ranking of the two policies. As the policy becomes more stringent and high levels of abatement become necessary, the CES's disadvantage in terms of fuel substitutions becomes sufficiently important that the CES becomes more costly than C&T.

Figure 6 panel B displays the costs in the steady state. When transition costs are ignored, the CES emerges as less costly, even at high levels of stringency. This reflects the differing impacts of CES and C&T on investment. The electricity transmission and distribution sector is very capital intensive, and the electricity generators are highly capital intensive as well. In our 2010 dataset, the capital-output ratio for this industry is 2.28, while the capital intensities of the coal-fired, other-fossil, and nonfossil generators are 3.26, 1.78, and 7.14, respectively. This compares with an average of 1.57 for all industries. Higher electricity prices significantly affect demands for capital in this industry and reduce (relative to baseline) investment demands. Because the CES has a smaller impact on electricity prices, it has a less deleterious impact on investment and the capital stock. In all of our simulations, investment under C&T is lower than under the CES. In the medium stringency case, in particular, investment in 2020, 2035, and 2050 under the C&T is 0.33, 0.67, and 0.49 percent below the level under the CES; and the capital stock in the steady state is 0.47 percent below the level under the CES. In a realistic economy with preexisting capital taxes, capital is insufficiently supplied to begin with, and policies that discourage investment compound the distortion of capital markets. The greater adverse impact on investment under C&T accounts for its higher costs in the steady state.

Isolating the Tax-Interaction Effect.—The analytical model of Section I indicated that costs of both policies are an increasing function of preexisting taxes because

