Unemployment, Labor Mobility, and Climate Policy

Abstract

We develop a computable general equilibrium model of the United States economy to study the unemployment effects of climate policy and the importance of cross-sectoral labor mobility. We consider two alternate extreme assumptions about labor mobility: either perfect mobility, as is assumed in much previous work, or perfect immobility. The effect of a $35 per ton carbon tax on aggregate unemployment is small and similar across the two labor mobility assumptions (0.2–0.3 percentage points). The effect on unemployment in fossil fuel sectors is much larger under the immobility assumption – a 30 percentage-point increase in the coal sector – suggesting that models omitting labor mobility frictions may greatly under-predict sectoral unemployment effects. Returning carbon tax revenue through labor tax cuts can dampen or even reverse negative impacts on unemployment, while command-and-control policies yield larger unemployment effects.

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I. Introduction

The design of climate policy has important implications for its success. Many studies have modeled the effect of environmental policies on economies using computable general equilibrium (CGE) models. While CGE models are valuable in learning about both the economy-wide and sector-specific effects of policies, most CGE models allow for neither involuntary unemployment nor for cross-sector labor market immobility. By definition, these are *equilibrium* models, and that usually means that all markets, including the labor market, clear. While economists have typically focused on efficiency and cost-effectiveness impacts of policy, there is a great interest among policymakers and among the general public on unemployment effects. Much resistance to environmental policy comes from the presumed impact that it has on jobs and unemployment, like the impact of protecting the northern spotted owl on logging jobs or the impact of the Clean Power Plan on coal jobs.[1] Studying these effects is impossible using only models that impose the assumptions of full employment in and perfect mobility across all sectors.

Previous studies have used general equilibrium models or econometrics to calculate the effects of environmental policies on unemployment. Hafstead and Williams (2018) and Aubert and Chiroleu-Assouline (2019) use analytical general equilibrium models to study unemployment effects of climate policy. Some CGE models of environmental policy do allow for unemployment in various ways, but many of these have been limited to analysis of countries other than the United States (André et al. 2005, Böhringer et al. 2003, and O'Ryan et al. 2005). To our knowledge, Hafstead et al. (2018), a recent working paper, is the only other study that develops a CGE model of the US economy allowing for involuntary unemployment to study climate or environmental policy.

[1] See Carattini et al. (2018) for a review of drivers of public resistance to climate policy.

The purpose of this paper is to develop a CGE model of the US economy that explicitly allows for involuntary unemployment and cross-sectoral immobility and use it to study the effect of climate policy on jobs as well as on overall economic efficiency. Like a standard full-employment CGE model, this model includes a specification of various sectors of the economy, including fossil-fuel sectors that are expected to be more exposed to effects of climate policy. The model includes a detailed calibration of each sector's production process and responsiveness to price changes. We allow for involuntary labor unemployment with a wage curve, a la Blanchflower and Oswald (2005). We then compare a model with perfect cross-sectoral labor mobility to one with perfect cross-sectoral labor immobility to assess the importance of labor mobility. We compare the unemployment effects of a carbon tax to the effects of a command-and-control policy, and we study the ability of policy to respond to the adverse employment effects through targeted revenue return.

Relative to most CGE models of domestic environmental policy, this paper furthers our understanding of the employment effects of policy by explicitly modeling involuntary unemployment within each sector. Simply using a full-employment CGE model and studying voluntary changes in employment will be misleading. Relative to Hafstead et al. (2018) and other CGE models of environmental policy that do include involuntary unemployment, we extend the literature by considering the effect of assumptions about labor mobility. One extreme assumption is perfect labor mobility across sectors, an assumption imposed by most previous studies. The other extreme assumption is perfect immobility: sector-specific labor and sector-specific unemployment rates. We present results under both assumptions and compare them to study the effect of labor mobility. Hafstead et al. (2018) argue that sectoral unemployment effects might be large, but aggregate unemployment effects are small since workers are able to reallocate. We investigate this claim when workers are unable to reallocate.

Some empirical studies find evidence of inter-industry labor reallocation costs.[2] Industry reallocation frictions are determined by several factors. Workers may face training costs, moving costs, or they may have distaste for other types of work. Firms may be more likely to hire workers with industry-specific knowledge, or there may be industry-specific information networks. We do not attempt to identify which mechanisms lead to immobility, but rather assess the impact of two alternate extreme mobility assumptions. While the primary motivation of our analysis is quantifying the effects of climate policy, our results shed light on a much broader set of policies and how assumptions about labor mobility affect outcomes.

We find that the effect of climate policy on sectoral unemployment depends on the assumption made about labor mobility. Under the assumption of perfect labor mobility, a $35 per ton carbon tax with revenue returned lump-sum increases the aggregate unemployment rate by just 0.2 percentage points, and the increase under the assumption of perfect labor immobility is only 0.1 percentage points larger (0.3 percentage points). However, this small aggregate effect on unemployment masks large increases in unemployment in the most vulnerable sectors, and it masks substantial differences between the two labor mobility assumptions. Under the assumption of perfect immobility, the unemployment rate increases by 6.5 percentage points in the oil and gas extraction sector and by a whopping 31.6 percentage points in the coal mining sector. This would likely be a considerable issue for policy makers in regions that have high shares of labor employed in a regulated sector. The effect of carbon policy on emissions reductions is not sensitive to the assumption over labor mobility, but the effect on output quantity and prices is. Output in the vulnerable sectors decreases somewhat more

[2] Walker (2013) finds that the Clean Air Act induced substantial mobility costs for affected workers – earnings losses for workers in regulated sectors average 20% post-regulation, and almost all of these losses are driven by workers forced to find a new job. Vonn et al. (2018) explore this point by identifying the types of skills that are in demand for both "green" and "brown" jobs and by estimating the effect that environmental regulation has on the demand for green skills. To the extent that acquiring green skills is costly, this contributes to inter-sectoral labor mobility frictions.

under mobile labor than it does under immobile labor. The price of carbon-intensive goods increases more under the immobile labor assumption than under the mobile labor assumption. The carbon tax can lead to an increase of labor employed in other sectors, including renewable electricity generation.

We also find that policy design matters. For a carbon tax, the choice over how to recycle tax revenues can affect unemployment. When the tax revenues are returned via a uniform cut in the labor tax, the result may be a *decrease* in aggregate unemployment – a type of double dividend where the benefit from reducing the labor tax dominates the cost from the carbon tax. This decrease in unemployment is larger when labor is mobile, though the change in unemployment in the fossil fuel sectors is very small. When revenues are returned with a labor tax cut targeted just at the fossil fuel sectors, then the aggregate unemployment effect depends crucially on the labor mobility assumption: unemployment decreases when labor is mobile but increases when labor is immobile. Finally, a command-and-control policy that imposes a sector-specific emissions quantity goal yields the largest aggregate unemployment increase (rising to 5.9% for a 30% emission reduction, compared to just 5.2% for the carbon tax with lump-sum revenue return).

II. Literature Review

Computable general equilibrium (CGE) models are simulations of the economy widely used to model the effects of government policy. CGE models are often used to examine the effects of environmental regulation.[3] Most CGE models assume full employment in labor markets, and therefore the only source of changes in employment in the model is consumers choosing more leisure or workers being reallocated across sectors. However, three basic frameworks have been used in CGE models to incorporate involuntary unemployment.[4] They are the efficiency wage model of Shapiro and Stiglitz

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[3] Carbone (2017), for example, uses several CGE models to determine the effect of environmental regulations on domestic competitiveness in international trade markets.

[4] For a thorough discussion of these three methods, see Boeters and Savard (2013).

(1984), the search and matching model developed by Mortensen and Pissarides (1994), or sticky wages, where labor market frictions are created by a downwardly rigid wage, and unemployment is equal to the excess demand for labor (Kehoe & Serra-Puche, 1983). An alternative to these three specifications of involuntary unemployment is to use a less structural relationship between wages and unemployment: a wage curve. Blanchflower and Oswald (2005) find consistent evidence across countries that the elasticity of the wage with respect to the unemployment rate is about –0.1.

CGE models differ in their assumptions about cross-sectoral labor mobility.[5] Most CGE models assume perfect mobility, implying that there is a single economy-wide wage rate equalized across all sectors. We will consider both this assumption and the opposite assumption, that there is perfect immobility across sectors. Under perfect labor immobility, workers are unable to move between industries. This is certainly a strong assumption, but so is the assumption that labor is perfectly mobile across industries. It is more likely that there is some friction between industries, whether it be industry-specific human capital or even network problems in finding jobs in new industries. To avoid trying to support a nuanced theory about inter-industry mobility, we simply consider the assumptions of perfect mobility and perfect immobility to be the two extreme cases, to see what difference it can make.

A growing literature uses general equilibrium models to study the impact of environmental regulations on the labor market, in particular on unemployment.[6] Hazilla and Kopp (1990) use a full-employment CGE model and report a 1% reduction in employment from Clean Air and Clean Water acts. Bernstein et al. (2017) is a more recent full-employment CGE model that reports the effects of environmental regulations on employment; in their case, they find that the manufacturing sector could lose 440,000 jobs in 2025 due to the Clean Power Plan. Other papers use relatively simple, e.g. two-sector, general equilibrium models to study this issue. An advantage of this simplicity is that often

[5] Empirical evidence for immobility between industries in labor markets is found in Neal (1995) and Walker (2013).
[6] Bergman (2005) and Jorgenson et al. (2013) provide overviews of the use of CGE models in environmental economics.

analytical closed-form solutions can be found and interpreted, rather than relying solely on a CGE "black box" for results.

The closest papers to ours are those that use CGE models that allow for involuntary unemployment to calculate the effects of environmental policy.[7] The paper most similar to ours is Hafstead et al. (2018), which also develops a CGE model (based on the CGE model in Goulder et al. (2016) and the unemployment modeling in Hafstead and Williams (2018)) of the US economy allowing for involuntary unemployment to study environmental policy. They compare the model with unemployment to a full-employment model.

The contributions of our paper relative to this literature are the following. First, we focus on the United States, allowing for a more detailed description of the domestic economy though not focusing on other economies. Hafstead et al. (2018) and Balistreri (2002) also study the United States, though Balistreri (2002) uses a relatively simple CGE model merely to demonstrate his innovation in modeling unemployment. Second, we consider the effect of labor mobility to a greater extent than any of the previous literature. Only Babiker and Eckaus (2007) allow labor immobility. Hafstead and Williams (2018) model immobility, but only in the context of their two-sector model. Third, we model alternative forms of revenue recycling and their impacts on efficiency and unemployment, including lump-sum transfers and cuts in the labor tax rate, and we compare a carbon tax to a command-and-control quantity policy.

[7] These papers are summarized in Appendix Table A1. Most of these papers are looking at specific countries other than the United States, or are using a world-wide CGE model. In almost all of the papers, labor is modeled as homogeneous and perfectly mobile across sectors (though immobile across regions in multi-region models). Only O'Ryan et al. (2005) and Küster et al. (2007) model heterogeneous labor (two types: skilled and unskilled), and only Babiker and Eckaus (2007) model rigidities in sectoral labor mobility. The most common specifications of unemployment are either a reduced-form wage curve (as in Böhringer et al., 2003, 2008 and André et al., 2005) or a type of wage rigidity based on sticky wages (Babiker and Rutherford, 2005) or a wage floor (Babiker and Eckaus, 2007).[7] Balistreri (2002) and Hafstead et al. (2018) both base unemployment on a search and matching model, though Balistreri (2002) develops a way of modeling this process as a negative externality of unemployment in labor markets.

III. Model Description

In the first version of our model, workers are perfectly immobile across industries, resulting in a vector of industry-specific wages. In the second version, workers are perfectly mobile, resulting in a single economy-wide wage. We begin by describing the model under the assumption of perfect immobility.

