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UNEMPLOYMENT, LABOR MOBILITY, AND CLIMATE POLICY

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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-industry 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 (0.2–0.4 percentage points). The effect on unemployment in fossil fuel sectors is much larger under the immobility assumption – a 24 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 less efficient outcomes.

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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), Fernández Intriago (2019), 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) 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 search and matching model, à la Pissarides (2000). We then compare a model with perfect cross-sectoral labor mobility to one where workers are unable to switch sectors at all. 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 by returning the revenue through tax cuts.

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 in multiple disaggregated industries. Simply using a full-employment CGE model and studying voluntary changes in employment, as some other CGE models do, 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 0.25 percentage points, and the increase under the assumption of perfect labor immobility is only 0.1 percentage points larger (0.34 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 4.3 percentage points in the oil and gas extraction sector and by a whopping 23.7 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 increase in unemployment rates is slightly smaller, 0.15 and 0.19 percentage points for the mobile and immobile model respectively. This increase in unemployment is smaller 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: aggregate unemployment rate increases are smaller when labor is immobile but remain about the same when labor is mobile. Finally, a command-and-control policy that imposes a sector-specific emissions quantity goal yields lower unemployment rates, though employment losses are larger due to more workers leaving the labor force altogether.

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 structural frameworks have been used in CGE models to incorporate involuntary unemployment.[4] They are the efficiency wage model of Shapiro and Stiglitz (1984), sticky wages, where labor market frictions are created by a downwardly rigid wage and

[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).

unemployment is equal to the excess demand for labor (Kehoe & Serra-Puche, 1983), or the search and matching model developed by Mortensen and Pissarides (1994), which is our approach. 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 and Williams (2020), 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 and slow adjustments between sectors. They compare policies that phase-in at different rates to show the distributional effects of adjustment in the short run. In this paper we focus on steady state results and simulate different revenue returns.

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) focuses on measures of aggregate unemployment to demonstrate a new unemployment model. Second, we consider the effect of labor mobility to a greater extent than any of the previous literature. Babiker and Eckaus (2007) and Balistreri (2002) allow some form of labor immobility, but mobility is not the focus of these papers. 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). 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.

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

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 stage s can be either the final good, value added, intermediate goods, energy, materials, or electricity $\{Final, VA, I, E, M, Elec\}$. 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.

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

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

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

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

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. We divide all of the sectors in our data into either energy sectors or materials. 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, $Elec_i^d$.)

$$A_i^d = F_i^I(E_i^d, M_i^d) \tag{4}$$

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

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

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

Producers observe commodity prices P_i^c and wages P_i^L and capital rents P_i^K, which are prices of capital and labor to the firm. 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. Producer i's problem is

$$\min_{VA_i^d, A_i^d} P_i^{VA} VA_i^d + P_i^A A_i^d \tag{8}$$

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

$$P_i^{VA} = P_i^L \times L_i^* + P_i^K \times K_i^* \tag{10}$$

$$P_i^A = P_i^E \times E_i^* + P_i^M \times M_i^* \tag{11}$$

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

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 maximize a quasilinear utility function over consumption and labor force participation. Households purchase final goods for consumption 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:

$$\max_{C,LF_j} C_j - \psi\left(\frac{LF_j}{1+\frac{1}{\nu}}\right)^{1+\frac{1}{\nu}} \tag{13}$$

$$s.t. \quad P_jC_j = \bar{P}_j^L(1-u_j)LF_j + \bar{P}^K K_j + TR_j \tag{14}$$

$$C_j = \prod_{i=1}^{I} c_j^{i\,\vartheta_j^i} \quad and \quad P_j = \prod_{i=1}^{I}\left(\frac{\bar{P}_i^C}{\vartheta_j^i}\right)^{\vartheta_j^i} \quad and \quad c_j^i = \left(c_j^{iF\,\omega^i}\right)\left(c_j^{iD\,(1-\omega^i)}\right)$$

The variable C_j is a Cobb-Douglas combination of c_j^i, which is the amount of final good i that consumer j demands. P_j is the price index of total consumption, which is calculating using the consumption parameters and the price of good i, $\bar{P}_i^c$. The value of leisure (not being engaged in the labor force) is determined by a constant ψ and the Frisch elasticity of labor supply ν. $\bar{P}_j^L$ is the net-of-tax wage that the worker in industry j receives and LF_j is the labor force committed to industry j either by being employed or searching for work. The return to labor is the industry wage times the total employment in industry j. Income is on the right-hand side of equation 14. $\bar{P}^K$ is the net-of-tax price of capital (which is the same across industries), and K_j^S is the capital allocated to consumer j. Each consumer also receives a lump sum transfer from the government TR_j, which is specific to each household. Each consumption good, c_j^i, is a Cobb-Douglas composite of foreign and domestic goods denoted c_j^{iF} and c_j^{iD}, respectively, where ω^i is the share of foreign expenditure for good i.

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 regions. 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

$$Q_i = \left(\frac{\omega_f^i}{P_i^D}\right) * (P^F \cdot X^F) \tag{15}$$

where ω_f^i is the Cobb-Douglas parameter on consumption for the ith good for the foreign consumer, P_i^D is the domestic price on the ith good, P^F is the vector of prices of foreign goods, and X^F is the vector of imports demanded by the domestic consumer.

III.D. Carbon Emissions

Carbon emissions are a byproduct of production of two fossil fuel industries: coal mining, and oil and gas extraction.[9] The level of 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

[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.

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 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 agent receives the income from the scarcity rents.

III.E. Government

A single government, composed of state, local, and federal entities, 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 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.

The net of tax prices for labor and capital that the household receives is:

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

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:

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

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

We incorporate unemployment into our model using a flow model of search and matching that is common in macroeconomic models. The model dates to the canonical Diamond-Mortensen-Pissarides (DMP) labor search models.[10] Workers in the labor force can exist in two states: employed and unemployed. Unemployed workers search for vacancies posted by firms. The matching function, which describes how unemployed workers match to vacancies, is:

[10] See Diamond (1982) and Mortensen and Pissarides (1994).

$$m_i = Au_i^{\alpha} v_i^{1-\alpha}$$

This function is constant returns to scale, so we express all variables – matches m_i, unemployment u_i, and vacancies v_i – in relation to the total labor force, LF_i. The variables are indexed by i to indicate that they differ across sectors in the immobile model. All unemployed workers in the labor force search for work. We define the filling rate on vacancies for the firm, q_i, and the job finding rate for unemployed workers, f_i.

$$q_i = \frac{m_i}{v_i}$$

$$f_i = \frac{m_i}{u_i}$$

$$\theta_i = \frac{f_i}{q_i} = \frac{v_i}{u_i}$$

The variable θ_i is the labor market tightness, which is the ratio of the job finding rate to the filling rate, which, due to the structure of the matching function, is equal to the ratio of the vacancy and unemployment rates. There is an exogenous job separation rate x identical for all sectors; this fraction of all employed workers loses their jobs each period. Using the job finding rate and the exogenous separation rate, we can solve for the steady-state unemployment rate as $u_i = x/(x + f_i)$.

For the household, the values of an employed and unemployed worker are:

$$E_i = \left(1 - T_i^L\right)P_i^L + \beta[xU_i' + (1 - x)E_i']$$

$$U_i = \xi\bar{C} + \beta[f_i E_i' + (1 - f_i)U_i']$$

E_i is the present value of employment and U_i is the present value of unemployment to household i. In this section, household j is matched with the firm in industry i such that $j = i$. For this model, we consider two time periods, and denote the values of employment and unemployment in the second period with superscripts E_i' and U_i', respectively. We will only use this notation momentarily, as we solve for a steady state equilibrium. The first equation represents the present value of an employed worker to the household. The household earns the net of tax wage plus the expected future value of continued employment and, in the event of separation, unemployment, which is discounted at rate β. The second equation represents the present value of an unemployed worker. They receive $\xi\bar{\mathrm{C}}$, which is the value of searching measured in aggregate consumption units. The variable $\bar{C}$ indexes consumption to the baseline scenario, and the parameter ξ determines the utility of searching in consumption units. The value to the unemployed worker is this value of searching plus the future discounted value of either employment or unemployment. The value of searching could include unemployment benefits or leisure. We solve for the steady-state solution where $E_i' = E_i$ and $U_i' = U_i$. The difference between these two functions is the excess value of an employed worker to the household, relative to an unemployed worker.

$$E_i - U_i = \left(1 - T_i^L\right)P_i^L - \xi\bar{\mathrm{C}} + \beta(1-x)(E_i - U_i) - \beta f_i(E_i - U_i) \tag{21}$$

This difference represents the surplus or the economic rent from a match, which the firm and the worker will bargain over (described below). The firm also has two value equations, for a filled and unfilled position:

$$V_i = -cP_v + \beta[q_i J_i' + (1-q_i)V_i']$$

$$J_i = y_i - P_i^L - \beta[(1-x)J_i' + xV_i']$$

The first equation is the value of a vacancy to the firm. Again, we denote the value of a vacancy and a match in the second period using superscripts V_i' and J_i', respectively. The cost of posting a vacancy is cP_v, which is a linear function of the price on business services P_v. This allows us to estimate the full cost of posting a vacancy including labor, capital, and intermediate input costs. The firm pays the cost of the vacancy and receives the present value of the expected vacancy filling plus the possibility of not filling the vacancy. The second equation is the value of a filled job to the firm, where y_i is the marginal product of labor (MPL) for industry i, and P_i^L is the wage they pay. The firm receives the difference between the marginal product of labor and the wage as well as the expected future value of continued employment or possible separation.