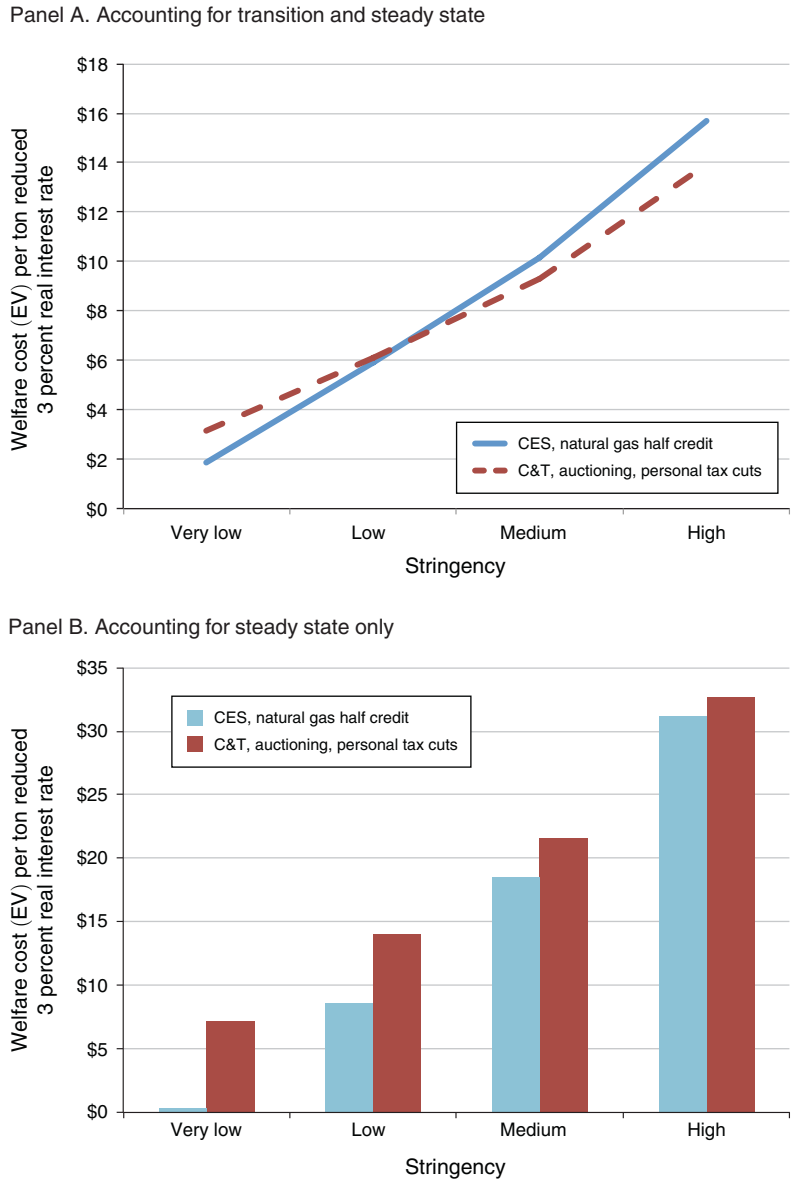

FIGURE 6. WELFARE COSTS OF CES AND CAP AND TRADE

higher prior taxes imply a larger tax-interaction effect. That model also indicated that the relative cost of the CES would decline with higher preexisting taxes. To assess these predictions with the numerical model, we perform simulations in a counterfactual setting in which the preexisting marginal rates for personal income taxes (taxes on wages, interest, dividends, and capital gains) are 25 percent lower or 25 percent higher. Results are displayed in Figure 7. The results square with the analytical model's findings. For both policies, costs increase with the level of preexisting taxes. And the ratio of the CES policy's cost to that of the C&T policy

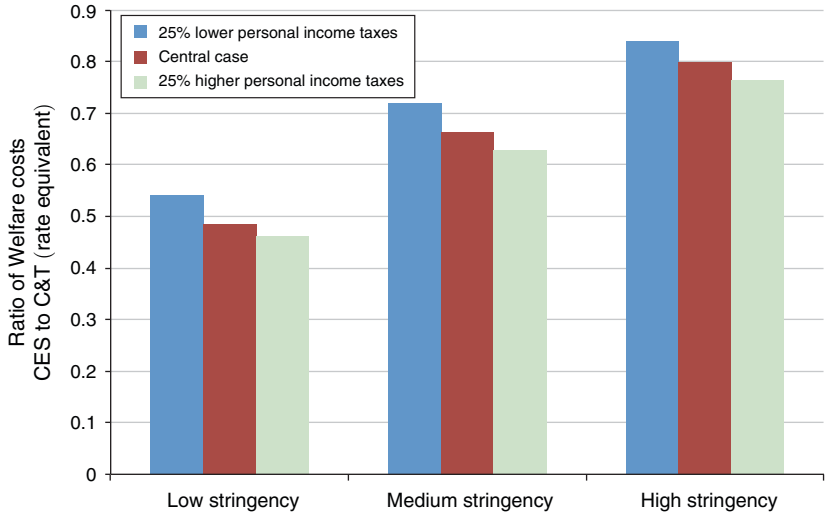

FIGURE 7. IMPACT OF PREEXISTING INCOME TAXES ON RELATIVE POLICY COSTS

is decreasing in the size of preexisting taxes, though the effect on the cost-ratio is quite small.

D. *Sensitivity Analysis*

Here we present results from a range of simulations that reveal further the forces underlying the differing costs of CES and C&T. In all cases, the measure of the change in welfare is the equivalent variation evaluated over the infinite horizon. Except where otherwise noted, the exogenously specified paths for the CES ratios in the low-, medium-, and high-stringency cases are the same in the simulations for our sensitivity analysis as in the central case simulations. The emissions time-profiles associated with given CES ratio time-profiles can change when parameters change.

Alternative C&T Specifications: Differing Allowance Allocation and Revenue-Recycling Methods.—In the central case C&T policy simulations considered above, emissions allowances were auctioned and the auction revenues were recycled through cuts in the marginal rates of personal income taxes. Figure 8 compares costs of C&T and the CES under alternative revenue-recycling specifications for the C&T policy. The method of revenue-recycling can significantly affect the relative costs. As prior studies have emphasized,[14] 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 the figure, when C&T has either of these two features the previously observed cost-advantage of C&T over CES at moderate or