III.A. Production

Production is undertaken by I different firms, each representing an industry aggregate (we will interchangeably refer to these representative firms as industries or sectors). Technology is modeled using a nested constant elasticity of substitution (CES) production function that exhibits constant returns to scale, as shown in equation 1.

$$F_i^s(\boldsymbol{X}) = \gamma_i^s \left[\sum_j \alpha_{i,k}^s X_k^{\rho_i^s} \right]^{\frac{1}{\rho_i^s}} \quad (1)$$

The elasticity parameter ρ_i^s, the share parameters $\alpha_{i,k}^s$, and the shift parameter γ_i^s can potentially differ across industries i and across stages of the nested production process.[8] The stages s can take a value in $\{Final, VA, I, E, M, Elec\}$. X_k is a quantity of an input indexed by k, which differs across the different nests, described below.

Figure 1 shows a diagram of the nesting structure for production. In the first nest, output from industry i, Y_i, is produced by combining the value-added composite VA_i^d and an intermediate goods composite A_i^d, where the d superscripts denote domestic production.

$$Y_i = F_i^{Final}(VA_i^d, A_i^d) \quad (2)$$

Capital and labor are combined into the value-added composite.

[8] The substitution elasticity is $\sigma_i^s = \frac{1}{1-\rho_i^s}$.

$$VA_i^d = F_i^{VA}(K_i^d, L_i^d) \quad (3)$$

In turn, the intermediate composite is made with two other types of composites: an energy composite E_i^d and a materials composite M_i^d, each of which is composed of demands from energy and material industries, respectively. The number of energy sectors in the economy is denoted by $\bar{e}$ and the number of material sectors is $\bar{m}$, and they are listed in Figure 1. In addition to the division of energy goods, we subdivide electricity into "renewable" and "non-renewable," where the renewable electricity sector does not use fossil fuels. The inputs to the energy composite E_i^d are the energy inputs $e_{1i}^d, \dots, e_{\bar{e}i}^d$, and the input to the materials composite M_i^d are the inputs $m_{1i}^d, \dots, m_{\bar{m}i}^d$. For the electricity sector, the inputs are the quantities of renewable and non-renewable electricity inputs, Z_i^d and NZ_i^d. (All other sectors just use the composite electricity input, $Elec_i^d$.)

$$A_i^d = F_i^I(E_i^d, M_i^d) \quad (4)$$

$$E_i^d = F_i^E(e_{1i}^d, \dots, e_{\bar{e}i}^d) \quad (5)$$

$$M_i^d = F_i^M(m_{1i}^d, \dots, m_{\bar{m}i}^d) \quad (6)$$

$$Elec_i^d = F_i^{Elec}(Z_i^d, NZ_i^d) \quad (7)$$

Producers observe commodity prices P_i^c and wages $\bar{P}_i^L$ and capital rents $\bar{P}_i^K$, which are the net-of-tax returns to capital and labor. They then use these prices to determine their cost-minimizing factor demands. Factor prices can be industry-specific, both because labor and capital tax rates can be industry-specific (though in the base case, all labor tax rates are identical across industries), and because, for wages, labor is industry-specific in the case of labor immobility. Demands by consumers are determined by gross-of-tax commodity prices, the net-of-tax prices of capital and labor, and labor supply. Producer i's problem is

$$\min_{VA_i^d, A_i^d} P_i^{VA} VA_i^d + P_i^A A_i^d \quad (8)$$

$$s.t.\ Q^* = F_i^{Final}(VA_i^d, A_i^d) \quad (9)$$

$$P_i^{VA} = \bar{P}_i^L \times L_i^* + \bar{P}_i^K \times K_i^* \quad (10)$$

$$P_i^A = P_i^E \times E_i^* + P_i^M \times M_i^* \quad (11)$$

$$P_i^E = \boldsymbol{P}^{Ce} \cdot \boldsymbol{e}_i^* \ \ and \ \ P_i^M = \boldsymbol{P}^{Cm} \cdot \boldsymbol{m}_i^* \quad (12)$$

Here E_i^* and M_i^* are vectors containing the cost-minimizing demands of the energy and materials composites which make up the intermediate composite A_i^d. The value-added composite is made up of the optimal demands for labor and capital, denoted L_i^* and K_i^* respectively. The producer's problem is solved backwards (or up the nesting tree). First, the producer chooses how much non-renewable and renewable electricity to use in production. Then each firm decides the cost-minimizing inputs of energy goods (i.e. what ratio between energy goods produces one unit of the energy composite most cheaply), which includes the electricity composite. The firm then makes the same decision for material goods and the material composite. After this step, the minimum costs of one unit of the energy and one unit of material composite have been determined. The price of the energy composite is then calculated by taking the dot product of the prices of energy commodities $\boldsymbol{P}^{Ce}$and the cost-minimizing demands for each commodity in the energy composite $\boldsymbol{e}_i^*$. The price of the materials composite $\boldsymbol{P}_i^M$ is calculated the same way using prices of material commodities $\boldsymbol{P}^{Cm}$ and demands of material commodities $\boldsymbol{m}_i^*$. The producer then determines the cheapest way to produce one unit of intermediate composite A_i^d, which is made up of the energy and material composites. After determining the cost-minimizing mix of capital and labor for the value-added composite, the final firm problem is finding the cost-minimizing inputs of the value-added composite and the intermediate composite.

III.B. Households

Consumption is undertaken by a single representative household for each industry; therefore there are I consumers. Consumers have a Cobb-Douglas utility function defined over final goods consumed from each industry, both from domestic and foreign producers. Leisure is not an argument of the utility function. Households purchase these final goods using income from capital and labor as well as government transfers. In the following section we index a household with j and a good with $i.$ The household's problem is:

$$\max_{X_{j1},\dots,X_{jI},X_{j1}^F,\dots,X_{jI}^F} U_j\left(X_{j1},\dots,X_{jI},X_{j1}^F,\dots,X_{jI}^F\right) \tag{13}$$

$$s.t. \quad \sum_{i=1}^{I}\left[\bar{P}_i^c X_{ji} + P_i^F X_{ji}^F\right] = P_j^L L_j^s + P^K K_j^s + TR_j \tag{14}$$

Where X_{ji} is the amount of domestically-produced final good i that consumer j demands, and $\bar{P}_i^c$ is the gross-of-tax price of X_{ji}. Income is on the right hand side of equation 13; P_j^L is the net-of-tax wage that the worker in industry j receives, L_j^s is the industry-specific labor supply, P^K is the net-of-tax price of capital (which is the same across industries), and K_j^s is the capital supplied to the market by consumer j. Each consumer also receives a lump sum transfer from the government TR_j, which is specific to each household. Foreign good imports X_{ji}^F are also demanded by each consumer. These are treated as a different set of goods entirely, appealing to the Armington assumption that goods are differentiated by place of origin. Consumers have Cobb-Douglas preferences over both domestic and imported goods, calibrated to match consumption shares. In this case, the share of income for an imported good could be considered the equivalent of an Armington elasticity.

III.C. Foreign Sector

The foreign sector is modeled as an external consumer who trades goods with consumers in the home country. This means that trade is only in final goods and that trade is balanced between the two countries. To calculate this, we first calculate import demands from home consumers, and then this is treated as income for the foreign sector. The foreign consumer uses this income to purchase goods from the home country, which enter the final demands equation as exports. The demand equation for the vector of exports Q is given by

$$Q_n = \left(\frac{\alpha_n}{P_n^D}\right) * (P^F \cdot X^F) \tag{15}$$

Where α_n is the Cobb-Douglas parameter on consumption for the foreign consumer, P_n^D is the domestic price on the nth good, P^F is the vector of prices of foreign goods, and X^F is the vector of imports demanded by the domestic consumer. There is no trade in intermediate goods, only in final goods.

III.D. Carbon Emissions

Carbon emissions are produced as a byproduct of production of two fossil fuel industries: coal mining, and oil and gas extraction.[9] Carbon emissions for each of these industries is a multiple of their output. A tax T_i^{Carbon} is levied per unit of carbon dioxide created by the industry. The "carbon coefficient" CC_i equals the tons of carbon produced from one unit of output Y_i. The total carbon tax revenue for each polluting industry i is:

$$CTaxRev_i = T_i^{Carbon} * CC_i * Y_i \tag{16}$$

Note that if a sector i does not produce a polluting fuel, its carbon coefficient is zero; this is true for all industries i other than coal mining and oil and gas extraction. This is a fully upstream implementation, so all other firms that use these fuels as input take the tax into account in their cost-minimization problems. The tax is collected at the point of sale, so all producer's input prices, and prices of final goods are modified to take account of the carbon tax. As described below, we will consider three different options for returning the carbon tax revenues: lump-sum, through a uniform labor tax cut, and through a labor tax cut targeted just at the two polluting sectors.

The other policy that we model is a command-and-control quantity restriction, where each polluting sector (coal, and oil and gas) must reduce its output (and therefore its emissions) by a specified

[9] Oil and gas extraction are combined as one industry in the social accounting matrix and so also combined as one industry in our model. This means we do not capture any substitutions between those two sectors due to climate policy.

amount. To model this, we constrain the output level of each of the two polluting sectors to a set amount, then endogenously solve for the shadow price of the constraint (Liu et al. 2014), along with the other prices in the model. The tax revenues generated by this shadow price represent scarcity rents for the right to pollute, and we assume they are returned to consumers lump-sum. Since we assume representative households with Cobb-Douglas utility functions, demands are simply constant shares of income. Thus, it does not matter which particular agent receives the income from the scarcity rents.

III.E. Government

A single government, composed of state, local, and federal, has a balanced budget condition imposed to close the model. The government has four functions: collecting taxes, transferring income, producing a public good, and imposing environmental regulation. The government levies input taxes on capital and labor and sales taxes on final production, in addition to the aforementioned carbon tax. The public good is produced using the same nested CES production function structure as the private industries. However, this final good is not bought by any agent, and it is non-rival and non-excludable.

Taxes on capital and labor, T_i^K and T_i^L, are withheld at the source, changing producer input prices.

$$\bar{P}_i^L = \left(1 + T_i^L\right)P_i^L \quad and \quad \bar{P}_i^K = \left(1 + T_i^K\right)P^K \tag{17}$$

Some industries may have negative taxes on capital to incorporate government subsidies. The government also imposes a sales tax T_i^S on all final goods to consumers, changing consumer commodity prices.

$$\bar{P}_i^C = \left(1 + T_i^S\right)P_i^C \tag{18}$$

Final government revenue is the sum of taxes collected on the factors of production, emissions, and final goods. The government's revenue G is:

$$G = \sum_{i=1}^{I} \left\{ \left(T_i^L \times L_i^d\right) + \left(T_i^K \times K_i^d\right) + \left(CC_i \times T_i^{Carbon} \times Y_i\right) + T_i^S \sum_{j=1}^{J} X_{ij}^d \right\} \tag{19}$$

The government spends its revenue two ways. Some of it is returned to consumers in a lump sum transfer, giving TR_j to household j. The rest is used to purchase goods from different industries, where government consumption of good i is g_i. So, the government's expenditure function is:

$$G = \sum_{j=1}^{J} TR_j \; + \sum_{i=1}^{I} \overline{P^C}_i \times g_i \tag{20}$$

The fraction spent on government expenditure is exogenously set to match ratios of government spending to lump sum transfers. When we return carbon tax revenues to households in a lump sum return, it is through this transfer amount. Government spending g_i is determined by a Cobb-Douglas demand function calibrated to match government demands in the BEA tables. Transfers to individuals TR_j are calibrated to matching lump sum transfers by state and concentrations of industries in those states.

III.F. Labor Market

Labor market frictions are summarized using an exogenously parameterized wage curve, giving a relationship between unemployment u_j and wages P_j^L at the industry level:

$$\ln\left(P_j^L\right) = \eta_{1,j} \ln\left(u_j\right) + \eta_{2,j} \tag{21}$$

Blanchflower and Oswald (2005) give estimates for η_1 of -0.1 across most nations, with remarkable consistency. This means that a 1% decrease in wages is associated with a 10% increase in the local unemployment rate. $\eta_{2,j}$ is a sector-specific shift in the unemployment level. This wage curve specification of unemployment is a reduced-form approach, as opposed to a structural model of unemployment like a Diamond-Mortensen-Pissarides search and matching model as used in Hafstead et al. (2018). Because the purpose of our paper is not to identify or study the causes or mechanisms behind labor immobility, but rather to assess the effect of different assumptions about mobility on quantitative predictions, such a reduced-form approach is sufficient.

