Unemployment, Labor Mobility, and Climate Policy

Abstract

We develop a computable general equilibrium model of the United States economy to study the unemployment effects of climate policy and the importance of cross-sectoral labor mobility. We consider two alternate extreme assumptions about labor mobility: either perfect mobility, as is assumed in much previous work, or perfect immobility. The effect of a $36 per ton carbon tax on aggregate unemployment is small, though about 15% greater under the assumption of perfect immobility than under the assumption of perfect mobility (0.40 vs. 0.46 percentage points). The effect on unemployment in fossil fuel sectors is much larger under the immobility assumption (a more than 50 percentage-point increase in the coal sector), suggesting that models omitting labor mobility frictions may greatly under-predict sectoral unemployment effects. Carbon taxes that return revenue through labor tax cuts reduce policy distortions, while command-and-control policies are more distortionary than carbon tax cuts.

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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 overall (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. 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. Greenstone (2002) and Yamazaki (2017) both use reduced-form identifications to directly measure the effect on unemployment, and Walker (2013) measures the policy-induced labor reallocation costs. Hafstead and Williams (2018) and Aubert and Chiroleu-Assouline (2017) use analytical general equilibrium models to study unemployment effects of climate policy. Some CGE models of environmental policy do allow for unemployment in various ways, but many of these have been limited to analysis of countries other than the United States (André et al. 2005, Böhringer et al. 2003, and O'Ryan et al. 2005). To our knowledge, Hafstead et al. (2018), a recent working paper, is the only other study that develops a CGE model of the US economy allowing for involuntary unemployment to study climate or environmental policy.

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 those that are expected to be more exposed to effects of climate policy, like energy sectors. The model includes a detailed calibration of each sector's production process and responsiveness to price changes. Unlike many CGE models, we allow for involuntary labor unemployment with a wage curve, a la Blanchflower and Oswald (1995). We compare a model with perfect cross-sectoral labor mobility to one with perfect labor immobility to assess the importance of labor mobility. We compare the unemployment effects of a carbon tax to the effects of a command-and-control policy, and we study the ability of policy to respond to the adverse employment effects through revenue return. Relative to most CGE models of domestic environmental policy, this paper furthers our understanding of the employment effects of policy by explicitly modeling involuntary unemployment within each sector. Simply using a full-employment CGE model and studying voluntary changes in employment will be misleading.

Relative to Hafstead et al. (2018) and other CGE models of environmental policy that do include involuntary unemployment, we extend the literature by considering the effect of assumptions about labor mobility. One extreme assumption is perfect labor mobility across sectors, an assumption imposed by most previous studies. The other extreme assumption is perfect immobility: sector-specific labor (and sector-specific unemployment rates). We present results under both assumptions and compare them to study the effect of labor mobility. Hafstead et al. (2018) argue that sectoral unemployment effects might be large, but aggregate unemployment effects are small. Some sectors may experience large decreases in unemployment, but other sectors will increase their employment due to the new cheaper labor exiting regulated industries. This small net effect is likely to increase if workers are unable to easily shift from one sector to another. 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.

We find that the effect of climate policy on unemployment depends on the assumption made about labor mobility. Under the assumption of perfect labor mobility, a $36 per ton carbon tax with revenue returned lump-sum increases the aggregate unemployment rate by just 0.40 percentage points, while the increase under the assumption of perfect labor immobility is about 15% larger (0.46 percentage points). Furthermore, this aggregate effect on unemployment masks large increases in unemployment in the most vulnerable sectors. While aggregate unemployment effects are small, sector-specific unemployment effects are large: the unemployment rate increases by 6.7 percentage points in the oil and gas extraction sector and by a whopping 50 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 under perfect labor mobility than it does under perfect labor immobility, though aggregate output decreases slightly less (1.5% vs. 0.7%). The price of goods increases more under the perfect mobility assumption than it does under the perfect immobility assumption.