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

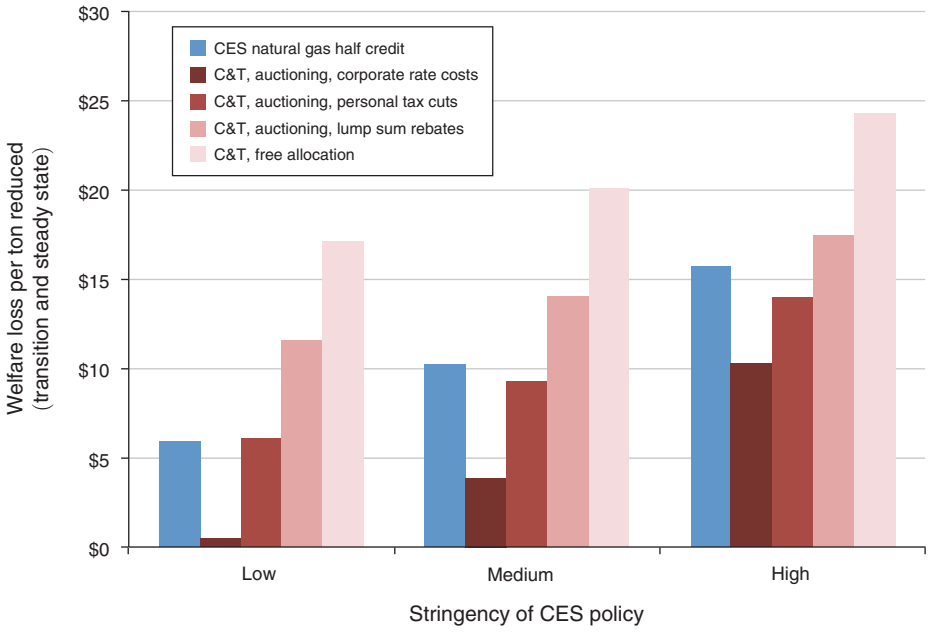

Figure 8. Impact of Revenue Recycling Method on Policy Costs

high levels of stringency disappears, as C&T emerges as more costly than the CES at all levels of stringency.

The analytical section also indicated that C&T's costs are lower when the revenue it generates is used to cut a more distortionary tax than when its revenue is used to reduce a less distortionary tax. In our model, the marginal excess burden (MEB, a concept similar to the MCPF)[15] of personal income taxes is 0.86 and of corporate income taxes is 1.72. This explains Figure 8's result that C&T is less costly when corporate income taxes are reduced than when personal income taxes are reduced.

A comparison of MEBs also offers a further explanation as to the relative costs of the CES and C&T. A tax on electricity generation in the model would have an MEB of 1.3. This means that the implicit subsidy (i.e., a negative tax) on electricity under the CES is initially a more efficient use of revenue than C&T's recycling of revenue via a lump-sum transfer (MEB of 0) or through a reduction in personal income taxes, while it is a less efficient use of revenue compared with C&T's recycling through a cut in the corporate income tax. Therefore, as indicated in the figure, a sufficiently small CES will be more cost-effective than C&T with revenues recycled lump-sum or as cuts in the personal income tax, but will always be less cost-effective than C&T when revenues are devoted to corporate tax rate cuts.[16]

[15] The MEB of a given tax is the burden of the tax above and beyond the revenue it raises, or to be more precise, the remaining cost of the tax to the household after the revenues from the tax have been returned lump-sum to the household.

[16] This reasoning applies strictly to marginal introductions of the CES and C&T policies, when for both polices the direct costs defined in Section I will be zero. For more stringent CES and C&T policies, the direct cost advantage of C&T becomes an issue.

Alternative CES Specifications: Partial Credit for Natural Gas.—We next consider of the welfare cost of CES to that of C&T as a function of the size of the credit to natural-gas-generated electricity. In the absence of a credit, relative share of natural-gas-generated electricity by utilities will be insufficient from an efficiency point of view: relatively low-cost reductions of greenhouse gas emissions could be accomplished through greater use of natural gas.[17] As indicated in Table 3, higher credits improve efficiency and lower costs.[18]

Alternative Generator Elasticities of Substitution.—Table 3 also displays the welfare costs under alternative elasticities of substitution across generators in the utilities' production function. Both the level of welfare costs and the relative cost of CES to C&T are decreasing in this elasticity. A higher value for this elasticity implies a lower cost of reducing emissions by substituting from dirtier to cleaner generators. This lowers the cost under both policies. As discussed in the context of the analytical model (see subsection ID), the CES relies more heavily on this emissions-reduction channel than does C&T, which (because of higher electricity prices) makes more 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.