Using the free entry condition that $V_i = 0$ and the steady-state assumptions that $J_i' = J_i$ and $V_i' = V_i$, we solve for the value of a match for the firm:

$$J_i = \frac{c}{\beta q_i} = y_i - P_i^L + (1-x)\frac{cP_v}{q_i} \tag{22}$$

We then use Nash bargaining to find how the firm and the worker split the economic rents from the match.

$$\max(E_i - U_i)^b J_i^{1-b}$$

$$s.t. \qquad E_i - U_i + J_i = Surplus$$

This leads to constant shares of the economic surplus.

$$(1-b)(E_i - U_i) = bJ_i \tag{23}$$

Combing equations 21 – 23, we find the expression for the resulting wage.

$$P_i^L = \frac{(1-b)\xi\bar{\mathrm{C}} + b(y_i + \theta_i c P_v)}{1 - T_i^L + b - (1 - T_i^L)b} \tag{24}$$

To add this module into the main model of the paper, we first solve for the unemployment rate, wage, and vacancy costs using the labor market tightness parameter θ_i. The wage and unemployment rate are then used to calculate an expected wage for each industry, which is used in the household's problem to find the labor force engaged in each industry. Once we have the labor force engaged in each industry along with unemployment rates, we can determine total labor supply. Using the labor supply and labor demand for each industry, we can find total production and then solve for the remaining macroeconomic variables. In solving this model, we only look at steady-state solutions, and we do not consider short-term transitions or simulate a dynamic model. Instead, we solve for a static general equilibrium in the macroeconomy portion of the model conditional on a steady-state equilibrium in the labor market.

Search and matching models like the one we use are a common choice for modeling unemployment in the labor market.[11] However, as we document in Appendix Table A1, the majority of CGE papers that consider the unemployment effects of environmental policy use a simpler, reduced-form specification of unemployment: a wage curve. A wage curve sets an exogenous relationship between the wage and the unemployment rate, both of which are determined in equilibrium constrained by the wage curve relationship (Blanchflower and Oswald 2005). An exception is the model used in Hafstead et al. (2018) and Hafstead and Williams (2020), which also employs a search and matching model. A third modeling choice that can generate unemployment and has been used in environmental CGE models comes from Balistreri (2002); it employs a similar static version of search and matching that is framed as a mixed complementarity problem. In Appendix A.III, we explore how the choice of modeling unemployment affects our results, by comparing outcomes under our specification (search and matching) to those under a wage curve and under the method proposed by Balistreri (2002). We find largely similar results for the lump-sum revenue return policy, but returns through a tax cut may give different results depending on the parameterization.

III.G. Equilibrium

Equilibrium is determined by maximization by the household, cost-minimized production by the firm, a balanced government budget, and clearing in the matching market. Factor constraints are:

[11] See Pissarides (2000) for a summary and Yashiv (2007) for a literature survey.

$$\sum_{i=1}^{I} K_i^* = \sum_{i=1}^{I} K_i^s \tag{25}$$

$$L_i^* = (1 - u_i) LF_i^s \quad \forall\, i = 1, \dots, I \tag{26}$$

$$Y_i = \sum_{j=1}^{I} c_j^i + Q_i + \sum_{z=1}^{I} I_i^z + g_i \;\; \forall\, i = 1, \dots, I \tag{27}$$

Equations 25 and 26 are factor market clearing conditions for capital and labor, respectively. Capital is perfectly mobile across sectors, but there is a fixed total capital stock. Labor can be sector-specific, with an immobile labor stock, L_i, in each sector. Equation 27 is the goods market clearing condition, it introduces a new variable I_i^z, which is the intermediate demand for good j by producer z. It requires that the quantity supplied from each firm Y_i is equal to the quantity demand for output from that sector. The right-hand side represents this demand and is the sum of final goods for domestic consumers ($\sum_{j=1}^{I} c_j^i$), exports (Q_i), intermediate inputs to other industries ($\sum_{z=1}^{J} I_i^z$), and final goods purchased by the government (g_i). Equilibrium additionally imposes that government revenues, equation 19, are equal to government expenditure, equation 20. Equilibrium also requires that the labor search market clears, specifically that equation 24 holds as well as the expression for steady-state unemployment. The algorithm then searches over a simplex of prices for capital, labor (in all sectors), and commodities for an equilibrium.[12]

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

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

consider is that of perfect labor mobility. In the perfectly mobile case, there is just one wage 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

$$\sum_{i=1}^{I} L_i^* = \sum_{i=1}^{I} (1 - u_i) LF_i^S \tag{28}$$

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 proportion. 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.

<u>IV.A Lump-sum revenue return</u>

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 28.6% 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 26% reduction from a $35 tax in the short run, increasing to 31% reduction after a few years (Goulder and Hafstead, 2013; Goulder and Hafstead, 2017).[13] Similarly, under a $35 per ton carbon tax, we find a GDP loss of 0.28% in the mobile model, which is consistent with the E3 CGE model's prediction of a 0.21% GDP loss in the first year, which increases to 0.56% after 10 years.

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 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 5.27%, and under the immobile labor assumption the aggregate unemployment rate rises from 5% to 5.34%.

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

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

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 29% 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 9.3%. In the mobile model, the unemployment rate is the same across all sectors at just 5.27%. 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.[14]

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 sectors in the model. It presents the change in 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 approximately the same 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 slightly 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.

[14] 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).

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 decreases for the non-renewable electricity sector, though the decrease is smaller in magnitude than the increase to renewables. 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, and for the non-renewable electricity sector, labor demands decrease across all carbon tax amounts. The gains in the renewable electricity sector are three times larger under the mobile labor assumption, but the losses in the non-renewable sector are only 30% larger in magnitude.

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 rates are lower when revenues are returned through a labor tax cut, as shown in the second panel of Figure 4. While both models decrease unemployment rates under the tax cut, the reduction in unemployment for the immobile model is larger. For a $35 per ton carbon tax, returning revenues through an aggregate tax cut results in a 5.15% unemployment rate in the mobile model, and a 5.19% unemployment rate in the immobile model.

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 smaller 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.[15]

Figure 5 focuses on the two electricity sectors and presents their labor demand changes. Labor demands increase for the renewable sector, and decrease for the non-renewable sector. However, when comparing to the lump-sum return policy, not much is different. The only discernable difference is that losses in the non-renewable sector are smaller under the immobile labor assumption. Thus, while an aggregate tax cut may cushion the employment shock for the non-renewable sector in the immobile model, it does not seem to be effective at encouraging workers to move to the renewable sector in the mobile model.

The policy implications are that a tradeoff exists between the taxed and non-taxed industries. Although a few other sectors have employment gains, such as non-renewable electricity and government services, 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 unemployment rates of close to 30%, a small labor tax cut does not do much to offset it.

IV.C Targeted Labor Tax Cut

[15] 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.

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. In the mobile case, the carbon tax raises more money than labor taxes in the oil and gas extraction sectors. In the immobile case, however, less revenue is collected from labor and sales taxes in downstream industries, so the result is only about a 10 percentage point tax cut. Aggregate results are summarized in Figure 6. The first panel show emissions reductions, which are the same as previous policies. The second panel shows the change in the aggregate unemployment rate. For the mobile case, unemployment stays at a rate slightly lower than the lump-sum return case, but without a noticeable difference. However, in the immobile case we see a noticeable decrease in the aggregate unemployment rate compared to the lump-sum return case.