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 effect on unemployment can actually be to *decrease* aggregate unemployment – a type of double dividend where the benefit from reducing the labor tax dominates the cost from the carbon tax. This decrease is larger when labor is immobile, though the change in unemployment in the fossil fuel sectors is very small. When revenues are returned with a targeted labor tax cut – one that reduces the labor tax only for the fossil fuel sectors – then the aggregate unemployment benefit is greatly reduced, but unemployment drops by a greater amount in the targeted sectors. Finally, a command-and-control policy that imposes a sector-specific emissions quantity goal is the most distortionary policy overall, and it yields a much larger aggregate unemployment increase (rising to 5.5% for the equivalent of a $36 carbon tax, compared to just 5.1% for the carbon tax with lump-sum revenue return).

The next section provides a brief literature review. Section III describes the CGE model, and section IV describes the data, calibration, and solution methods. Section V presents base-case simulation results, and section VI presents sensitivity analysis.

II. Literature Review

Computable general equilibrium (CGE) models are simulations of the economy. CGE analysis was first introduced in Herbert Scarf (1967), which outlined an algorithm for numerically solving general equilibrium problems. This is done by developing a system of equations then searching over prices to find where excess demands are zero. CGE models did not become a common analytical tool for economics until Shoven and Whalley (1984) developed a way of including a government sector. This development spurred the use of CGE models to analyze public policy. After some work in trade models, this was extended to analyzing tariffs in addition to taxes on domestic goods. The typical way these programs are used is to determine the effects of specific policies by simulating them. The program is first run under a base scenario, which is a simulation of the economy under current tax policy calibrated to current data, then a counterfactual scenario is simulated under the proposed tax policy. As they have become more advanced, CGE models are a now common tool for analyzing tax policies. Recent papers have used CGE models to model trade and the effects of business cycles (Cravino and Levchenko 2016). CGE models are often used to examine the effects of environmental regulation. Carbone (2017), for example, uses several CGE models to determine the effect of environmental regulations on domestic competitiveness in international trade markets.

Most CGE models assume full employment in labor markets, and therefore the only source of changes in employment in the model is consumers choosing more leisure or workers being reallocated across sectors. However, three basic frameworks have been used in CGE models to incorporate involuntary unemployment.[1] The first is the efficiency wage model of Shapiro and Stiglitz (1984). Workers can choose one of two effort levels – "work" or "shirk" – and can either be employed or unemployed. Monitoring is imperfect, but if workers shirk and unemployment is high, then there is a higher probability that they will be replaced, so unemployment acts as deterrent for shirking (Basu, 1998; Chen, 2011). The second framework is the search and matching model developed by Mortensen and Pissarides (1994). It is costly for employers to post vacancies and find workers so there is a friction in the labor market. However, this friction is driven by labor market tightness (the ratio of vacancies to unemployed), much like the efficiency wage model. This unemployment framework is used in USAGE, a CGE model created for the U.S. International Trade Commission (Dixon, Johnson, & Rimmer, 2011). It is also used by other papers that model unemployment effects of environmental policy (Hafstead and Williams 2018, Hafstead et al. 2018, Aubert and Chiroleu-Assouline 2017). The third model is sticky wages, where labor market frictions are created by a downwardly rigid wage, and unemployment is equal to the excess demand for labor (Kehoe & Serra-Puche 1983).

An alternative to these three specifications of involuntary unemployment is to use a less structural relationship between wages and unemployment: a wage curve. Blanchflower and Oswald (1995) find consistent evidence across countries that the elasticity of the wage with respect to the

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

unemployment rate is about –0.1. Wage curves have been used to model unemployment in CGE models (Böhringer et al. 2008, Fæhn et al. 2009). Wage curves can incorporate any of the more structural specifications of unemployment (Balistreri 2002, Boeters and Savard 2013).

CGE models differ in their assumptions about cross-sectoral labor mobility. 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. An important distinction should be made: we look at industry-specific labor as opposed to occupation- or firm-specific capital.[2] Some general equilibrium models have looked at skill-specific labor markets, typically defining two labor markets for high and low skill workers (Shimer and Alvarez 2009). It is also well known from Todaro (1969) that geographical frictions must be considered, especially when analyzing less-developed countries. Industry-specific labor markets, however, are rarely discussed in the literature.