The assumption of perfect labor immobility implies a distinct labor stock for each industry that cannot move into other sectors. Each industry has a sector-specific wage and labor supply, and each labor market clears in equilibrium. To incorporate involuntary unemployment, the wage curve (equation 21) is calibrated for each industry. We assume the estimate for $\eta_{1,j} = -0.1$ is true for all industries j, and we shift the $\eta_{2,j}$ parameter to match industry unemployment rates from the Bureau of Labor Statistics (described below).

The total stock of labor force for each industry is fixed at $\hat{L}_j$. The labor that is actually employed is $L_j^s = (1 - u_j)\widehat{L_J}$. Under the perfectly immobile labor assumption, the labor force for each industry is calculated to match sectoral unemployment rates. Each industry represents a different labor market and thus has a different unemployment rate. For the perfectly mobile labor assumption, unemployment rates across sectors are identical ($u_j = u$), so each sector's labor supply is a function of that sector's total labor stock and the economy-wide unemployment rate: $L_j^s = (1 - u)\widehat{L_J}$.

III.G. Equilibrium

Equilibrium is determined by utility maximization, cost minimization, market clearing, and zero profit conditions.

$$\sum_{i=1}^{I} K_i^* = \sum_{j=1}^{J} K_j^s \tag{22}$$

$$L_i^* = L_j^s \quad \forall\, i = 1, \dots, I \tag{23}$$

$$Y_i = \sum_{j=1}^{J} X_{ij} + Q_i + \sum_{z=1}^{J} I_z^i + g_i \;\; \forall\, i = 1, \dots, I \tag{24}$$

Equations (22) and (23) are factor market clearing conditions for capital and labor, respectively. Capital is perfectly mobile across sectors, with a fixed capital stock K. Labor is sector-specific, with a fixed, immobile labor stock L_i in each sector. Equation (24) is the goods market clearing condition, it introduces a new variable I_z^j, which is the intermediate demand for good j by producer z. It requires that supply from each firm Y_j is equal to the demand for output from that sector. The right-hand side represents this demand and is the sum of final goods for domestic consumers ($\sum_{j=1}^{J} X_{ij}$), exports (Q_i), intermediate inputs to other industries ($\sum_{z=1}^{J} I_z^i$), and final goods purchased by the government (g_i). The algorithm then searches over a simplex of prices for capital, labor (in all sectors), and commodities for an equilibrium.[10]

III.H. Differences between the perfect mobility and perfect immobility labor assumption

Up to now we have described the model under the assumption of perfect labor immobility, so that each industry's labor stock is fixed with its own unique wage. The alternative assumption that we consider is that of perfect labor mobility. In the perfectly mobile case there is just one wage and one unemployment rate across all sectors. When the mobile case is calculated, the unemployment rate is used to determine the amount of labor stock each household can supply (there is one household for each sector like in the immobile case) at the economy-wide wage. Each household supplies as much labor as it can under the unemployment rate and then these rates are summed to determine the aggregate labor supply. Equilibrium condition (23) changes to

$$\sum_{j=1}^{J} L_j^s = \sum_{i=1}^{I} L_i^* \tag{25}$$

[10] Code is written in the open-source programming language Julia, and it is available upon request and posted on the authors' websites.

Thus, the perfectly mobile labor model has only one aggregate labor market that needs to clear for the equilibrium conditions to be satisfied.

Appendix A.I. describes the calibration method and data sources.

IV. Simulation Results

We simulate several different policy scenarios. For all simulations we assume that all industries start at a 5% unemployment rate, which is close to the natural rate of unemployment implied by most literature. Counterfactual results are from a carbon tax rate set at \$35 per metric ton of CO_2, which was the value of the social cost of carbon calculated by the EPA for 2015 based on a 3% discount rate. We also present results for outcomes under different tax rates.

The first policy modeled is a carbon tax where revenues are returned in a lump-sum fashion to all households. Revenues are returned in shares to each representative household determined by employment shares and transfers.

The second policy modeled is a carbon tax where revenues are returned as a cut to the labor tax rate. The labor tax rate is reduced equally across all sectors so that the policy is revenue neutral.

The third policy returns revenues in a way intended to offset the deleterious effects of the policy on the targeted industries. It returns the carbon tax revenues as a cut in the labor tax rate just for the coal mining and oil and gas extraction sectors, the two sectors directly affected by the carbon tax. The labor tax rate is cut identically across the two sectors from its initial value, based on the government budget constraint.

The fourth and last policy we call a command-and-control policy, where each of the two polluting industries faces a binding emissions quantity restriction. The percentage reduction is identical across the two industries, and its level is set so that the total emissions reduction equals that found under the \$35 carbon tax. Scarcity rents – the revenues from the shadow price on the emissions constraint – are returned lump-sum to consumers in a similar fashion to the first policy. While we call this a command-and-control policy, it is still the case that within each of the sectors, emissions reductions are being achieved at lowest cost. It is the aggregate emissions reductions that are not achieved at lowest cost, since each sector is constrained to reduce pollution by the same amount. Thus, this policy is equivalent to a carbon tax where the tax rate differs across the two fossil fuel sectors, or a cap-and-trade policy with no trading between sectors. This simulation underestimates the inefficiency of more realistic command-and-control policies.

These four policy scenarios are each simulated under both assumptions about labor mobility, resulting in eight total sets of results. We present the following outcomes for each of these eight combinations, all presented as relative to the base case: the change in total emissions, the change in the unemployment rate for each sector, and the change in aggregate unemployment.

IV.A Lump-sum revenue return

Results from the carbon tax with lump-sum revenue return are summarized in Figure 2. Our model predicts reductions in emissions that are comparable with previous studies. The reduction in total emissions is shown in the upper left panel of Figure 2, for various levels of the carbon tax rate. A $35 per ton carbon tax leads to a 30.8% reduction in carbon emissions. This magnitude is comparable to that of Resources for the Future's "tax calculator," based on the Goulder-Hafstead E3 (Energy-Environment-Emissions) CGE model. Their model predicts a 25% reduction from a $35 tax in the short run, increasing to 44% reduction after a few years (Goulder and Hafstead, 2013; Goulder and Hafstead, 2017).[11]

For the perfectly mobile model, we use an economy-wide unemployment rate for all sectors, so changes in unemployment rates are the same for all industries. For the immobile labor model, we also

[11] http://www.rff.org/blog/2017/introducing-e3-carbon-tax-calculator-estimating-future-co2-emissions-and-revenues

choose an initial unemployment rate of 5% for all industries. When we shock the system with a carbon tax, a different unemployment rate is calculated for each industry. So, to compare these models we calculate an unemployment rate for the immobile model based on aggregate labor demands and initial labor allocations.

The change in the aggregate unemployment rate is shown for both the mobile and immobile case in Figure 2, top right panel. While the two are close to each other, the immobile model predicts a slightly higher unemployment rate as compared the mobile model. Under a $35 carbon tax, the unemployment rate increases from 5% to 5.22%, and under the immobile labor assumption the aggregate unemployment rate rises from 5% to 5.31%.

Although the aggregate unemployment rates are similar between the two models, the industry-level unemployment rates are very different from each other. Unemployment rates for the oil and gas extraction and coal mining sectors are much higher in the immobile model. The bottom two panels of Figure 2 show the differences between the two models for the oil and gas extraction and coal mining industries, respectively. Coal is clearly hit the hardest since it has the most carbon-rich product. At a $35 carbon tax the unemployment rate in the coal sector climbs to 36.6% in the immobile labor model. This is much higher than what the mobile labor market model predicts. The oil and gas extraction sector similarly has a larger spike in unemployment under the immobile labor assumption, though a $35 tax only increases unemployment to 11.5%. In the mobile model, the unemployment rate is the same across all sectors at just 5.22%. Taken together, this shows that the labor mobility assumption has just a modest effect on overall unemployment but can have large effects on sectoral unemployment.[12]

Effects in other industries can differ between the two labor mobility assumptions as well. Table 1 presents a summary of results for a $35 carbon tax with lump-sum revenue return, across all of the

[12] The large sectoral difference does not translate to a large aggregate difference, since those two sectors are small relative to the aggregate economy (accounting for less than 1% of total output).

sectors in the model. It presents the change in output price (relative to the numeraire price, which is a weighted average of all output prices), change in total production, and the change in labor demand. The changes in output prices are dampened in the immobile model, since industries can substitute towards cheaper labor trapped in their industry. While almost all industries see a reduction in output, the affected industries are hit much worse. Heavily-affected downstream industries, such as non-renewable electricity and natural gas distribution, also see large reductions in output. The change in output under the immobile labor assumption is slightly smaller than under the mobile labor assumption. Finally, the changes in labor are much larger (more negative) for the two affected industries than overall, while labor quantity increases for some of the sectors, including government services. The changes in labor are larger in absolute value when labor is mobile, since there is no response across industries in the price of labor (set economy-wide) and adjustments are forced to occur on the quantity margin.

The electricity sector is of special interest, because of its heavy use of fossil fuel inputs. The substitution towards renewables shows up in the labor market. Table 1 shows that labor quantity increases in the renewable sector, one of the few sectors of the economy that sees an increase. Labor demand increases are larger for the renewable electricity sector than for the non-renewable sector, which actually sees a small decrease in labor demand. Figure 3 shows changes in labor quantity in the two electricity sectors in response to a carbon tax of varying levels, for the mobile and immobile labor models. For renewable electricity production, labor demands increase across all carbon tax amounts, though the increase in labor demand is more than three times higher for the mobile labor model than for the immobile labor model. The growth in the renewable electricity sector in response to carbon policy may be overestimated in models ignoring mobility frictions. For non-renewable electricity labor demands decrease across all tax amounts, and the magnitude is similar across the two mobility assumptions.

IV.B Uniform Labor Tax Cut

Aggregate results for the carbon tax coupled with a uniform labor tax cut are summarized in Figure 4. The first panel shows that the change in aggregate emissions resulting from a tax is virtually independent of the labor mobility assumption and of the choice of revenue return.

Aggregate unemployment under the carbon tax actually decreases when revenues are returned through a labor tax cut, as shown in the second panel of Figure 4. For all carbon tax rates, the net effect of the tax swap is to reduce unemployment. The distortion from the new carbon tax is outweighed by the reduced distortion from the cut in the labor tax because the polluting industries are a relatively small fraction of the aggregate economy.[13] The unemployment decrease is slightly larger under the immobile model than under the mobile model. At a $35 per ton carbon tax, using the immobile labor assumption, we find a decrease in unemployment to 4.8%, and while using the mobile labor assumption, we find a decrease to 4.7%.

Looking at the oil and gas extraction and coal mining industries in the bottom two panels of Figure 4, the reduction in labor quantity under the labor tax cut revenue return is roughly the same as under the lump sum revenue return. The only discernable difference in sectoral unemployment is for the oil and gas extraction sector, which sees a slightly lower increase in unemployment under the labor tax cut than under the lump-sum revenue return. Thus, the substantial differences in aggregate unemployment (upper right panel) do not come from the polluting industries but rather from the rest of the economy.[14]

[13] This is analogous to the "double dividend" literature, although here we are not examining welfare effects.
[14] This is explored more fully in Appendix Table A4, which presents sectoral results for a $35 and a uniform labor tax cut. Under the lump-sum return and a $35 carbon tax, the oil and gas extraction industry reduces labor demand by 13.1% (Table 1). For the same carbon tax rate, revenue returned through a labor tax cut reduces labor by 12.5%. The untaxed industries show a substantially lower decrease in labor or bigger increase in labor under the labor tax cut than under the lump-sum return. Even though these magnitudes are small in other sectors, they make up large shares of employments and the net effect is an increase in labor demand.

Figure 5 focuses on the two electricity sectors and presents their labor demand changes. Labor demand changes are positive in both sectors when returning the revenue through a labor tax cut. However, the gains in the non-renewable sector diminish as the tax increases. Under the tax return, labor demand increases for the renewable sector are about 5 to 10 times larger than the non-renewable sector. Labor demand is increasing although output is decreasing in the two electricity sectors (see Table 4) because they are shifting away from other inputs, especially the fossil fuel inputs which represent a large fraction of their inputs.