The bottom two panels of Figure 6 show unemployment rates in the coal and oil and gas extraction industries. The targeted tax cut reduces these unemployment rates relative to the other revenue return policies, especially in the oil and gas sector. In the oil and gas extraction industry, the unemployment rate rises to 6.2% for a $35 per ton carbon tax, compared to 9.3% under the other revenue return policies. For the coal industry, the unemployment rate rises to 23.6%, which is lower than previous policies, but still quite high. Reductions in labor demands confirm this; under the lump-sum case, total labor demand in the fossil fuel industry fell by 12%, compared to the targeted tax rate return, which reduced total fossil fuel labor demand by 10%.[16]

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 depending on labor mobility assumptions. A tax cut across all industries could yield a larger aggregate unemployment decrease, and emissions abatement

[16] Our results on the targeted tax rate return are sensitive to assumptions about the bargaining parameter. In line with previous search and matching literature, we chose a very low bargaining parameter. However, choosing a higher bargaining parameter can lead to large unemployment reductions in the fossil fuel industries. This is because workers receive more of the tax cut, so unemployment is more responsive. We explore how this parameter changes our results in Appendix A.

would not change very much. However, unemployment in the taxed industries would still be quite high.[17]

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 $79.14, and in the coal mining industry it is only $12.33. For a given carbon tax rate, coal will reduce output and emissions by a higher percent than oil and gas will

[17] Appendix Table A6 presents the sectoral results for a $35 carbon tax with a targeted labor tax cut.

(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 change in aggregate unemployment that is not much different than under the carbon tax with lump-sum revenue return, especially for the immobile labor case. For a 30% emissions reduction, the command-and-control policy increases aggregate unemployment to 5.14% in the immobile model and 5.33% in the mobile model, compared to 5.27% and 5.38% for the carbon tax with lump-sum revenue return. At first glance, this seems inconsistent with other results, namely that GDP losses are slightly higher for the CAC policy as compared to the carbon tax. The reason for this is that under the CAC policy, workers are more likely to exit the labor force completely. So, while unemployment rates are lower under the CAC policy, total labor losses are larger. Under a lump-sum return policy, total labor losses are about 0.4% for both the mobile and immobile model. That increases to 0.5% and 0.6% for the mobile and immobile models, respectively, under the CAC policy. [18]

The bottom two panels of Figure 7 show 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, unemployment is higher in the oil and gas extraction sector and lower in the coal mining sector under a command-and-control policy than under the carbon tax with lump-sum returns. At about 30% emissions reduction, the oil and gas extraction industry has an 10.3% unemployment rate under a carbon tax, but that almost doubles under the CAC policy to 17.7%. The coal mining sector sees almost a 50% reduction from a 30.6% unemployment rate under the carbon tax to 16.3% under the CAC policy. This indicates that a command-and-control policy that reduces each

[18] See Appendix Table A7 for the sectoral results for a command-and-control policy mandating a 30% emissions reduction.

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. In addition, while the unemployment effects are spread more evenly between the two fossil fuel extraction sectors, aggregate employment of the two sectors (the sum of labor supplied to these industries) falls under the CAC policy. A carbon tax results in a 19% and 12% decline in aggregate fossil fuel sector employment for the mobile and immobile models, respectively. These employment losses are smaller in magnitude than the CAC policy, which generates employment losses in the fossil fuel sectors of 28% and 22% for the mobile and immobile labor models, respectively. The distribution of the burden across the two sectors depends heavily on the assumptions over labor mobility.

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 times two labor mobility assumptions for each policy) so that the policy results in a 30% aggregate reduction in emissions.[19] 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 uniform labor tax cuts yield smaller drops in GDP than lump-sum revenue

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[19] 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.

return. As described above, the command-and-control policy modeled here will underestimate the inefficiency of a more realistic command-and-control policy.

Table 2 also presents the effects on overall unemployment. The CAC policy yields the smallest unemployment rates, but, again, these mask larger employment losses due to workers exiting the labor force entirely. 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 immobile, and the aggregate tax cut yields the smallest unemployment rate when labor is mobile. With mobile labor, the targeted tax cut is more distortionary (larger decrease in GDP) than the aggregate tax cut and yields a higher unemployment rate. With immobile labor, this pattern is reversed and a targeted tax cut is less distortionary and is able to lower the unemployment rate.

Appendix A.II discusses sensitivity analysis over parameter values, and Appendix A.III compares results from our search-and-matching labor market model to those from alternatives.

V. Conclusion

We develop a computable general equilibrium model of United States climate policy that allows for involuntary unemployment through a search and matching model of the labor market and compares 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 4.3 percentage points and 28.3 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. 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 we 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	-1.4%	-1.9%	-16.5%	-15.9%	-15.8%	-9.2%
Coal Mining	14.9%	13.0%	-50.2%	-49.9%	-42.3%	-37.1%
Non-Renewable Electricity	0.3%	0.6%	-2.7%	-2.5%	-0.4%	-0.3%
Renewable Electricity	-3.0%	-2.4%	2.5%	2.3%	1.8%	0.5%
Natural Gas Distribution	2.5%	2.7%	-4.0%	-3.8%	0.2%	-0.1%
Mining	-2.5%	-2.3%	-0.8%	-0.6%	-1.0%	-0.6%
Agriculture	-2.2%	-2.2%	-2.6%	-2.2%	-2.6%	-1.3%
Construction	-2.4%	-2.0%	0.2%	0.2%	0.1%	-0.1%
Manufacturing	-1.4%	-1.1%	-1.2%	-1.0%	-0.4%	-0.3%
Chemicals	-2.3%	-2.1%	-0.8%	-0.6%	-0.9%	-0.5%
Services	-2.7%	-2.4%	-0.3%	-0.2%	-0.7%	-0.5%
Govt	-2.1%	-1.1%	2.0%	1.0%	2.1%	0.5%
Aggregate	-3.0%	-2.6%	-0.7%	-0.7%	-0.4%	-0.4%

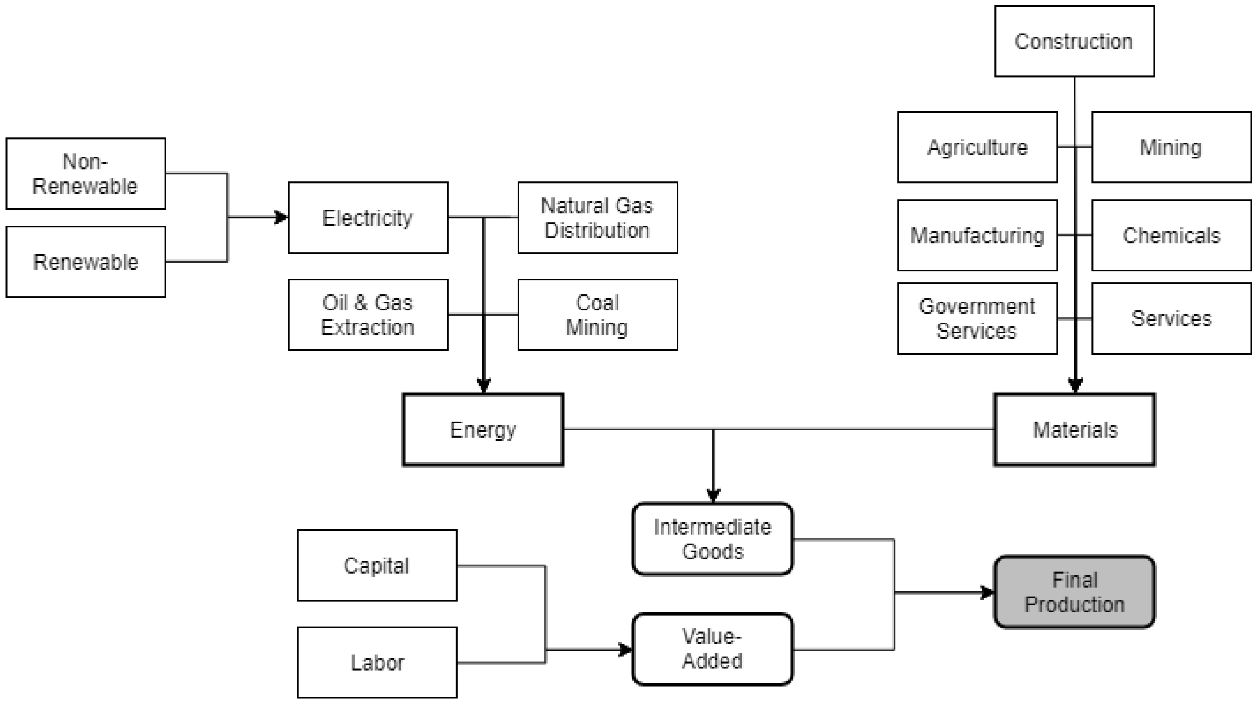
Notes: This table provides changes in output price (relative to the numeraire), output quantity, and labor quantity for each industry in response to a $35 carbon tax with lump-sum revenue return, for both the perfectly mobile and perfectly immobile labor assumptions. The change in total production in 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	$38.49	$39.74	-0.29%	-0.32%	5.27%	5.38%
Carbon tax with uniform labor tax cut	$38.28	$39.52	-0.25%	-0.27%	5.16%	5.22%
Carbon tax with targeted labor tax cut	$38.28	$38.42	-0.31%	-0.14%	5.27%	4.16%
Command-and-Control Mandate	-	-	-0.31%	-0.38%	5.14%	5.33%