Alternative Adjustment Costs.—Higher adjustment costs raise the overall costs of achieving a given emissions reduction target. Higher adjustment costs also raise the relative costs of CES to C&T. Because the CES raises electricity prices less than C&T does, it has a less deleterious impact on investment than C&T. Thus, changes in adjustment costs—changes in the costs of installing new capital—affect the costs of CES more than those of C&T.

Moreover, higher adjustment costs make it more difficult to achieve emissions reductions by substituting among different types of generators (higher adjustment costs make it more costly to scale up the clean generators and scale down the dirty generators). Again, this channel is particularly important for the CES, and thus making it more costly will raise the costs of CES by more than those of C&T.

Factor Intensities of the Electricity Sector.—The analytical model predicted that the CES will fare better to the extent that the factor with the higher marginal cost of public funds occupies a larger share as an input in production of the polluting good. In the numerical model, the "polluting good" is electricity and the factor with the higher MCPF is capital, as taxes on individual and corporate capital income have

[17] Changing the natural gas credit while holding fixed the required CES ratio can significantly change the stringency of the CES policy. In these simulations we compare CES policies that yield the same reductions in the present value of cumulative emissions as in our central case. This necessitated minor changes to the CES ratios, relative to the ratios used in the central case.

[18] In the various stringency cases the optimal credit is close to 100 percent. This is higher than what one would arrive at solely by comparing emissions per megawatt hour of coal and natural gas: that would suggest an optimal credit of 58 percent. In our simulations, the optimal credit is higher than this because natural gas is subject to higher preexisting taxes than other electricity generators. Giving a larger credit to gas than its emissions would suggest boosts efficiency because it offsets that preexisting distortion. This result is broadly 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.

Table 3—Welfare Costs under Alternative Parameter Assumptions

	Policy stringency					
	Low		Medium		High	
	CES	C&T	CES	C&T	CES	C&T
Central case	\$5.92	\$6.21	\$10.38	\$9.46	\$16.05	\$14.19
	0.953		*1.097*		*1.131*	
Natural gas credit central value: 50%						
0%	\$8.19	\$6.36	\$13.32	\$9.64	\$19.35	\$14.44
	1.288		*1.381*		*1.340*	
100%	\$4.93	\$6.22	\$8.80	\$9.46	\$14.72	\$14.20
	0.793		*0.930*		*1.037*	
Generators' elasticities of substitution central value: 3						
2	\$10.16	\$8.79	\$17.73	\$14.20	\$27.99	\$22.36
	1.155		*1.249*		*1.252*	
4	\$4.22	\$4.73	\$7.31	\$6.96	\$11.07	\$10.23
	0.893		*1.051*		*1.082*	
Adjustment cost parameter ξ central value: 3						
1.5	\$5.60	\$5.62	\$9.73	\$8.97	\$15.42	\$13.79
	0.997		*1.085*		*1.118*	
4.5	\$6.03	\$5.55	\$10.32	\$9.10	\$16.27	\$14.15
	1.087		*1.134*		*1.149*	
Factor intensity (K/Y) of power sector central value: 2.28						
1.17	\$5.65	\$6.43	\$9.68	\$9.35	\$14.64	\$13.47
	0.878		*1.035*		*1.087*	
0.55	\$5.25	\$6.06	\$9.00	\$8.75	\$13.57	\$12.48
	0.867		*1.029*		*1.087*	

Notes: Welfare costs measured as EV per ton reduced in the power sector over the entire time-path, using a 3 percent real discount rate. All policies are revenue-neutral with personal income tax rate adjustments. Ratios of CES welfare costs to C&T welfare costs in italics.

higher distortionary costs per dollar raised than do taxes on labor income. Thus, the analytical model predicts that the ratio of the cost of the CES to the cost of C&T will fall, the lower the capital intensity of the electric power sector. To test this prediction we run counterfactual simulations in which we reduce the capital intensity of the electric utility sector. To do this, we shift \$200 billion or \$400 billion from capital to labor in the electricity transmission and distribution sector with opposite changes of equal magnitude in the services sector to maintain the aggregate level of factor inputs. Table 3 shows, in keeping with the analytical model's prediction, that the ratio of costs under the CES to costs under C&T declines with a reduction in the power sector's capital intensity. The table also shows that the costs of both CES and C&T decline as capital intensity declines, which is also consistent with the analytical model's predictions.