The policy implications are that a tradeoff exists between the taxed and non-taxed industries. Although other sectors have employment gains, including electricity, the losses in the taxed industries do not differ very much between the two revenue return scenarios. The reason they do not differ much is likely that the tax cut ends up being rather small. Labor tax income makes up a large share of the government budget, so the tax cut is only about 2 percentage points. So, when coal mining is experiencing labor losses greater than 30%, a small labor tax cut does not do much to offset it.

IV.C Targeted Labor Tax Cut

Our third revenue return scenario is a targeted tax cut, where only the coal mining and oil and gas extraction industries receive a labor tax cut. It turns out that the tax revenue from the carbon tax is greater than the revenue from the labor tax in these two industries, so the post-policy labor tax actually becomes a subsidy for those two industries. This subsidy is quite large, reaching over 70% for the case with a $50 per ton carbon tax. Aggregate results are summarized in Figure 6. The first panel shows emissions reductions. The immobile model yields similar results to the previous policies since the allocation of labor cannot shift to more carbon-producing activities. The mobile model, however, shows a smaller reduction in emissions for each carbon tax level. Because the targeted tax cut subsidizes labor specifically in polluting industries, this subsidized labor makes production cheaper for those industries, so the decline in output and pollution is less under the targeted tax cut than under the other two policies.

The next panel of Figure 6 shows aggregate unemployment under the targeted tax cut. Under both mobile and immobile labor assumptions, we see a decrease in aggregate unemployment for low carbon tax rates. In the mobile model, this decrease is approximately as large as it is under the aggregate tax rate cut. This effect arises because the polluting industries hire workers leaving unsubsidized industries. The immobile model has a much smaller unemployment decrease due to those industries not being able to expand their labor force. For higher tax rates, the two curves diverge significantly, and the mobile labor assumption yields a decrease in unemployment while the immobile labor assumption yields an increase. Though the labor tax cut targets just two small industries, when labor is mobile, the positive effects on the labor market can dissipate throughout the economy. When labor is immobile, though, those effects are constrained to just the small targeted sectors. The last two panels of Figure 6 focus on the polluting industries; with the labor tax cut targeted to these industries, their unemployment rates drop substantially when labor is immobile. Under the mobility assumption, this effect vanishes because of the single economy-wide labor market. The immobile labor model shows a much different result because these industries cannot expand past their allocated supplies. They simply exhaust all the labor in their respective industries.[15]

These results give an important consideration for policy makers. While a subsidy to these industries from a targeted tax cut would curb unemployment in these specific industries, it may come at the expense of higher aggregate unemployment and lower emissions abatement depending on labor mobility assumptions. A tax cut across all industries would yield a larger aggregate unemployment

[15] Appendix Table A5 presents the sectoral results for a $35 carbon tax with a targeted labor tax cut. Under the mobile labor assumption, labor demands in these two industries increase rather dramatically. The oil and gas extraction industry more than doubles its labor quantity, and the coal mining industry sees a much smaller increase of just 5.3%, under a $35 carbon tax.

decrease, and emissions abatement would not change very much. However, unemployment in the taxed industries would still be quite high.

IV. D. Command-and-Control Policy

The last policy we consider is a command-and-control (CAC) quantity restriction policy, where each of the two fossil fuel industries is given a maximum allowable output. The regulator sets an amount of allowable output based on an emission reduction target, and we solve for the resulting shadow tax or shadow price of the restriction. The revenues from the shadow price are returned lump-sum to consumers. If we simply model such a policy with an aggregate emissions quantity restriction and one single economy-wide shadow price, the outcome will be identical to a carbon tax with a lump revenue sum return, shown earlier. Instead, our policy assigns a binding emissions reduction goal to each industry, which implies a different shadow price for each of the two industries. Therefore, even for a command-and-control policy that achieves the same aggregate emission reduction, the outcomes under this policy may differ from those under the equivalent carbon tax. This allows us to set the same abatement amount for each industry, such as a 30% reduction for each. By contrast, under a carbon tax, as we have shown earlier, the coal mining industry reduces output more than the oil and gas extraction industry does.

The results of this simulation are presented in Figure 7. Here, the policy variable is the percent of abatement mandated, presented on the x-axis. The top left panel plots this against the shadow price of the policy, which is different for the two polluting industries. We see a much higher price in the oil and gas extraction industry than in the coal industry. At a 30% emissions reduction, the shadow price of a ton of carbon in the oil and gas industry is $76.50, and in the coal mining industry it is only $7.36. For a given carbon tax rate, coal will reduce output and emissions by a higher percent than oil and gas will (e.g., see Table 3), so mandating the same percent reduction in output and pollution yields a lower shadow tax for coal. Under the immobile labor case, shadow prices are slightly higher than in the mobile labor case. Shadow prices are higher under the assumption of perfectly immobile labor.

The remaining panels of Figure 7 show the effects on aggregate and sectoral unemployment. The command-and-control policy yields a much higher increase in aggregate unemployment than the carbon tax with lump-sum revenue return. For a 30% emissions reduction, the command-and-control policy increases aggregate unemployment to 6.2% in the immobile model and 5.95% in the mobile model, compared to 5.3% and 5.2% for the carbon tax with lump-sum revenue return. This represents the inefficiency from this command-and-control policy relative to a more flexible carbon tax, even when either policy is targeted as just these two industries. It is quite inefficient for both industries to reduce their emissions by the same amount since the coal mining sector has a lower marginal abatement cost.

Lastly Figure 7 shows unemployment in the two targeted sectors. Unemployment is (as expected) higher in the two sectors in the immobile model than in the mobile model. For the immobile labor model, when comparing to the carbon tax with lump-sum return, unemployment is higher in the oil and gas extraction sector and lower in the coal mining sector under a command-and-control policy. At about 30% emissions reduction, the oil and gas extraction industry has an 11.4% unemployment rate under a carbon tax, but that more than doubles under the command-and-control policy to 22%. The coal mining sector sees a dramatic reduction from 36.6% unemployment under the carbon tax to 18.6% under the command-and-control policy. This indicates that a command-and-control policy that reduces each sector's emissions by different amounts could alleviate unemployment effects in the coal mining sector, but it comes at the cost of increasing unemployment in the oil and gas extraction sector and unemployment overall. The distribution of the burden across the two sectors depends heavily on the assumptions over labor mobility.[16]

[16] Appendix Table A6 presents the sectoral results for a command-and-control policy mandating a 30% emissions reduction. The two polluting sectors are disproportionately burdened by the mandate, but other sectors can still see a burden.

IV.E. Employment and Output Effects Across Policies

Finally, we compare the four policies directly to each other and examine their impacts on the overall economy. We do this by solving the eight policy simulations (four policies time two labor mobility assumptions for each policy) so that the policy results in a 30% aggregate reduction in emissions.[17] In Table 2, we present the decrease in GDP (total final demands) and the level of the unemployment rate for each policy simulation. Because our model does not include any damages from pollution, these reported changes in GDP are overestimates of the distortion from climate policy. In fact, a well-designed climate policy will reduce or eliminate the pre-existing distortions from the market failure caused by pollution. These reductions should be the same across all rows in Table 2, since all rows simulate the same aggregate pollution reduction.

Comparing GDP across the policies shows that the command-and-control policy yields the largest drop in GDP, and the labor tax cuts yield smaller drops in GDP than lump-sum revenue return. As described above, the command-and-control policy modeled here will underestimate the inefficiency of a more realistic command-and-control policy. Furthermore, under either labor mobility assumption, the uniform labor tax cut yields a smaller drop in GDP than does the targeted labor tax cut.

Table 2 also presents the effects on overall unemployment. Mirroring its effect on GDP, the command-and-control policy yields the highest unemployment rates, and a carbon tax with an offsetting reduction in the labor tax yield the lowest unemployment rates. However, the ranking between the targeted and aggregate tax cut policies depends on the labor mobility assumption: the targeted tax cut yields the smallest unemployment rate when labor is mobile, and the aggregate tax cut yields the smallest unemployment rate when labor is immobile. With mobile labor, the targeted tax cut is more

[17] For the command-and-control policy, that means just setting the mandate to a 30% reduction. For the carbon tax policies, it means finding the right carbon tax that yields a 30% emissions reduction. These tax rates are presented in the first columns of Table 2.

distortionary (larger decrease in GDP) than the aggregate tax cut but yields a lower unemployment rate – this is evidence of a trade-off between efficiency and impacts on the labor market. Such a trade-off does not exist with immobile labor – the aggregate tax cut is both least distortionary and has the lowest negative impact on the labor market.

Appendix A.II discusses sensitivity analysis.

V. Conclusion

We develop a computable general equilibrium model of United States climate policy that allows for involuntary unemployment and two alternate assumptions about cross-sectoral labor mobility: perfect mobility and perfect immobility. We consider the effect of a carbon tax on labor market outcomes including the unemployment rate, and we study how different assumptions about labor mobility affect these outcomes. Labor mobility does not have a substantive effect on emissions abatement or aggregate unemployment, but it can have a large effect on sectoral labor market outcomes. The increase in the aggregate unemployment rate when labor is modeled as perfectly immobile is just 0.1 percentage point larger than the increase in the unemployment rate when labor is modeled as perfectly mobile. Unemployment in fossil fuel industries is enormously higher when labor is modeled as perfectly immobile – increasing by 6.5 percentage points and 31.6 percentage points in the oil and gas extraction sector and the coal mining sector, respectively, compared to just 0.2 percentage points when labor is modeled as perfectly mobile. When carbon tax revenues are returned as a labor tax cut rather than lump sum, the unemployment rate can decrease for some industries or overall, and the immobile labor assumption yields a higher decrease in labor than the mobile labor assumption does.

As with any CGE model, the results depend on several modeling assumptions made, including calibration of the elasticity and other parameters. While we have performed several robustness checks, there is potential for even more investigation of the effect of these assumptions on the outcomes. Our modeling of mobility was intentionally extreme – we compared both extreme cases of perfect mobility and perfect immobility to highlight the potential for differences. However, an extension would be to consider cases of intermediate or limited mobility. Our modeling of unemployment was a reduced-form wage curve, in contrast to other CGE models that have included more structural equilibrium unemployment specifications, like search and matching models. While most of the intuitions and quantitative results from more complicated structural models can be captured with this reduced-form approach, it is also possible that our approach misses some important elements. Ours is a static, not dynamic, model, so we can study neither transition periods nor policies that change over time, like a carbon tax that increases over time. The model could include even more sectoral disaggregation, for example by disaggregating the oil and natural gas extraction sectors, or could include geographical disaggregation.

Our paper's policy implications are important. Models that omit any labor market frictions or unemployment entirely are unreliable for gauging the effects of policy on unemployment, though full-employment models have been used to make predictions about unemployment effects. But even models that explicitly include equilibrium unemployment often make the extreme assumption that labor is perfectly mobile across sectors – an assumption unlikely to be relevant for policies that affect workers in fossil-fuel-extracting industries. By showing the importance of assumptions about labor mobility, we demonstrate that the impact on unemployment from climate policy may be greater than previously anticipated based on previous CGE models. Policymakers concerned with distributional impacts of climate policy can take this finding into account when determining policy options.