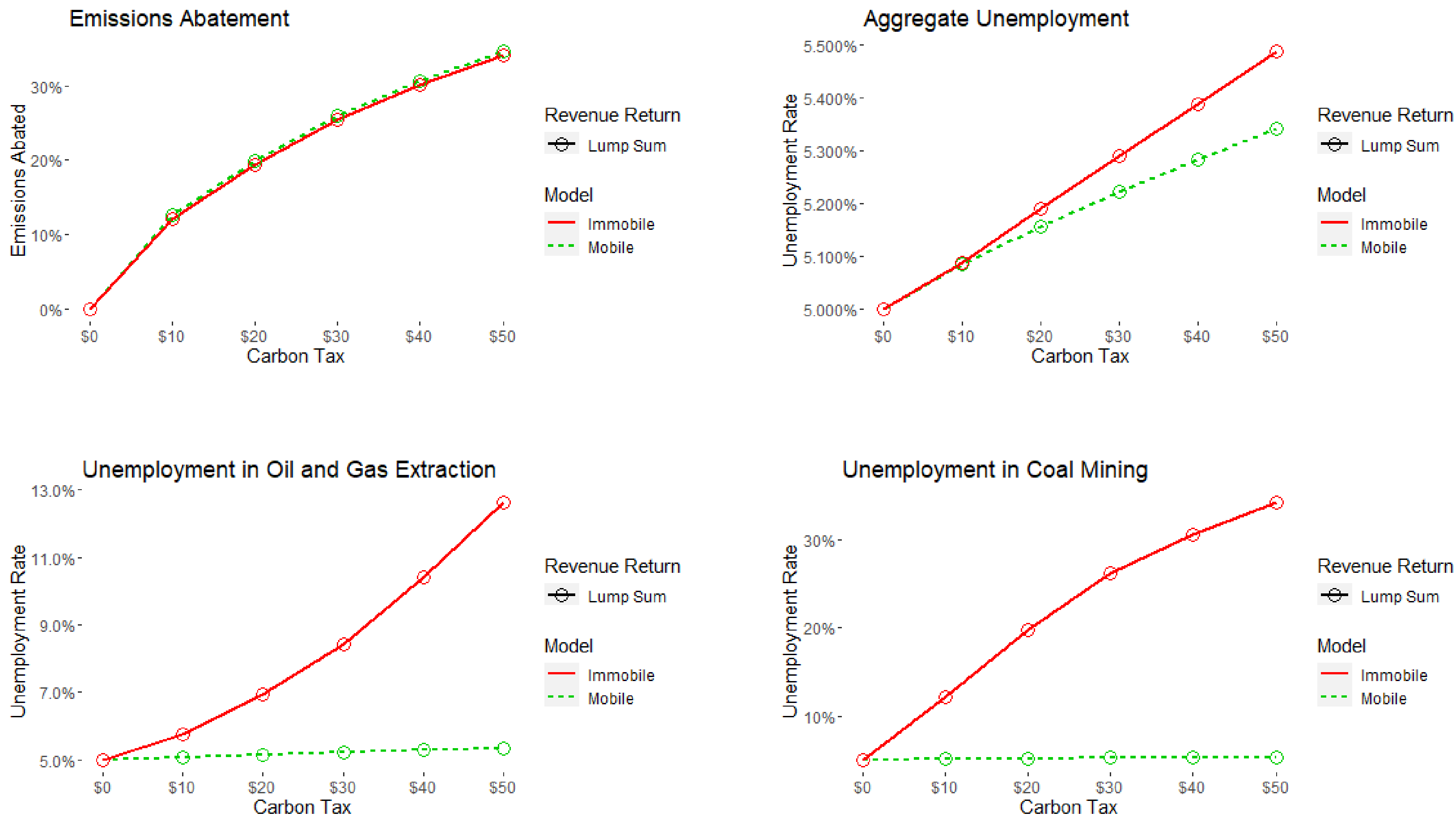
Notes: This table presents the decrease in GDP (aggregate output) and the level of aggregate unemployment due to a 30% reduction in emissions across the four different policies. For the three carbon tax policies, we also present the tax rate that must be levied to yield a 30% emissions reduction. The 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



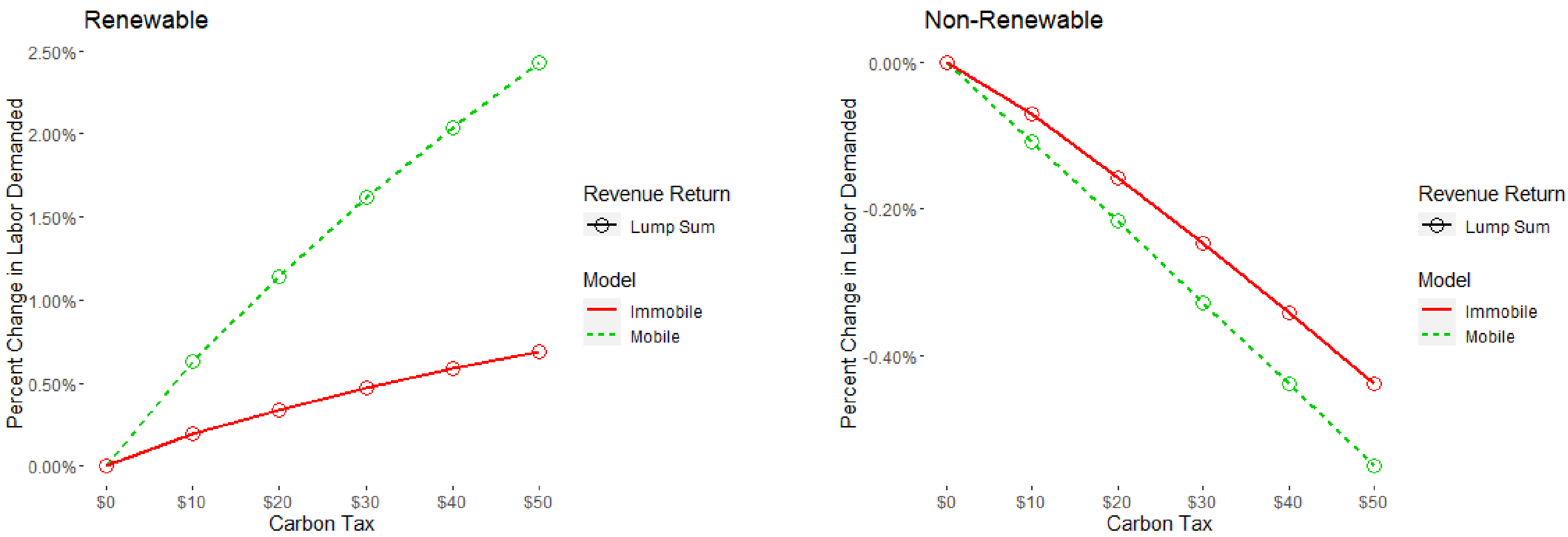
Notes: This figure presents the nested production structure of the CGE model used in this paper.