V. Conclusions

Economists have tended to view intensity standards as less cost-effective than equivalently scaled emissions pricing policies. Using analytical and numerical general equilibrium models, this paper brings out a dimension along which intensity standards have a cost advantage. The models show that in a realistic economy with other taxes on factors of production, intensity standards such as the CES have a potential attraction relative to emissions pricing policies such as C&T because they give rise to a smaller tax-interaction effect. This raises the possibility that the CES might not suffer an overall disadvantage relative to C&T on cost-effectiveness grounds.

The models indicate that because of significant preexisting tax distortions (especially on capital) and the high capital intensity of the electricity sector, the tax-interaction advantage of the CES can be substantial. And because fuel-switching is much more important than reducing electricity use for achieving emissions reductions, the direct-cost disadvantage of CES is small. Consequently, when minor reductions in emissions are called for, a well-designed CES is more cost-effective than C&T. Even when the C&T policy auctions emissions allowances and recycles auction revenues via reductions in personal income taxes (which substantially reduces the cost of C&T), CES can be more cost-effective. When the emissions-reduction target is more ambitious, however, the C&T policy becomes more cost-effective. In this case the advantage of C&T in discouraging electricity consumption dominates its disadvantage of facing a larger adverse tax-interaction effect.

This tax-interaction advantage of the CES is expressed in large part through its effect on capital. Because it raises electricity prices by a larger amount, C&T has a larger adverse impact on investment, which augments by a larger amount the existing distortions in capital markets. Consequently, cap and trade implies a lower long-run (steady-state) capital stock and higher steady-state cost, irrespective of the stringency of the abatement target.

Although emissions pricing remains an exceptionally attractive vehicle for reducing greenhouse gas emissions, these results demonstrate that emissions pricing's advantage over intensity standards in terms of cost-effectiveness depend importantly on policy stringency and how the policies interaction with preexisting distortions, especially with capital.

The results are highly relevant to current climate policy initiatives. States currently rely heavily on intensity standards in the form of renewable portfolio standards (the state-level equivalent to a federal CES). In addition, meeting a federally imposed intensity standard is the default option for states under the Obama administration's recently proposed Clean Power Plan to control emissions from fossil-fuel power plants. Our results indicate the importance of considering interactions with the tax system in evaluations of the costs of these options relative to emissions pricing.

Some limitations in our analysis are worth noting. First, we have not accounted for possible distortions caused by existing tax preferences (i.e., implicit subsidies) for consumption of housing, health insurance, or other goods and services. Lowering the rates of individual income taxes reduces the effective size of these implicit subsidies. Hence, to the extent that cap-and-trade policies bring in revenues and use them

to finance cuts in individual income tax rates, they reduce the subsidy-related distortions, which lowers the policy costs.[19] Including this effect would tend to favor C&T, though the issue is complex and beyond the scope of this paper.

Second, our analysis implicitly assumes that electricity is priced at marginal cost. In practice, the marginal cost of electricity varies widely, often well above prices during peak-use periods and far below during off-peak periods. It appears that in many regions, prices exceed marginal cost on average.[20] To the extent that electricity prices exceed marginal cost, our analysis would overstate the distortionary impact of the CES's output subsidy, since this subsidy might serve to reduce the distortions from above-marginal-cost pricing of electricity. We have not attempted to capture here this complex and important issue.

Appendix: Equivalence of Intensity Standards to a Tax-Subsidy Combination

Here we show that an intensity standard (a term we use to represent a general class of standards that impose a constraint on some quantity θ per unit of output, such as a constraint on emissions per unit of output, a clean-energy standard, or a renewable portfolio standard) is equivalent to an unconstrained problem with a tax on θ and subsidy to output.