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Table 1: Sectoral Results, $35 per ton carbon tax, lump-sum revenue return

	Output Price		Total Production		Labor Quantity	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	0.3%	-0.6%	-15.5%	-14.9%	-13.1%	-6.8%
Coal Mining	17.2%	13.1%	-52.5%	-51.8%	-43.1%	-33.3%
Non-Renewable Electricity	2.3%	2.2%	-6.3%	-6.0%	-0.3%	-0.3%
Renewable Electricity	-0.7%	-0.4%	-1.9%	-2.2%	2.6%	0.7%
Natural Gas Distribution	3.5%	3.2%	-7.0%	-6.7%	-0.8%	-0.5%
Mining	-0.1%	-0.7%	-10.9%	-10.3%	-4.3%	-2.0%
Agriculture	0.1%	-0.8%	-8.4%	-7.8%	-4.4%	-2.0%
Construction	0.0%	0.9%	-2.4%	-3.0%	3.6%	1.0%
Manufacturing	0.9%	0.7%	-7.7%	-7.3%	-0.5%	-0.3%
Chemicals	0.1%	-0.4%	-9.5%	-9.0%	-2.5%	-1.2%
Services	-0.3%	-0.6%	-5.9%	-5.5%	-1.1%	-0.6%
Govt	0.2%	1.6%	-0.8%	-2.2%	3.9%	1.1%
Aggregate	0.0%	0.0%	-6.1%	-5.9%	-0.2%	-0.3%

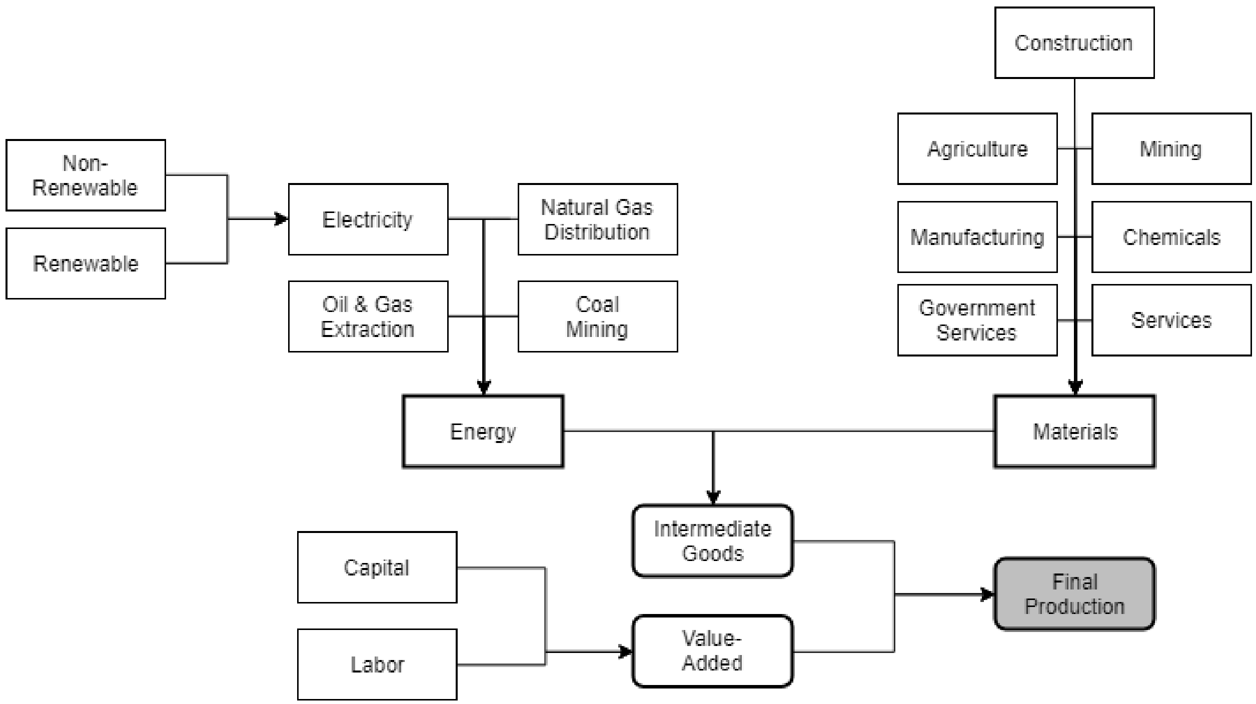
Notes: This table provides changes in output price (relative to the numeraire), output quantity, and labor quantity for each industry in response to a $35 carbon tax with lump-sum revenue return, for both the perfectly mobile and perfectly immobile labor assumptions. The numeraire is a weighted average of all output prices, so the aggregate price change is zero. The change in total production in each industry is inclusive of both intermediate and final demands, and is not a measure of GDP.

Table 2: Change in GDP (excluding pollution damages) and aggregate unemployment across policies, 30% emissions reduction

	Tax Rate ($/ton)		Decrease in GDP		Unemployment	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Carbon tax with lump-sum return	$33.47	$34.07	-0.92%	-1.05%	5.21%	5.31%
Carbon tax with uniform labor tax cut	$33.69	$34.97	-0.64%	-0.50%	4.72%	4.79%
Carbon tax with targeted labor tax cut	$49.94	$37.08	-0.70%	-0.71%	4.55%	5.16%
Command-and-Control Mandate	-	-	-3.42%	-3.71%	5.95%	6.24%

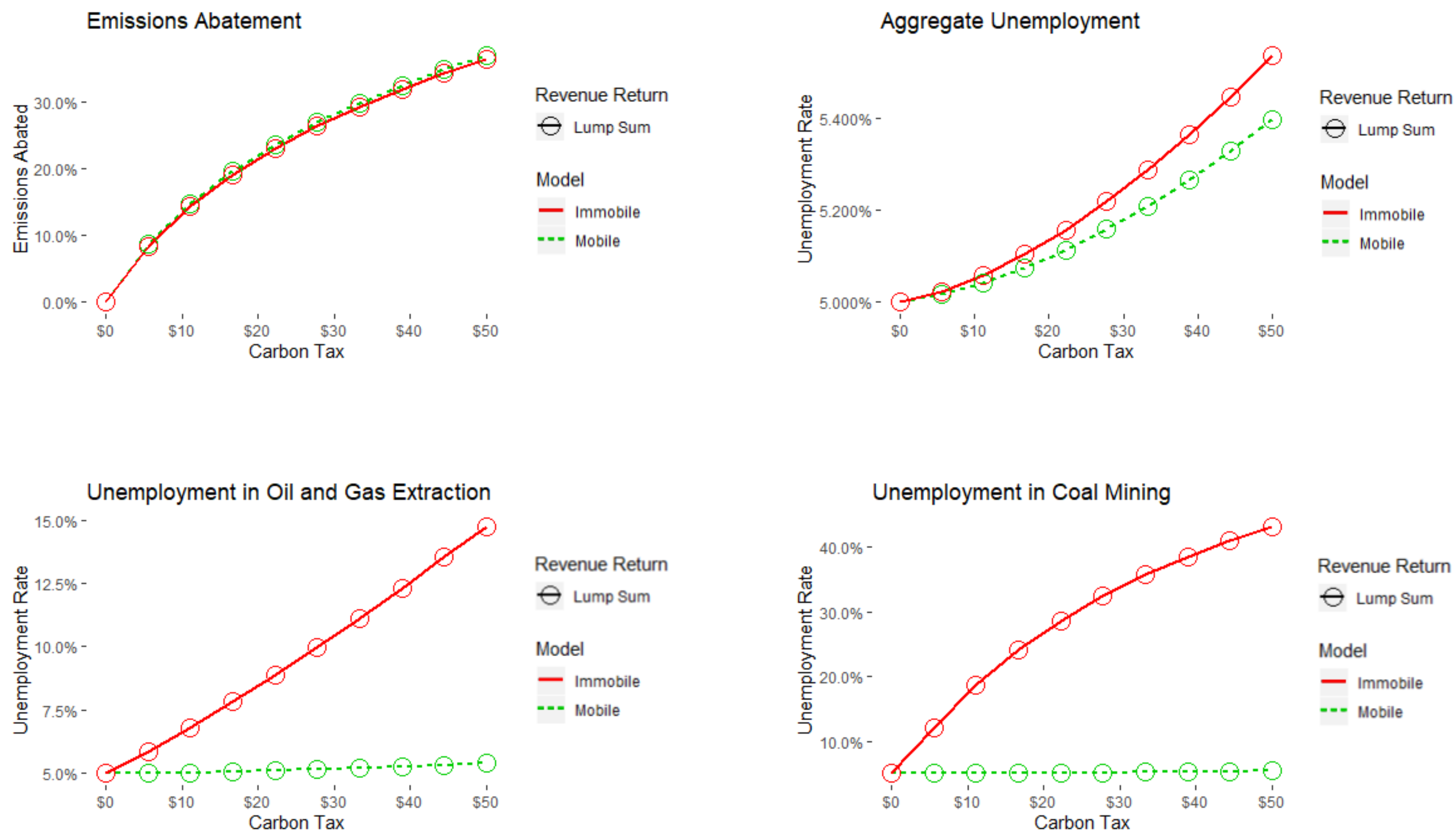
Notes: This table presents the decrease in GDP (aggregate output) and the level of aggregate unemployment due to a 30% reduction in emissions across the four different policies. For the three carbon tax policies, we also present the tax rate that must be levied to yield a 30% emissions reduction. The model does not include pollution damages, so the reported changes in GDP do not reflect any potential productivity improvements from reducing pollution.

Figure 1: Nested Production Structure



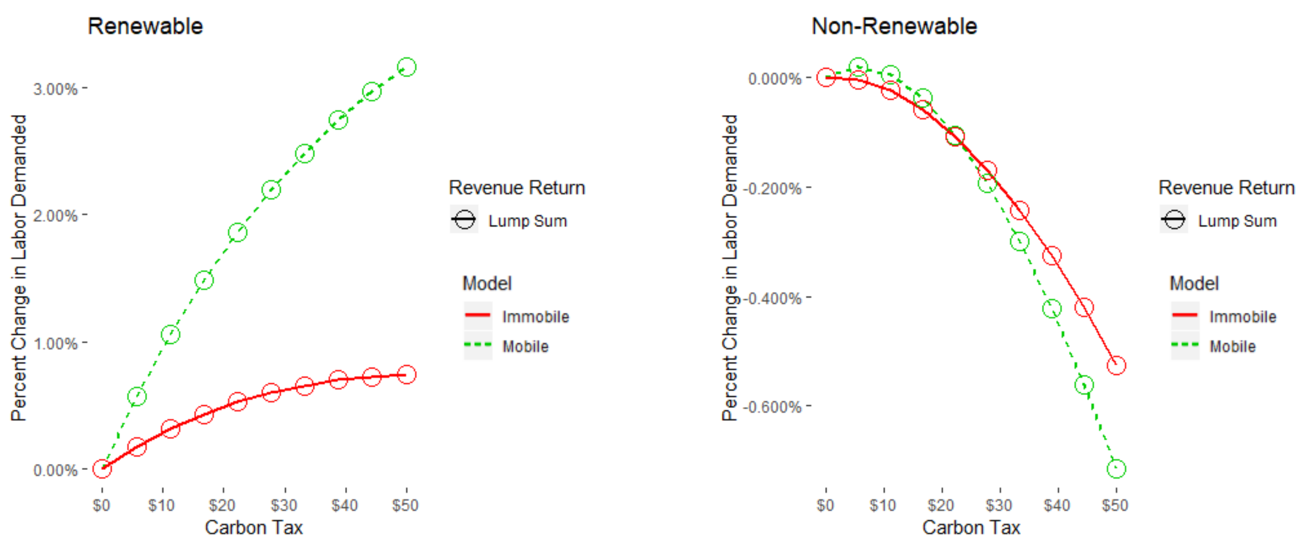
Notes: This figure presents the nested production structure of the CGE model used in this paper.