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



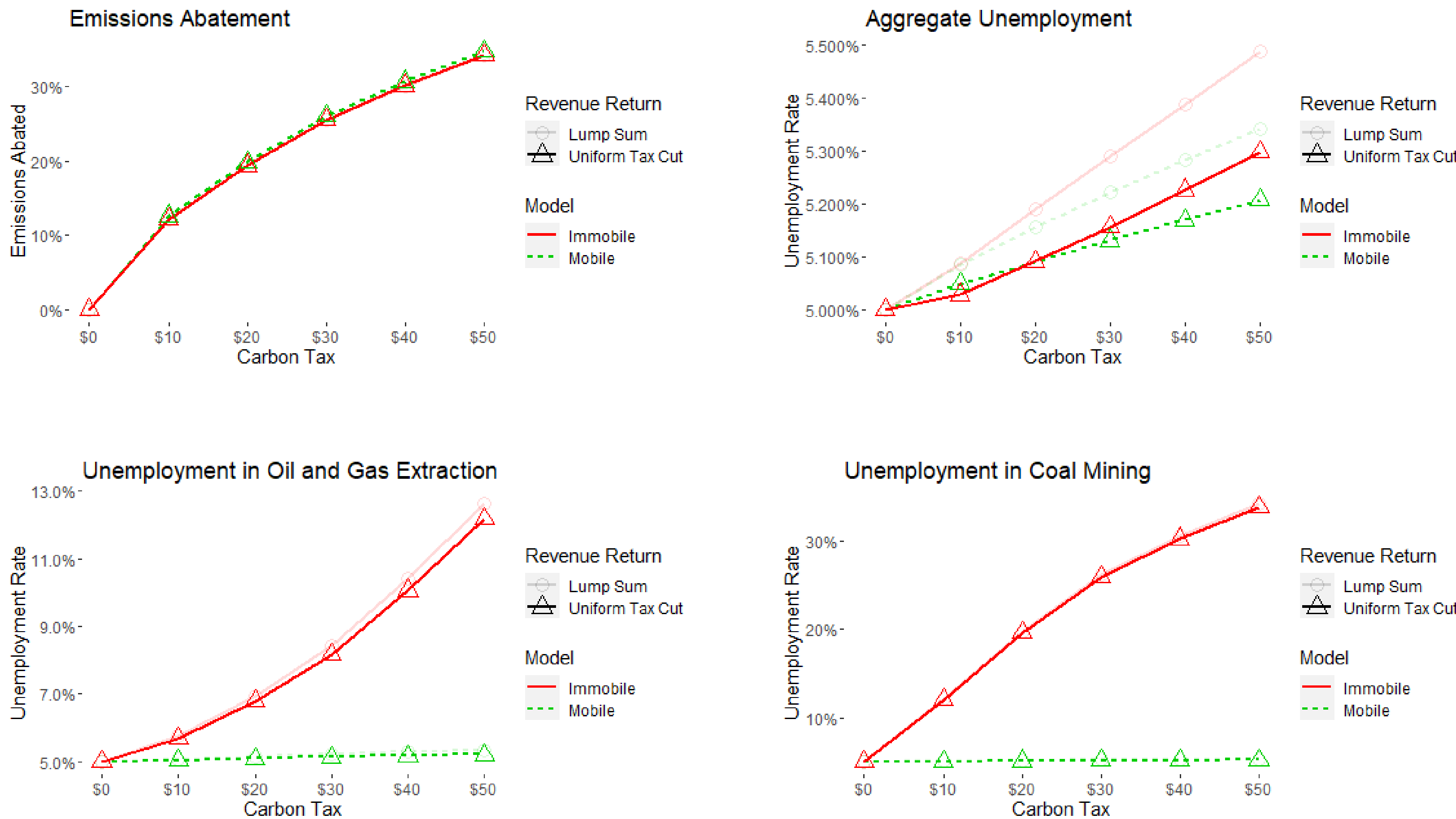
Notes: These graphs present results under a carbon tax of varying levels (x-axis) with lump-sum revenue return. The first panel shows the amount of emissions abatement (%). The second panel shows the aggregate unemployment rate from the base level (5%). The bottom two panels show the unemployment rate 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



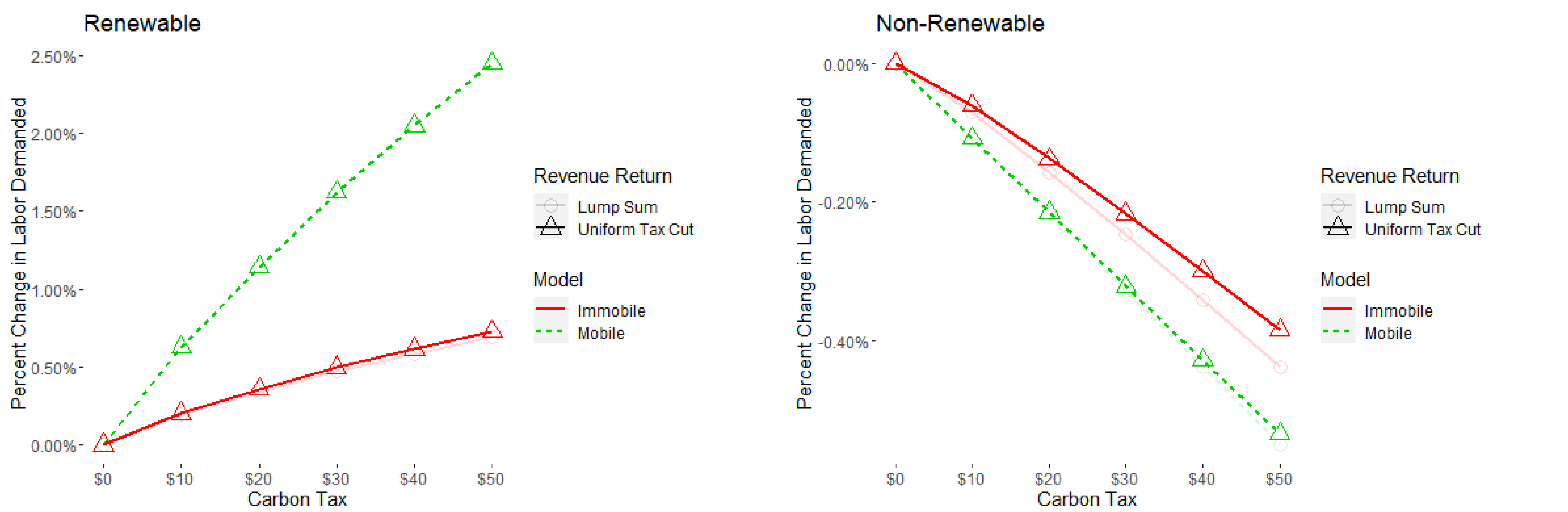
Notes: These graphs present the change in the quantity of labor for just the non-renewable and renewable electricity sectors (y-axis) resulting from differing levels of a carbon tax (x-axis) where revenues are returned lump-sum. In each panel, we show results under the perfectly immobile labor assumption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