In their two-sector general equilibrium model of the unemployment effects of environmental policy, Hafstead and Williams (2018) do not include cross-sectoral mobility frictions in their main specification. However, they are included in an extension (their section 5.2). The Mortensen-Pissarides matching function is generalized to include a term representing the higher cost of a displaced worker from one sector being hired in the other sector. A parameter ξ can take any value between 0 (no cross-sectoral frictions) to 1 (infinite cross-sectoral frictions); they present simulation results for these two values as well as for two intermediate values. They find that perfect cross-sectoral immobility slightly increases the overall unemployment effects of policy and that partial immobility ($\xi < 1$) only affects the transition time to the same steady state (their Figure 8).

[2] Babiker and Eckaus (2007) includes industry-specific labor, but labor market effects are not reported, and it is not the primary research interest of the paper.

There is some empirical evidence for immobility between industries in labor markets. Neal (1995) shows the existence of industry-specific human capital using the Displaced Worker Survey, by looking at workers who lost their jobs as a result of a layoff from a plant closing, employer going out of business, or some other similar reason. Workers who switched industries saw lower returns to experience and tenure than those who found jobs in their pre-displacement industry. Walker (2013) estimates the labor market effects of the Clean Air Act, incorporating the fact that the reallocation of workers across firms and sectors can lead to earnings losses since workers can lose productivity after moving jobs. He finds that the total earnings losses from the sectoral shift in production is $5.4 billion (in 1990 dollars).

Under our assumption of 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 degenerate cases.

A large literature estimates the effect of environmental policy on labor markets, and in particular on unemployment, using reduced-form identification techniques rather than CGE modeling. Greenstone (2002) uses county-level attainment status as an instrumental variable and finds that nonattainment counties lost about 590,000 jobs in the first 15 years of the Clean Air Act. Colmer et al. (2018) estimate the effect of the European Union's emissions trading scheme (EU ETS) on French manufacturing firms, including on their employment levels, and they find no effect of the policy on employment. Petrick and Wagner (2014) also find a null effect of the ETS on employment among German manufacturing firms. Yamazaki (2017) and Azevedo et al. (2018) both estimate the effect of the British Columbian carbon tax on jobs. Azevedo et al. (2018) use synthetic control methods, and they find no effect at the industry level but heterogeneity across firm size and type: small service firms see a boost in employment while large manufacturing firms see a decline. Yamazaki (2017) finds a small but significant overall increase in employment from the tax, though a fall in employment among the most carbon-intensive sectors.

CGE models have been used in environmental research mainly in two respects.[3] The first is measuring the effect of economic activity on the environment. For example, models may be used to predict resource depletion rates or the amount pollution in the air or water. Due to the popularity of using CGE to model trade, many studies have tried to measure the impact of trade liberation or tariffs on the environment (Beghin, Dessus, Roland-Holst, & van der Mensbrugghe, 1996; Xu & Xu, 2012). The second body of research focuses on the effects of environmental regulations on different sectors and markets in the economy. There are a few models that have been created for common use by academics, such as the GREEN model from the OECD (Lee, Martins, & Van der Mensbrugghe, 1994). Initially these models were used to measure how much output is affected by regulation or taxes in sectors that heavily use polluting resources like fossil fuels (Al-Amin, Abdul Hamid, & Chamhuri, 2008; Hazilla & Kopp, 1990; Jorgenson & Wilcoxen, 1990; Masui, 2005; Nestor & Pasurka, 1995; Xie & Saltzman, 2000). A common finding in this literature is a modest reduction, of approximately 5 to 15 percent, in output due to environmental policy regulations. Goulder et al. (2016) find that a federal clean energy standard is surprisingly more cost-effective than emissions pricing using a CGE model of the US economy.