Figure 2: Results, carbon tax, lump-sum revenue return



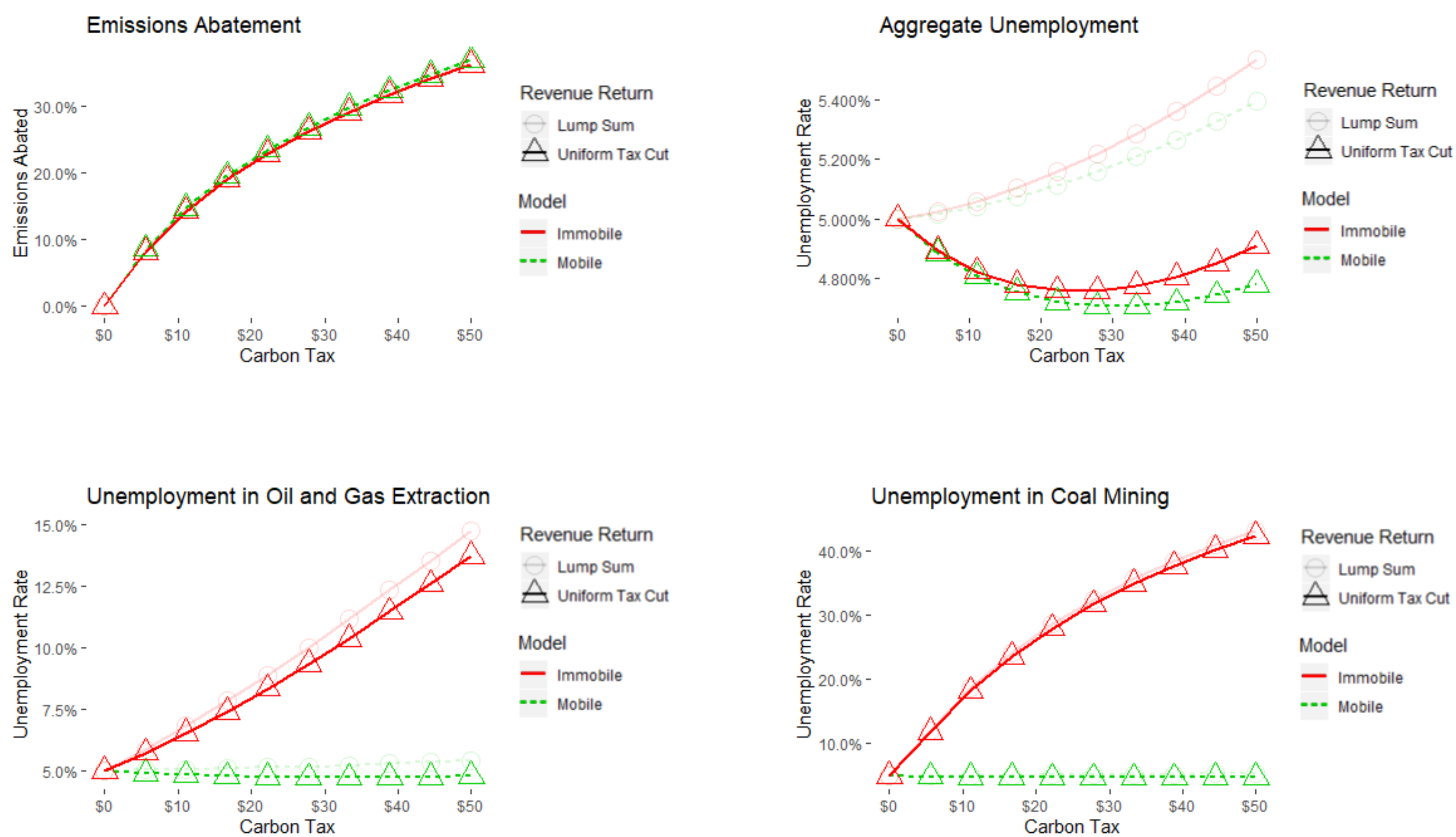
Notes: These graphs present results under a carbon tax of varying levels (x-axis) with lump-sum revenue return. The first panel shows the amount of emissions abatement (%). The second panel shows the aggregate unemployment rate from the base level (5%). The bottom two panels show the unemployment rate for the two polluting industries (oil and gas extraction and coal mining). In each panel, we show results under the perfectly immobile labor assumption (red circles) and under the perfectly mobile labor assumption (green circles).

Figure 3: Labor quantity changes in electricity sectors, carbon tax, lump-sum revenue return



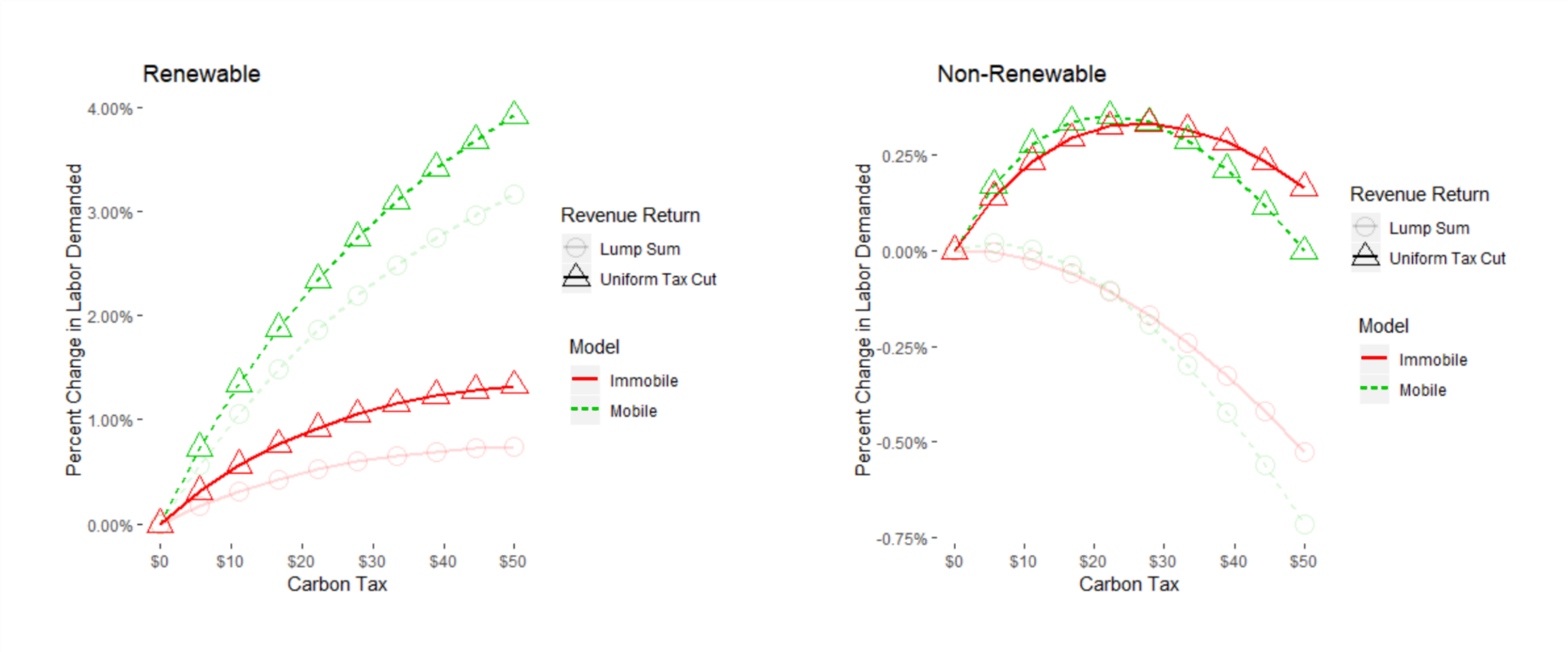
Notes: These graphs present the change in the quantity of labor for just the non-renewable and renewable electricity sectors (y-axis) resulting from differing levels of a carbon tax (x-axis) where revenues are returned lump-sum. In each panel, we show results under the perfectly immobile labor assumption (red circles) and under the perfectly mobile labor assumption (green circles).

Figure 4: Results, carbon tax, revenue return through uniform labor tax cut



Notes: These graphs present results under a carbon tax of varying levels (x-axis) with revenue returned through a uniform labor tax cut. The first panel shows the amount of emissions abatement (%). The second panel shows the aggregate unemployment rate from the base level (5%). The bottom two panels show the unemployment rate for the two polluting industries (oil and gas extraction and coal mining). In each panel, we show results under the perfectly immobile labor assumption (red triangles) and under the perfectly mobile labor assumption (green triangles). The faded curves with the circles replicate the results under the lump-sum revenue return (Figure 2) for comparison.

Figure 5: Labor quantity changes in electricity sectors, carbon tax, revenue return through uniform labor tax cut

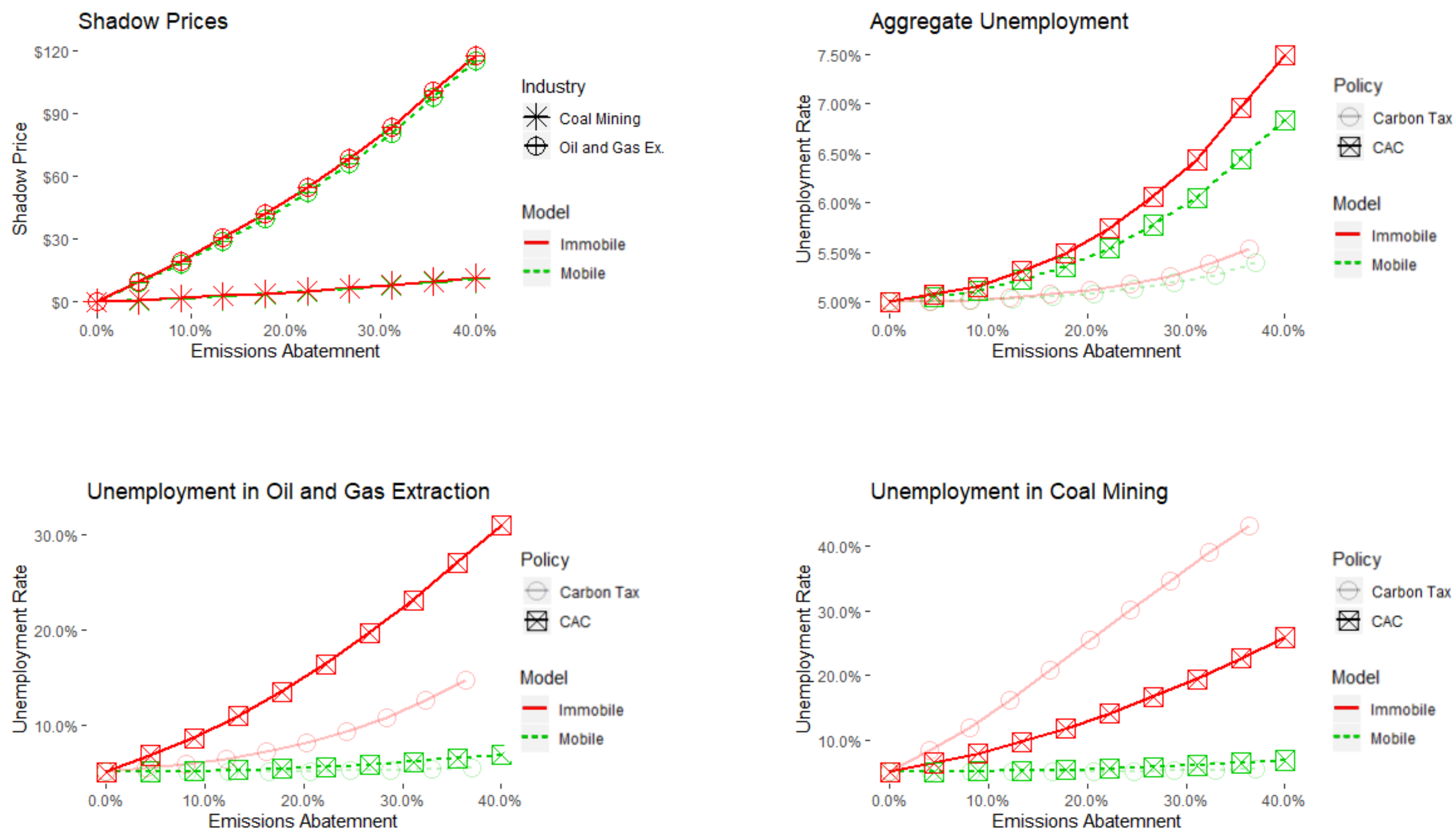


Notes: These graphs present the change in the quantity of labor for just the non-renewable and renewable electricity sectors (y-axis) resulting from differing levels of a carbon tax (x-axis) where revenues are returned lump-sum. In each panel, we show results under the perfectly immobile labor assumption (red triangles) and under the perfectly mobile labor assumption (green triangles). The faded curves with the circles replicate the results under the lump-sum revenue return (Figure 3) for comparison.

Figure 6: Results, carbon tax, revenue return through targeted labor tax cut

Notes: These graphs present results under a carbon tax of varying levels (x-axis) with revenue returned through a targeted labor tax cut (only cut for the two polluting industries, oil and gas extraction and coal mining). The first panel shows the amount of emissions abatement (%). The second panel shows the aggregate unemployment rate from the base level (5%). The bottom two panels show the unemployment rate for the two polluting industries. In each panel, we show results under the perfectly immobile labor assumption (red squares) and under the perfectly mobile labor assumption (green squares). The faded curves with the circles and triangles replicate the results under the previous revenue return assumptions (Figures 2 and 4) for comparison.