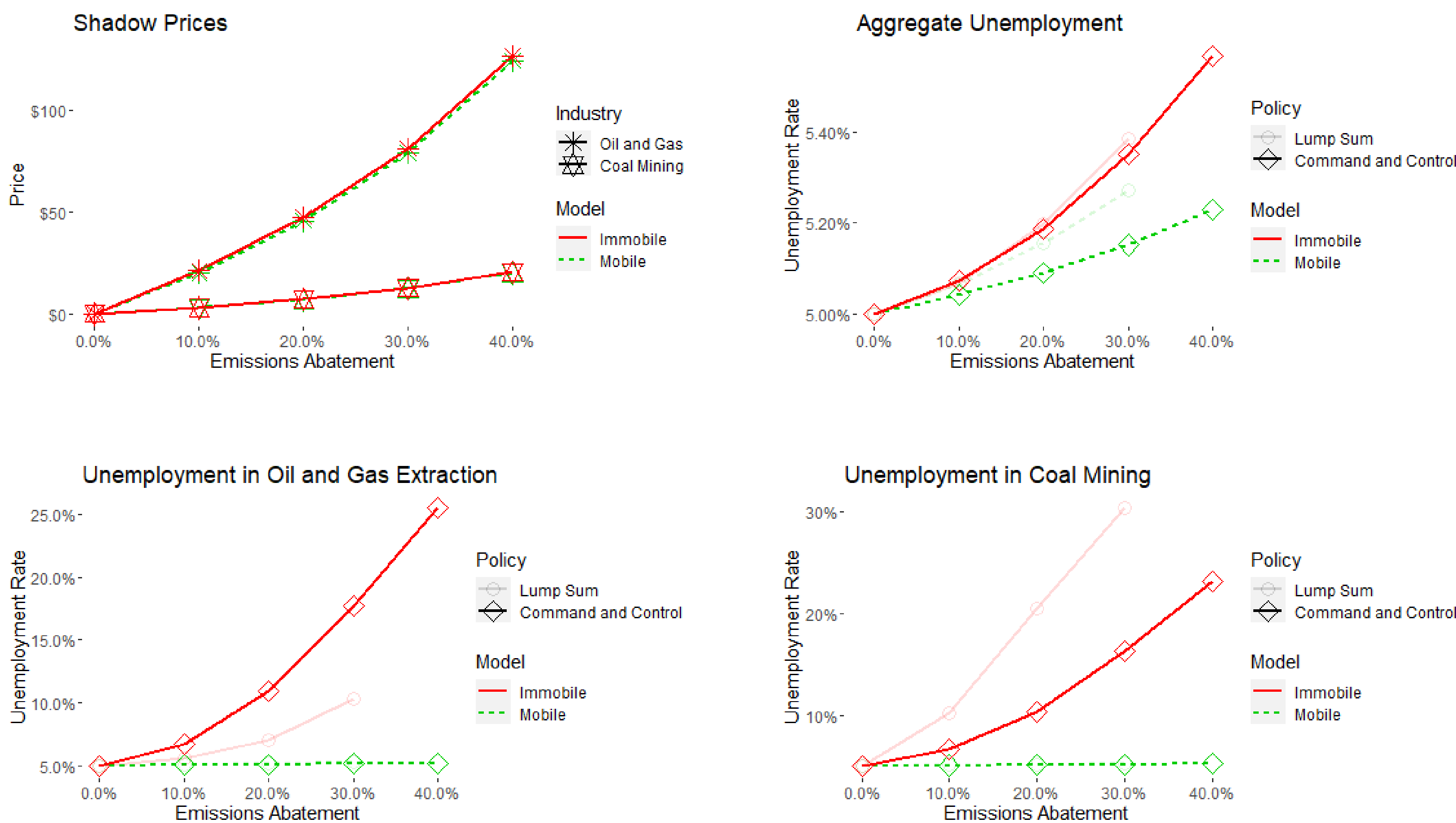


Notes: These graphs present the change in the quantity of labor for just the non-renewable and renewable electricity sectors (y-axis) resulting from differing levels of a carbon tax (x-axis) where revenues are returned lump-sum. In each panel, we show results under the perfectly immobile labor assumption (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.[20] 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. [21] 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.[22] 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.[23]

A.I.B. Calibration

Here we describe how we select our base-case parameter values. Appendix Tables A3 and A4 summarize the calibrated parameter values. The elasticity values are set based on existing literature.

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[20] Available here: https://www.bea.gov/industry/io_annual.htm.

[21] 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.

[22] https://www.cbo.gov/publication/44698

[23] https://www.census.gov/data/tables/2007/econ/qtax/historical.html

Elasticity values for the value-added and production nests 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 substitution 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 132 parameters are unique to each industry, and thus for space are not presented in Appendix Table A3.

The labor market parameters are chosen to match the previous literature as well. The full list of all labor market parameters we used along with comparisons to previous papers' calibrations can be found in Appendix Table A4. The first parameter is the rate of time preference, which we set at 0.96 to match an annual discount rate of 4%. The next parameter we set is the separation rate. According to the Bureau of Labor Statistics, during the years 2011 – 2015, approximately 54 million workers separated from their job each year. Over those same years, the average labor force was 155 million, indicating a separation rate of 0.35. We also assume a baseline unemployment rate of 0.05. Using the baseline unemployment rate and the separation rate, we can solve for the average job finding rate using the equation for steady state unemployment, $u = s/(s + f)$. We use a job finding rate of 7.3, which is higher than previous papers which use job finding rates in the range of 2.4-7.2. Our choice of a higher separation rate and lower baseline unemployment rate as compared to previous studies led to this number being larger than previous work.

We then set the vacancy cost parameter such that recruiting costs are 2.4% of output for firms. The next parameters to be chosen are the match elasticity and the bargaining parameter. We set a low bargaining parameter as suggested by Hagedorn and Manovskii (2008) and used in Gibson and Heutel (2020). After setting all the previous parameters, we set the match elasticity to target an elasticity between wages and unemployment of –0.1 as observed by Blanchflower and Oswald (1995, 2005). This gives us a value of 0.65, which is in-between values from previous papers. Combining this value with the job finding rate gives a value of 3.62 for the match function's scale parameter.

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.[24]

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.

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[24] https://www.census.gov/programs-surveys/stc/data/datasets.2007.html

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.[25]

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. 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. 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 A8. The first row presents the results for base case for

[25] https://www.eia.gov/environment/emissions/carbon/

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 A8 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. In general, as substitution between inputs becomes more inelastic abatement is smaller. We expect this result, as the quantity response decreases due to more inelastic substitution. GDP losses are largely the same across specifications, however a more inelastic substitution parameter in the value-added composite leads to lower GDP loss due to a smaller tax distortion. This leads to a lower unemployment rate for this specification as well. 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.

Row 10 presents an alternate value for the bargaining parameter b. In the base case we use an estimate of 0.05, but some researchers have used a number closer to 0.72. To incorporate this possible value change, we increase the bargaining parameter to 0.75 and set our other parameters to match the baseline economy and a wage to unemployment elasticity of -0.1. This will give us the closest prediction in terms of the response of unemployment to wage changes. This requires use to set a lower match elasticity of 0.5, and a lower separation rate of 0.25. In addition, we calibrate to a slightly higher baseline unemployment rate of 7.4%. To get the results in the table, we renormalize the increase in unemployment to a baseline of 5%. In general, GDP effects are slightly larger, but abatement and unemployment rates are about the same as the baseline specification.

In addition to row 10 in Table A8, we also run our two tax cut policy scenarios under the higher bargaining parameter. We find that our results on taxes are sensitive to this parameter's value. Appendix Figure A1 compares results for the aggregate tax cut under a high bargaining parameter to our baseline calibration (a low bargaining parameter). With the higher bargaining parameter, the worker receives more of the tax cut, so the net result of the tax swap is a decrease in aggregate unemployment rates. In addition, unemployment rates in the fossil fuel sectors fall dramatically relative to the baseline low bargaining parameter. Appendix Figure A2 compares results for a targeted tax cut under a high bargaining parameter to our baseline calibration. Again, as the worker receives more of the tax cut, responses in unemployment are larger. For this model, the pattern seen under the baseline calibration is reversed: unemployment reductions are higher in the immobile model compared to the mobile model. While our model is sensitive to this parameter, we rely on previous research from Hagedorn and Manovskii (2008), and set this parameter to be low in our main specification.

A.III Alternative Unemployment Specification

In our model, unemployment is generated via a DMP-style search and matching labor market model. In this section, we consider two alternative models of the labor market that generate endogenous unemployment: the method from Balistreri (2002), and a wage curve. The wage curve is the most common method in the literature for incorporating endogenous unemployment into environmental CGE models (see Appendix Table A1). We first describe the method and the changes introduced to the model and then present results under the case of a perfectly mobile labor market. The Balistreri method is based on the matching literature and uses external economies to introduce it into a

CGE framework. For the remainder of this section we refer to our original specification as the matching model and the model based on Balistreri (2002) as the external economies model.

We use a leisure-labor choice in the model, with RES as the reservation wage. Per Balistreri (2002) we specify the following relationship between market wages and the reservation wage:

$$w = H(E, u) \times RES$$

$$H(E, u) = (1 - u_0)\left(\frac{E}{E_0}\right)^{\sigma}\left(\frac{u}{u_0}\right)^{\eta}$$

Here w is the market wage, E is the employment level, and u is the unemployment rate. We assume the functional form for $H(E, u)$ used in the original paper. The constants E_0 and u_0 are benchmark values for the employment level and unemployment rate. For the unemployment rate we assume a benchmark level of 5%. Given the reservation wage and the market wage, consumers cost minimize expenditure between consumption and leisure using a Cobb-Douglas utility function. The unemployment rate and the employment level are determined endogenously. The model is specified and solved as a mixed complementarity problem. Model parameters for the external economies model are specified in Appendix Table A9.

In the second alternative model of the labor market, the wage curve specification, we set a reduced form relationship between the unemployment rate and wages.

$$\ln(u_i) = \eta_1 \ln\left(\bar{P}_i^L\right) + \eta_2$$

We set the elasticity, η_1, to –0.1 as observed by Blanchflower and Oswald (1995, 2005). The second parameter η_2 is an industry fixed effect that sets unemployment at a baseline rate. We set all unemployment rates to the 5% benchmark as in our main calibration.

Appendix Figure A3 presents the three different labor market models and the results over several carbon tax rates, for the three different carbon tax revenue return policies. We achieve very similar results in the lump-sum case to our original specification. Unemployment rates are much smaller under the tax cut revenue return schemes, however this is likely due to our use of a low bargaining parameter. In the external economies model, we use a bargaining parameter of 0.5. In the wage curve model, we use the net-of-tax wage, so the worker receives the full benefit of the tax cut. This is somewhat akin to using a bargaining parameter of 1. While the change in unemployment is somewhat different quantitatively when tax revenues are returned via labor tax cuts, any change in modeling assumptions will generate some changes in quantitative predictions. We could simply modify the parameters of the external economies or wage curve specification to match the quantitative results of our main specification, or vice versa. The purpose of this exercise is to demonstrate that either method yields predictions about the effect of policy on unemployment. We choose to keep the search and matching model with our specification due to its wide appeal among labor market modelers and empirical support.