Output is given by

$$Y = f(\mathbf{x}), \tag{A.1}$$

pollution by

$$Z = z(\mathbf{x}), \tag{A.2}$$

and the intensity-standard constraint by

$$\frac{\theta(\mathbf{x})}{Y} \leq \Theta, \tag{A.3}$$

where $\mathbf{x}$ is a vector of inputs and Θ is the level of the constraint. Note that production, emissions, and the policy constraints in the analytical and numerical sections of this paper each represent special cases of these functions. For example, in the analytical model, $\theta(\mathbf{x}) = Z$, and in the numerical model, $\theta(\mathbf{x}) = \sum_i (1 - a_i) m_i x_{it}$ and $\Theta = 1 - \overline{M}$. (Note that the representation of the CES in the analytical model is equivalent to the representation in the numerical model if emissions per megawatt for generator type i are fixed and a_i is set for each type such that $1 - a_i$ is proportional to emissions per megawatt).

[19] See Parry (2000) for a discussion. However, this argument applies only to the extent that the subsidies are distortionary. Some would argue instead that these subsidies internalize external benefits from home ownership or help overcome market failures associated with health insurance. For example, Coulson and Li (2013) estimate that home ownership creates external benefits of approximately $1,300 per household.

[20] See, for example, Borenstein and Bushnell (2015).

For given output price p_Y and input price vector $\mathbf{p}$ (representing the prices faced by the firm, which could include other taxes), the firm's profit maximization problem is

$$\max_{\mathbf{x}} p_Y f(\mathbf{x}, Z) \; - \; \sum_i \mathbf{p}_i \mathbf{x}_i \; \textit{subject to} \; \frac{\theta(\mathbf{x})}{Y} \; \leq \; \Theta. \tag{A.4}$$

The first-order conditions for this constrained optimization are given by

$$\left(p_Y + \gamma \frac{\theta(\mathbf{x})}{Y^2} \right) \frac{\partial f}{\partial \mathbf{x}_i} \; - \; \gamma \frac{1}{Y} \frac{\partial \theta}{\partial \mathbf{x}_i} \; - \; \mathbf{p}_i \; = \; 0 \; \forall \; i, \tag{A.5}$$

where γ is the shadow price on the constraint.

For the combination of a tax on $\theta(\tau_\theta)$ and output subsidy (represented as a negative tax, τ_Y), the firm's profit maximization problem is

$$\max_{\mathbf{x}} (p_Y - \tau_Y) f(\mathbf{x}) \; - \; \sum_i \mathbf{p}_i \mathbf{x}_i - \tau_\theta \theta(\mathbf{x}). \tag{A.6}$$

The first-order conditions for this unconstrained optimization are given by

$$(p_Y - \tau_Y) \frac{\partial f}{\partial \mathbf{x}_i} \; - \; \mathbf{p}_i \; - \; \tau_\theta \frac{\partial \theta}{\partial \mathbf{x}_i} \; = \; 0 \; \forall \; i. \tag{A.7}$$

Note that (A.5) is equivalent to (A.7) for

$$\tau_Y \; = \; -\gamma \frac{\theta(\mathbf{x})}{Y^2} \tag{A.8}$$

and

$$\tau_\theta \; = \; \gamma \frac{1}{Y}. \tag{A.9}$$

Finally, note that the revenue raised by τ_θ equals the revenue cost of τ_Y:

$$\tau_\theta \theta(\mathbf{x}) \; = \; \gamma \frac{\theta(\mathbf{x})}{Y} \; = \; -\tau_Y Y. \tag{A.10}$$

Therefore, the intensity standard is equivalent to a subsidy to output and a tax on θ, with the revenue from the tax exactly equaling the cost of the subsidy. In the analytical model, this is a pollution tax plus an output subsidy. In the numerical model, it is a subsidy to electricity (at the rate τ_Y per megawatt) plus a tax on dirty electricity (at the rate $\tau_\theta(1 - a_i)$ per megawatt), or, equivalently, a single tax rate on each type of electricity, where the tax on type i follows

$$\tau_i^{CES} \; = \; \tau_Y m_i + \tau_\theta (1 - a_i) m_i \; = \; \tau_\theta m_i (\overline{M} - a_i). \tag{A.11}$$

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