Figure 7: Results, command-and-control policy



Notes: These graphs present results under a command-and-control policy of varying levels (x-axis). The first panel shows the shadow price of the mandate. The second panel shows the aggregate unemployment rate from the base level (5%). The bottom two panels show the unemployment rate for the two polluting industries (oil and gas extraction and coal mining). In each panel, we show results under the perfectly immobile labor assumption (red diamonds) and under the perfectly mobile labor assumption (green diamonds). The faded curves with the circles replicate the results under the carbon tax with lump-sum revenue return (Figure 2) for comparison.

Appendix – For Online Publication

A.I. Data and Calibration

A.I.A. Data Sources

The model is calibrated to fit an input-output matrix for the United States from the Bureau of Economic Analysis (BEA) 2007 benchmark tables.[18] The BEA matrix contains over 300 industry classifications, which we aggregate to 11 industries. These industries, listed in Appendix Table A2, fall into the two categories of our model: energy and materials.[19] The energy sectors are oil and gas extraction, coal mining, electricity, and natural gas distribution. We further divide electricity generation into two sub-industries: renewable and non-renewable electricity generation. We also use information on final goods production, government spending, and indirect taxes from the BEA tables.

Federal tax revenue by source is taken from documentation by the Congressional Budget Office which includes information on transfers and spending. Specifically, we use "The Distribution of Federal Spending and Taxes in 2006," due to its high level of detail in expenditure and revenue categories[20]. State taxes must also be included, so we use state and local revenues by tax type from the 2007 Quarterly Summary of State & Local Tax Revenue Tables created by the Census bureau.[21]

A.I.B. Calibration

Here we describe how we select our base-case parameter values. Appendix Table A3 summarizes some of the important calibrated parameter values. The elasticity values are set based on

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[18] Available here: https://www.bea.gov/industry/io_annual.htm.
[19] The BEA data do not disaggregate electricity generation into renewable and nonrenewable generation, so those two sub-industries are not presented in Appendix Table A2. Later in this section we describe our calibration strategy for electricity.
[20] https://www.cbo.gov/publication/44698
[21] https://www.census.gov/data/tables/2007/econ/qtax/historical.html

existing literature. All elasticity values are set to 0.9 in our base case simulations. Estimates of these elasticities typically range from 0.75 to 1. Many papers specifically test the condition that they are equal to unity, which would indicate Cobb-Douglas demands (Van der Werf, 2008). In general, the empirical evidence is mixed, but it seems to indicate an elasticity slightly below unity. Fullerton and Ta (2019) use all Cobb-Douglas specifications (elasticity equal to unity) and finds aggregate results similar to the Goulder-Hafstead E3 model. We choose a lower value for intermediate goods substitution since these are often modeled as Leontief types production which would be a substation elasticity of 0. We later vary these base-case elasticity values to explore robustness. The remaining production shift and share parameters, α_i^s and γ_i^s, are determined by solving to match the input-output matrix from the BEA. These parameters are unique to each industry, and thus for space are not presented in Appendix Table A3.

The elasticity parameter in the wage curve η_1 is set to –0.1, and the baseline unemployment rate is set to 5%. The elasticity parameter comes from Blanchflower and Oswald who have found remarkable robustness to an estimate of -0.1 (1990, 2005). Recent CGE papers using wage curve specifications in models have used this estimate to calibrate models (Rivers 2013, Bohringer et. al. 2012). Modelers have also argued that this empirical relationship can be found as an reduced form of structural models of labor supply (Hutton and Ruocco 1999).

Government spending parameters are calculated from budget documentation from the Congressional Budget Office (CBO). The ratio of transfers to total government revenue, $\frac{TR}{G}$ is set at 25%, close to the CBO documentation that puts this number about 30-35%. The size of the government budget as a percent of GDP, $\frac{G}{FD}$, is set to 20% based on CBO documentation. We calibrate tax rates by first calculating total government revenue by tax source then comparing these to factor incomes from the BEA tables to create an effective tax rate, yielding an effective labor tax rate of 26.9% and an effective capital tax rate of 11.5%. While these tax rates are lower than marginal tax rates, we use all sources of income and total tax revenue by income source to derive an effective tax rate inclusive of any deductions or lower tax rates based on capital type. We calibrate the sales tax in a similar fashion, yielding a 5% sales tax. Data on tax collection revenues comes from the Annual Survey of State Government Tax Collections provided by the Census Bureau.[22]

Parameters for the utility function are determined using shares of personal consumption expenditure in the BEA tables. Capital and labor endowments for households are determined from industry data. We assume that in the calibrated equilibrium, supply stocks are equal to industry demands, given unemployment.

Additionally, we do not include international trade in intermediate goods. This reduces the complexity of the model by not having to create a multi-regional production process or estimate trade elasticities. Since a large portion of fossil fuel inputs in the US are imported, we target the domestic marginal cost structure and total domestic production when calibrating the model. We create an input-output matrix such that inputs are homogenous by country of origin and then use domestic production amounts to back out factor requirements. This makes final demand levels slightly less accurate but preserves industry marginal cost structures.

Carbon emissions are a linear relation to output for the two polluting sectors (coal mining and oil and gas extraction). Appendix Table A2 presents carbon coefficients for these two sectors as well as final domestic demands from each of the eleven industries in the BEA table. Total carbon emissions by fuel source come from the U.S. Energy Information Administration.[23]

The BEA tables do not provide information on this disaggregation between renewable and nonrenewable electricity generation, so we use data from the EIA Annual Energy Review from 2007 on renewable electricity generation by source and find that it is about 10% of total electricity generation.

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[22] https://www.census.gov/programs-surveys/stc/data/datasets.2007.html
[23] https://www.eia.gov/environment/emissions/carbon/

We create a non-renewable sector that uses the same ratio of inputs as the electricity sector from the BEA tables, except that the renewable sector uses no fossil fuel inputs and instead uses only non-fossil fuel energy, materials, and value-added composites.

A.II. Robustness

First, we conduct a sensitivity analysis exploring the influence of parameter values. Then, we consider the specification of the wage curve.

A.II.A. Sensitivity Analysis

We compare our results under alternative values for various parameters. We first consider changes in technology and the elasticity of substitution for different nests of the production function. Then we consider changes in the wage curve parameters and tax rates. Results for our sensitivity analysis are presented in Appendix Table A7. The first row presents the results for base case for comparison. For each parameterization, we present three summary statistics for each of the two labor mobility assumptions: aggregate unemployment, loss in output (GDP), and the percentage of emissions abated. All results in Appendix Table A7 are for the $35 per ton carbon tax with revenues returned lump-sum.

Rows 2 through 9 show changes in technology substitution parameters. We consider values 25% higher and lower for several parameter values. For most elasticity parameters, our sensitivity check gives expected results. As substitution between inputs becomes more inelastic GDP losses, abatement, and unemployment rates are smaller. We expect this result, as the tax distortion decreases due to more inelastic substitution. The substitution parameter between labor and capital (rows 4 and 5) has a different impact with a lower elasticity predicting a larger output loss, however the unemployment rate is much smaller than other specifications. For the electricity nest, our parameter value was chosen rather arbitrarily, since we could not find an estimate fitting our model specification. We believe it to be greater than 1 since electricity from different fuels are likely highly substitutable. We consider a wide range of values starting with just below Cobb-Douglas specification at 0.9 going up to 10 – a very high substitution elasticity. The overall impacts (rows 8 and 9) are modest due to the relatively small size of the electricity sector.

Rows 10 and 11 present alternate values for the wage curve elasticity parameter η_1. In the base case we use Blanchflower et. al.'s estimate of –0.1, but structural estimates of matching models put this number closer to –1 (Boeters and Savard 2013), implying a smaller response of unemployment to wage changes. As expected, decreasing the elasticity parameter to –1 in row 10 significantly lowers the effect of a carbon tax on unemployment, from 5.22% in the base case to 5.028% for the mobile model, and from 5.31% in the base case to 5.033% for the immobile model. Overall, the aggregate impacts are very similar across different elasticity assumptions. In the last row we also consider varying the wage curve elasticity across industries. One might assume that fossil fuel industries have a more elastic response and the wider economy has an inelastic response. In row 11 we set the wage curve elasticity equal to –0.1 for the fossil fuel industries and –1 for all others. The results are not much different from those in row 10, since the fossil fuel industries are small relative to the overall economy, though unemployment is slightly higher (5.10% vs. 5.03%) when labor is mobile

GDP losses and abatement rates in the immobile model are smaller under almost all specifications. Unemployment comparisons between the two mobility assumptions are nearly as robust. In specifications where elasticity among inputs is high relative to the elasticity of the wage curve, the immobile model predicts higher aggregate unemployment rates than the mobile labor model. Row 5 of Appendix Table A7 is a 25% increase in elasticity of substitution between labor and capital, and row 10 is a decrease in the elasticity of the wage curve. Both rows indicate lower unemployment in the immobile model than the mobile model.

A.II.B. Wage Curve Normalization

We take our specifications for the wage curve from the empirical literature. But, we must decide which wage to use in the wage curve – the net-of-tax wage or the gross wage. The wage curve posits that the unemployment effect depends on the wage, and so it crucially matters which wage we use. Throughout our analysis, we have used the net-of-tax wage in the wage curve, which is perhaps more intuitive – workers in the labor market respond to their take-home wage rather than pre-tax gross wages. Furthermore, most studies in the literature use net wages in the wage curve.[24] However, the literature is somewhat unclear on which wage is appropriate to use. But, in our analysis there can be a critical difference when considering policies that return tax revenues through cuts in the labor tax rate. When the labor tax rate changes, this introduces a wedge between net-of-tax and gross wages, and so the unemployment effect can depend on which wage is used in the wage curve. Indeed, the choice can reverse the sign of the policy effect on unemployment.

We demonstrate this in Appendix Table A8. We present three summary statistics – aggregate unemployment, and unemployment in the two polluting sectors – for each of the two labor mobility assumptions and for each of the two assumptions about the wage used in the wage curve (net-of-tax or gross). We simulate the second policy – the $35 carbon tax with revenues returned via a uniform labor tax cut. Using the gross wage predicts an increase in unemployment under the aggregate tax cut return that is the same as under the lump-sum return, because the reduction in wages is similar under both cases. Using the net wage, however, predicts a *decrease* in unemployment from a tax rate cut. This decrease arises because, as gross wages stay roughly the same, net wages increase due to the lower tax cut.

[24] For example, Hutton and Ruocco (1999) and the MIMIC model (Graafland et. al. 2001).

Appendix Table A1: CGE studies of environmental policy with involuntary unemployment

Study	Country/Region	Specification of Labor Market, Sectoral Mobility	Specification of Unemployment	Policy modeled	Summary of results
Balistreri (2002)	United States (open economy)	Homogeneous, perfectly mobile	Search and matching modeled as an externality in labor market	Emissions controls from MRN model	About 1% point increase in unemployment
Böhringer et al. (2003)	Germany and India	Homogeneous, perfectly mobile	Wage curve	Carbon tax to meet Kyoto protocol emissions levels	Sectoral unemployment increases 26.02 - 52.9% in industries such as coal.
André et al. (2005)	Andalusia, Spain	Homogeneous, perfectly mobile	Wage curve	Carbon tax	Unemployment increases from 0.5% to 5.4%.
Babiker and Rutherford (2005)	Multiple countries in GTAP database	Homogeneous, perfectly mobile	Keynesian sticky wages	Permit system with reduction to Kyoto protocol levels	Unemployment can increase sharply under voluntary export restraint regimes
O'Ryan et al. (2005)	Chile	Two types – skilled and unskilled, perfectly mobile	Full employment is assumed, though an alternative scenario analyzes effect of high unemployment	Tax on PM10 emissions as well as other pollutants.	Small yet insignificant decrease in unemployment due to lower wages and increases in employment in the construction sector.
Küster et al. (2007)	World – 10 regions from GTAP database	Two types – skilled and unskilled	Unskilled from rigid wages (wage floor), skilled from wage curve		
Babiker and Eckaus (2007)	Japan, Europe, China, USA, Former Soviet Union (pre 1995) – Countries from GTAP database	Sector-specific with mobility rigidities	Wage floor	Permit system with reduction to Kyoto protocol levels	Small (0.5 – 1%) increases in unemployment, greater in China and India

Böhringer et al. (2008)	Germany	Homogeneous, perfectly mobile	Wage curve	Carbon tax	Unemployment can be 1% point higher under imperfect competition as compared to perfect competition
McKibbin and Wilcoxen (2008)	U.S., Japan, Australia, Europe, Other OECD, China, India, OPEC, EEFSU (Former Soviet Union)	Homogeneous, perfectly mobile	Overlapping contracts model	Carbon tax with border adjustment taxes (BAT)	Do not report results on unemployment rates
Hafstead et al. (2018)	United States	Homogeneous, perfectly mobile	Matching model with search frictions	Carbon tax	Carbon taxes cause sectoral shifts in labor, but little changes in aggregate unemployment.
This paper	United States	Labor either perfectly mobile or perfectly immobile (sector-specific)	Wage curve	Carbon tax with alternative revenue recycling schemes	Mobility affects unemployment

Notes: This table briefly summarizes some of the modeling assumptions and results of several papers (including this one) that use CGE models that include involuntary unemployment to study environmental policy.