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, sector specific worker vintaging	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.
Hafstead and Williams (2020)	United States	Imperfect labor mobility between sectors.	Matching model with search frictions	Carbon tax with differing announcement times	Carbon taxes cause large sectoral unemployment rates in fossil fuel sectors during transition.
This paper	United States	Labor either perfectly mobile or perfectly immobile (sector-specific)	Matching model with search frictions	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	0.0069
Coal Mining	$2,527.86	0.0553
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	-

Notes: 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: Macroeconomic Parameter Values and Sources

Parameter	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.
ϑ_j^i	Final consumption shares	Varies	BEA input-output tables
ν	Labor supply Frisch elasticity	0.5	Chetty, Guren, Manoli, and Weber (2011)
ψ	Labor supply constant	0.92	Authors' calculations to match labor force in BEA data
$\frac{TR}{G}$	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: Labor Market Parameter Values

Parameter	Description	This paper	Gibson & Heutel	Hafstead & Williams	Shimer	Hagedorn & Manovskii
$\boldsymbol{\beta}$	Time preference	0.96	0.93	0.96	0.95	0.99
$\boldsymbol{\alpha}$	Match elasticity	0.65	0.72	0.5	0.72	-
A	Match scale param	3.62	2.56	-	5.42	-
$\boldsymbol{x}$	Separation rate	0.35	0.2	0.5	0.4	0.42
$\boldsymbol{b}$	Bargaining param	0.05	0.05	0.5	0.72	0.05
$\boldsymbol{\xi}$	Disutility of work	0.64	0.86	0.29	0.4	0.95
$\boldsymbol{u}$	Baseline unemployment rate	0.05	0.078	0.05	-	0.055
f	Job finding rate	7.32	2.36	-	5.4	7.2
c	Vacancy cost[1]	2.4%	1-2%	2.4%	-	2.7%

Note: This table compares this paper's calibrated parameter values for the labor market search and matching to previous. The column headings correspond to the following papers: Gibson and Heutel (2020), Hafstead and Williams (2018), Shimer (2005), and Hagedorn and Manovskii (2008). Several previous papers use frequencies at the monthly or quarterly level, so all values are adjusted to reflect annual rates (which is what this paper uses).

[1]The vacancy cost is presented as the cost ratio to output that is targeted by each paper, not the actual parameter value c. For some papers, the vacancy cost was calculated as a percent of labor compensation. In those cases, we use a ratio of 60% of income to labor compensation to convert it to a percent of total output.

Appendix Table A5: 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	-1.3%	-1.9%	-16.5%	-15.9%	-15.8%	-8.8%
Coal Mining	14.9%	12.9%	-50.2%	-49.9%	-42.3%	-36.7%
Non-Renewable Electricity	0.3%	0.6%	-2.7%	-2.6%	-0.4%	-0.3%
Renewable Electricity	-3.0%	-2.4%	2.5%	2.2%	1.8%	0.6%
Natural Gas Distribution	2.5%	2.7%	-4.0%	-3.8%	0.2%	0.0%
Mining	-2.5%	-2.2%	-0.8%	-0.7%	-1.0%	-0.5%
Agriculture	-2.2%	-2.2%	-2.7%	-2.3%	-2.6%	-1.2%
Construction	-2.4%	-2.0%	0.1%	0.1%	0.0%	-0.1%
Manufacturing	-1.4%	-1.1%	-1.2%	-1.1%	-0.4%	-0.3%
Chemicals	-2.3%	-2.1%	-0.8%	-0.7%	-0.9%	-0.5%
Services	-2.7%	-2.4%	-0.2%	-0.1%	-0.6%	-0.4%
Govt	-2.2%	-1.1%	2.0%	1.0%	2.1%	0.6%
Aggregate	-2.3%	-2.0%	-0.7%	-0.6%	-0.3%	-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 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 A6: 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	-1.4%	-1.9%	-16.5%	-16.5%	-15.9%	-7.1%
Coal Mining	14.9%	11.6%	-50.2%	-50.0%	-42.3%	-33.0%
Non-Renewable Electricity	0.3%	0.8%	-2.7%	-2.9%	-0.5%	-0.3%
Renewable Electricity	-3.0%	-2.2%	2.5%	1.8%	1.8%	0.4%
Natural Gas Distribution	2.5%	2.8%	-4.0%	-4.4%	0.1%	-0.2%
Mining	-2.5%	-2.1%	-0.8%	-1.4%	-1.1%	-0.7%
Agriculture	-2.2%	-2.1%	-2.7%	-3.1%	-2.6%	-1.3%
Construction	-2.4%	-2.0%	0.1%	-0.5%	0.0%	-0.3%
Manufacturing	-1.4%	-1.0%	-1.2%	-1.7%	-0.5%	-0.4%
Chemicals	-2.3%	-1.9%	-0.8%	-1.4%	-1.0%	-0.6%
Services	-2.7%	-2.1%	-0.3%	0.4%	-0.7%	0.0%
Govt	-2.1%	-1.0%	2.0%	0.9%	2.1%	0.5%
Aggregate	-2.3%	-1.7%	-0.7%	-0.6%	-0.4%	-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 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: Sectoral Results, 30% emissions reduction command-and-control policy

	Output Price		**Output Quantity**		**Labor Quantity**	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	0.7%	-0.1%	-30.0%	-30.0%	-28.4%	-21.9%
Coal Mining	4.9%	3.3%	-30.0%	-30.0%	-25.7%	-19.7%
Non-Renewable Electricity	0.3%	0.6%	-2.4%	-2.3%	-0.5%	-0.5%
Renewable Electricity	-2.9%	-2.4%	2.7%	2.5%	1.7%	0.4%
Natural Gas Distribution	8.2%	8.7%	-7.5%	-7.5%	1.0%	0.1%
Mining	-2.4%	-2.2%	-0.8%	-0.6%	-1.3%	-0.8%
Agriculture	-2.1%	-2.4%	-3.5%	-3.1%	-3.8%	-2.0%
Construction	-2.0%	-1.6%	0.2%	0.2%	0.0%	-0.3%
Manufacturing	-0.5%	-0.2%	-1.6%	-1.5%	-0.4%	-0.4%
Chemicals	-1.8%	-1.6%	-1.1%	-0.9%	-1.2%	-0.7%
Services	-2.5%	-2.2%	0.1%	0.1%	-0.6%	-0.6%
Govt	-1.8%	-0.9%	1.7%	0.8%	1.7%	0.2%
Aggregate	-1.9%	-1.6%	-0.9%	-0.9%	-0.5%	-0.6%

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 change in total production in each industry is inclusive of both intermediate and final demands, and is not a measure of GDP.

Appendix Table A8: Sensitivity Analysis

		Mobile			Immobile		
		Unemployment	GDP Loss	Abatement	Unemployment	GDP Loss	Abatement
(1)	Base Case[1]	5.25%	-0.26%	28.6%	5.35%	-0.27%	28.1%
(2)	σ = 0.375	5.28%	-0.27%	25.8%	5.37%	-0.27%	25.3%
(3)	σ = 0.625	5.24%	-0.26%	31.2%	5.33%	-0.27%	30.6%
(4)	σ^{VA} = 0.7	5.24%	-0.22%	28.6%	5.37%	-0.25%	28.1%
(5)	σ^{VA} = 1.13	5.26%	-0.29%	28.7%	5.34%	-0.29%	28.1%
(6)	σ^{prod}= 0.7	5.26%	-0.26%	28.3%	5.35%	-0.27%	27.7%
(7)	σ^{prod}= 1.13	5.25%	-0.26%	29.0%	5.34%	-0.27%	28.5%
(8)	σ^{ELEC}= 0.9	5.26%	-0.26%	28.6%	5.35%	-0.27%	28.1%
(9)	σ^{ELEC}= 10	5.26%	-0.26%	28.7%	5.36%	-0.27%	28.2%
(10)	b= 0.75	5.27%	-0.39%	28.8%	5.37%	-0.44%	28.3%

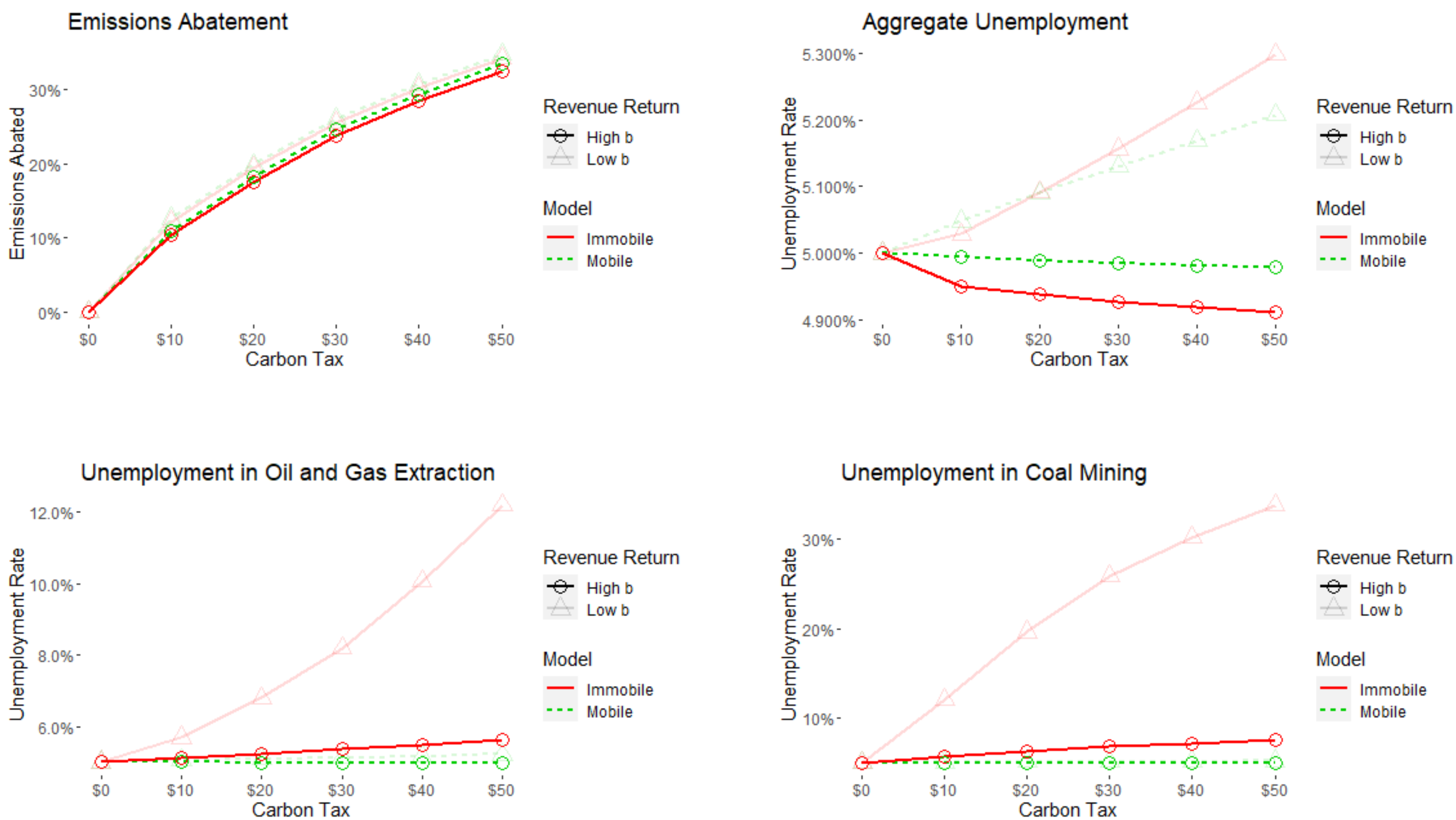
Notes: This table is predictions for specified aggregate variables after implementation of a $35 carbon tax, with revenues returned lump-sum. [1]The first row uses the base-case parameter values (listed in Appendix Table A3). All other rows change just one parameter from its base-case value as indicated.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

Appendix Table A9: Parameters for the external economies model from Balistreri (2002)

Description	Value
$\boldsymbol{\sigma}$ in the equation $\boldsymbol{H(E,u)}$	0.45
$\boldsymbol{\eta}$ in the equation $\boldsymbol{H(E,u)}$	0.15
Leisure share of total labor return	33%
Elasticity of substitution between consumption and leisure	1

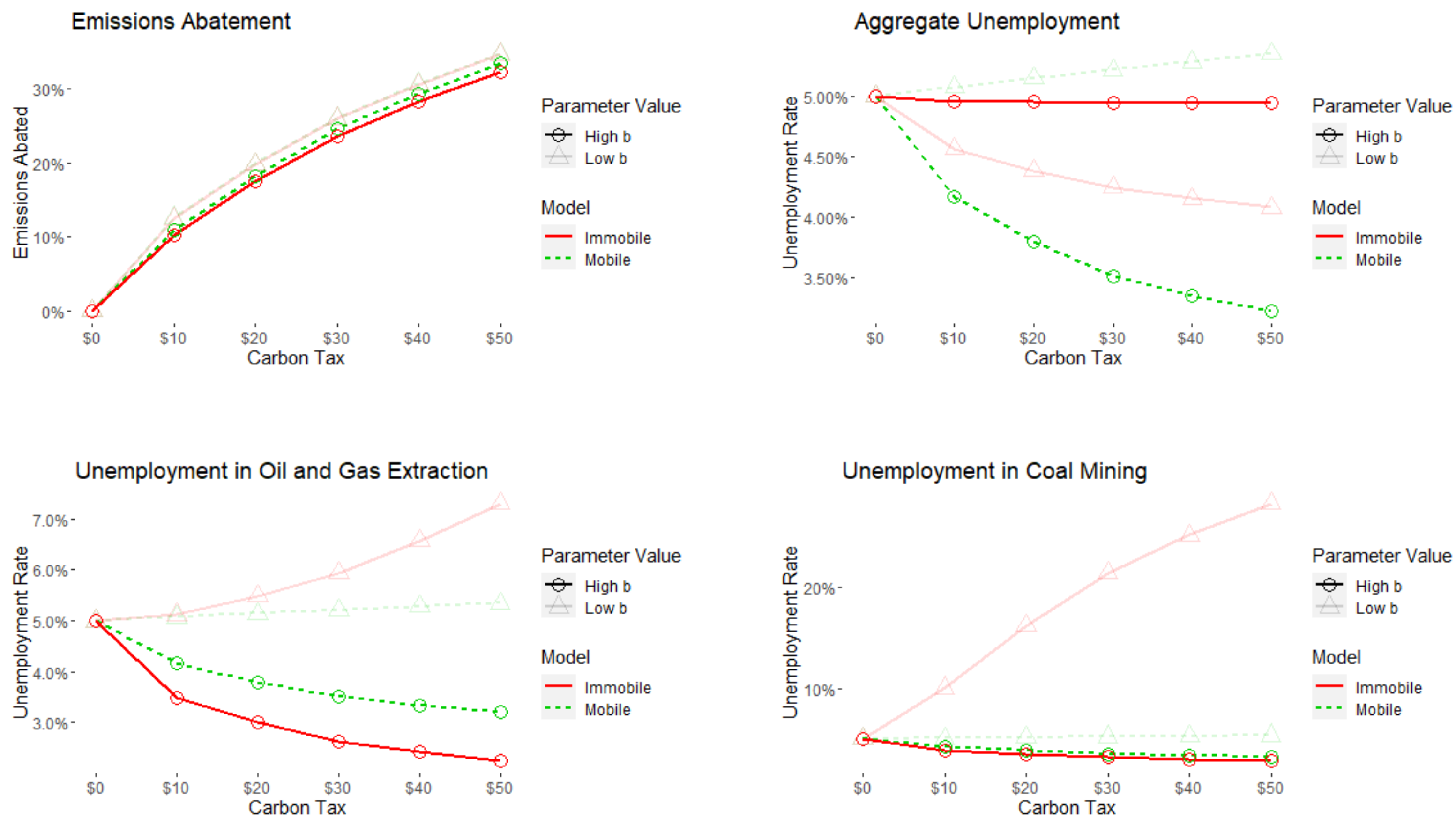
Notes: This table lists the parameter values used in the external economies labor market model from Balistreri (2002).

Appendix Figure A1: High Bargaining Parameter in Aggregate Tax Cut Policy



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 darker curves represent the model under a calibration that uses a high bargaining parameter. The faded curves show results of a model using our baseline calibration of a low bargaining parameter (see Figure 4 in the text for comparison).

Appendix Figure A2: High Bargaining Parameter in Targeted Tax Cut Policy



Notes: These graphs present results under a carbon tax of varying levels (x-axis) with revenue returned through a targeted 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 darker curves represent the model under a calibration that uses a high bargaining parameter. The faded curves show results of a model using our baseline calibration of a low bargaining parameter (see Figure 5 in the text for comparison).

Appendix Figure A3: Comparison of Three Unemployment Models