Appendix Table A2: Industry Production and Carbon Emissions

	Domestic Final Demands (2007 U.S. $Mil.)	Carbon Coefficient (MMt CO_2/$Mil.)
Energy		
Oil and Gas Extraction	$97,450.85	0.00508
Coal Mining	$2,527.86	0.05181
Electricity Distribution	$145,774.76	-
Natural Gas Dist.	$58,288.95	-
Materials		
Agriculture	$111,316.60	-
Non-Coal Mining	$61,695.81	-
Construction	$1,204,766.31	-
Manufacturing	$2,452,346.05	-
Chemicals	$305,637.52	-
Services	$9,394,995.55	-
Government Services	$2,269,651.13	-

Note: Values are from the BEA make tables, described in the text, aggregated to these eleven industries. Carbon emissions are from U.S. Department of Commerce.

Appendix Table A3: Parameter values

Parameter name	Description	Value	Source
σ	Elasticity of substitution among intermediate goods	0.5	Van der Werf (2008)
σ^{VA}	Elasticity of substitution between capital and labor	0.9	Van der Werf (2008)
σ^{prod}	Elasticity of substitution between value added components and intermediate goods	0.9	Van der Werf (2008)
σ^{ELEC}	Elasticity of substitution between renewable and non-renewable electricity	2	This was chosen as to give a great deal of substitution between non-renewable and renewable electricity.
η_1	Elasticity of unemployment to wages	–0.1	Blanchflower and Oswald (2005)
u	Baseline unemployment rate	5%	Estimate of natural rate of unemployment
$\frac{TR}{G}$	Percent of revenues dedicated to transfers	35%[1]	CBO budget documentation https://www.cbo.gov/publication/44924
$\frac{G}{FD}$	Tax revenues as percent of GDP	20%	CBO budget documentation https://www.cbo.gov/publication/44924
T^L	Tax rate on labor	26.9%[2]	BEA factor payments and CBO documentation
T^K	Tax rate on capital	11.4%	BEA factor payments and CBO documentation

Notes: Parameter values used in the model are presented here. Some estimates are taken from the literature, but most estimates are calculated to match a baseline social accounting matrix developed from the BEA make and use tables. Tax rates may seem smaller than those typically used in models, but we calculate the tax rates based on revenues by source rather than direct estimates of marginal rates.

[1]This number is an average across Federal, State, and Local expenditures. While at the Federal and State level transfers are close to 50%, at the local level there are much smaller direct transfers. The average of these rates is about 35%.

[2]The CBO puts this number closer to 31% (https://www.cbo.gov/publication/54911). So, using BEA income data may understate the average tax burden on labor.

Appendix Table A4: Sectoral Results, $35 per ton carbon tax, revenue return through uniform labor tax cut

	Output Price		**Total Production**		**Labor Quantity**	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	0.5%	-0.5%	-15.3%	-14.7%	-12.5%	-6.0%
Coal Mining	17.3%	13.1%	-52.4%	-51.7%	-42.7%	-32.5%
Non-Renewable Electricity	2.5%	2.3%	-6.1%	-5.8%	0.3%	0.3%
Renewable Electricity	-0.5%	-0.3%	-1.7%	-2.0%	3.2%	1.2%
Natural Gas Distribution	3.7%	3.3%	-6.9%	-6.5%	-0.2%	0.1%
Mining	0.0%	-0.6%	-10.7%	-10.2%	-3.8%	-1.3%
Agriculture	0.1%	-0.7%	-8.2%	-7.6%	-3.8%	-1.4%
Construction	0.0%	0.9%	-2.1%	-2.8%	4.2%	1.5%
Manufacturing	0.9%	0.7%	-7.5%	-7.1%	0.1%	0.2%
Chemicals	0.1%	-0.3%	-9.4%	-8.9%	-2.0%	-0.5%
Services	-0.3%	-0.6%	-5.7%	-5.2%	-0.5%	0.0%
Govt	0.1%	1.5%	-0.7%	-2.0%	4.3%	1.5%
Aggregate	0.0%	0.0%	-5.9%	-5.7%	0.3%	0.2%

Notes: This table provides changes in output price (relative to the numeraire), output quantity, and labor quantity for each industry in response to a $35 carbon tax with revenue returned through a uniform labor tax cut, for both the perfectly mobile and perfectly immobile labor assumptions. The numeraire is a weighted average of all output prices, so the aggregate price change is zero. The change in total production in each industry is inclusive of both intermediate and final demands, and is not a measure of GDP.

Appendix Table A5: Sectoral Results, $35 per ton carbon tax, revenue return through targeted labor tax cut

	Output Price		**Output Quantity**		**Labor Quantity**	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	-12.6%	-1.9%	-5.0%	-13.8%	198.7%	5.3%
Coal Mining	-7.3%	2.4%	-48.4%	-50.7%	71.5%	5.1%
Non-Renewable Electricity	1.9%	2.1%	-2.8%	-5.5%	-1.0%	-0.2%
Renewable Electricity	-0.4%	-0.4%	0.6%	-1.9%	0.7%	0.7%
Natural Gas Distribution	1.0%	3.0%	-2.2%	-6.1%	-1.3%	-0.4%
Mining	0.0%	-0.6%	-3.2%	-9.5%	-2.3%	-1.8%
Agriculture	0.3%	-0.7%	-3.9%	-7.3%	-3.5%	-1.9%
Construction	0.3%	0.8%	-0.9%	-2.7%	0.0%	1.0%
Manufacturing	0.7%	0.7%	-2.4%	-6.7%	-1.1%	-0.3%
Chemicals	0.0%	-0.3%	-2.9%	-8.3%	-1.9%	-1.0%
Services	0.1%	-0.5%	-1.7%	-5.0%	-1.2%	-0.5%
Govt	0.7%	1.5%	-0.8%	-2.0%	0.0%	1.0%
Aggregate	0.0%	0.0%	-1.9%	-5.4%	0.5%	-0.1%

Notes: This table provides changes in output price (relative to the numeraire), output quantity, and labor quantity for each industry in response to a $35 carbon tax with revenue returned through a targeted labor tax cut (only for the oil and gas extraction and coal mining sectors), for both the perfectly mobile and perfectly immobile labor assumptions. The numeraire is a weighted average of all output prices, so the aggregate price change is zero. The change in total production in each industry is inclusive of both intermediate and final demands, and is not a measure of GDP.

Appendix Table A6: Sectoral Results, 30% emissions reduction command-and-control policy

	Output Price		Output Quantity		Labor Quantity	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	36.5%	36.4%	-30.0%	-30.0%	-26.0%	-18.0%
Coal Mining	40.1%	39.4%	-30.0%	-30.0%	-21.1%	-14.3%
Non-Renewable Electricity	0.1%	-0.3%	-10.2%	-10.1%	-1.8%	-1.5%
Renewable Electricity	-1.9%	-2.0%	-7.4%	-7.8%	1.1%	-0.3%
Natural Gas Distribution	5.9%	5.5%	-13.9%	-13.9%	-2.6%	-1.8%
Mining	-1.0%	-2.2%	-20.7%	-20.6%	-9.0%	-5.2%
Agriculture	-1.5%	-3.0%	-15.5%	-15.0%	-8.7%	-5.1%
Construction	-0.5%	1.0%	-5.5%	-7.0%	6.4%	1.5%
Manufacturing	0.7%	0.2%	-15.0%	-14.9%	-1.7%	-1.4%
Chemicals	-0.5%	-1.4%	-18.5%	-18.4%	-5.5%	-3.2%
Services	-1.2%	-1.9%	-12.0%	-11.8%	-2.9%	-2.0%
Govt	-0.5%	3.0%	-0.8%	-4.2%	8.6%	2.0%
Aggregate	0.0%	0.0%	-12.1%	-12.3%	-1.0%	-1.4%

Notes: This table provides changes in output price (relative to the numeraire), output quantity, and labor quantity for each industry in response to a command-and-control policy mandating a 30% emissions reduction, for both the perfectly mobile and perfectly immobile labor assumptions. The numeraire is a weighted average of all output prices, so the aggregate price change is zero. The change in total production in each industry is inclusive of both intermediate and final demands, and is not a measure of GDP.

Appendix Table A7: Sensitivity Analysis

		Mobile			Immobile		
		Unemployment	GDP Loss	Abatement	Unemployment	GDP Loss	Abatement
(1)	Base Case[1]	5.23%	-1.04%	30.78%	5.31%	-1.06%	30.15%
(2)	σ = 0.7	5.22%	-1.05%	34.87%	5.31%	-1.07%	34.19%
(3)	σ = 1.13	5.22%	-1.06%	39.22%	5.33%	-0.99%	39.22%
(4)	σ^{VA} = 0.7	5.19%	-1.04%	30.70%	5.29%	-0.96%	30.93%
(5)	σ^{VA} = 1.13	5.29%	-1.03%	30.94%	5.36%	-0.98%	31.01%
(6)	σ^{prod}= 0.7	5.22%	-0.94%	29.95%	5.29%	-0.87%	30.08%
(7)	σ^{prod}= 1.13	5.25%	-1.31%	33.23%	5.37%	-1.24%	33.53%
(8)	σ^{ELEC}= 0.9	5.23%	-1.04%	30.77%	5.31%	-0.97%	30.94%
(9)	σ^{ELEC}= 10	5.23%	-1.04%	30.83%	5.31%	-0.97%	31.01%
(10)	η_1= –1	5.03%	-0.92%	30.79%	5.03%	-0.85%	30.97%
(11)	Mixed η_1[2]	5.03%	-0.92%	30.79%	5.10%	-0.85%	30.97%

Notes: This table is predictions for specified aggregate variables after implementation of a $35 carbon tax, with revenues returned lump-sum.
[1]The first row uses the base-case parameter values (listed in Appendix Table A3). All other rows change just one parameter from its base-case value as indicated. For each of the first four parameters, we consider values roughly 25% higher and lower for each substitution elasticity. We also consider a different wage curve elasticity and government revenue split.
[2]This row varies η_1 across industries. For fossil fuel industries it is set to –0.1 and for all other industries it is set to –1.

Appendix Table A8: Effect of wage curve assumption

	Mobile Labor		Immobile Labor	
	Net-of-tax wage in wage curve	Gross wage in wage curve	Net-of-tax wage in wage curve	Gross wage in wage curve
Aggregate Unemployment	4.71%	5.22%	4.78%	5.31%
Oil and Gas Extraction Unemployment	4.71%	5.22%	10.67%	11.49%
Coal Mining Unemployment	4.71%	5.22%	35.84%	36.64%

Notes: This table presents simulation results for aggregate unemployment and sectoral unemployment for the two polluting sectors for alternate assumptions about the wage curve, for both the mobile and immobile labor model. The wage curve is based on either the net-of-tax wage (as in the base case) or on the gross wage. The policy simulated is a $35 per ton carbon tax with revenues returned through a uniform labor tax cut.