Finally, there has recently been a growing literature using general equilibrium models to study the impact of environmental regulations on the labor market, in particular on unemployment. Even full-employment CGE models can be used to calculate employment effects of policy, though in these models reductions in employment are voluntary, resulting from households' labor-leisure trade-off in the face of

[3] Bergman (2005) and Jorgenson et al. (2013) provide overviews of the use of CGE models in environmental economics.

endogenously-changing prices. Hazilla and Kopp (1990) use a full-employment CGE model and reported a 1% reduction in employment from environmental policy. 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 analytical closed-form solutions can be found and interpreted, rather than relying solely on a CGE "black box" for results. Hafstead and Williams (2018) and Aubert and Chiroleu-Assouline (2017) develop analytical general equilibrium models of environmental policy with involuntary unemployment modeled using the Mortensen and Pissarides (1994) matching model.

The closest papers to ours are those that use CGE models that allow for involuntary unemployment to calculate the effects of environmental policy. These papers are summarized in Table 1. 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).[4] 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. McKibbin and Wilcoxen (2008) model

[4] Küster et al. (2007) models skilled unemployment with a wage curve and unskilled unemployment with a wage floor.

unemployment with an overlapping contracts where nominal wages are based on actual and expected inflation and labor demand determines unemployment. The paper most similar to ours is Hafstead et al. (2018), which also develops a CGE model (based on the CGE model in Goulder et al. (2016) and the unemployment modeling in Hafstead and Williams (2018)) of the US economy allowing for involuntary unemployment to study environmental policy. They compare the model with unemployment to a full-employment model. They find that using a full-employment model overestimates the magnitude of job losses from a carbon tax by a factor of 2.5.

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

III. Model Description

Here we briefly describe the model. We consider two different assumptions about labor mobility. In the first, workers are perfectly immobile across industries – there is no cross-sectoral movement of labor, and as a result there is a vector of industry-specific wages. In the second assumption, workers are perfectly mobile, and as a result there is a single economy-wide wage. We consider both of these extreme assumptions to highlight the importance of mobility in the labor market's response to environmental policy. We begin by describing the model under the assumption of perfect immobility, and then we discuss where the model differs under the alternate assumption.

III.A. Production

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

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

Although production in each stage is modeled with the CES function from equation 1, the elasticity parameter ρ_i^s, the share parameters $\alpha_{i,j}^s$, and the shift parameter γ_i^s can potentially differ across industries i and across stages of the nested production process s. The stages s can take a value in $\{Final, VA, I, E, M, Elec\}$.

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.

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

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 up by two other types of composites: an energy composite E_i^d and a materials composite M_i^d, each of which is composed of demands from energy and material industries respectively. The number of energy sectors in the economy is denoted by $\bar{e}$ and the number of material sectors is $\bar{m}$, and they are listed in Figure 1. In addition to the division of energy goods, there is also a subdivision of electricity into "renewable" and "non-renewable" with the difference primarily being that 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 $\bar{P}_i^L$ and capital rents $\bar{P}_i^K$, which are the prices net of taxes on capital and labor. They then use these prices to determine their cost-minimizing demands. Factor prices can be industry-specific, both because labor and capital tax rates can be industry-specific (though in the base case, all labor tax rates are identical across industries), and because, for wages, labor is industry-specific in the case of labor immobility. Demands by consumers are determined by the price of capital, wages, and labor supply, then prices are adjusted until excess demands are zero. Producer i's problem is

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

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

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

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

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

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 electricity sector 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 single representative household for each industry; therefore there are I consumers. Consumers have a Cobb-Douglas utility function defined over final goods consumed from each industry, both from domestic and foreign producers. Households purchase these final goods using income from capital and labor as well as government transfers. The household's problem is:

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

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

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

III.C. Foreign Sector

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

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

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

III.D. Carbon Emissions

Carbon emissions are produced as a byproduct of production of two energy industries: coal mining, and oil and gas extraction (oil and gas are combined as one industry in the social accounting matrix, described below). 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 of the two polluting industries is given by:

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

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

The other policy that we model is a command-and-control quantity restriction, where each polluting sector 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 particular agent receives the income from the scarcity rents.

III.E. Government

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

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

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

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

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

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

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

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

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

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. This is done by first calculating shares of lump sum transfers (state and federal) that are allocated to each state, and then determining the proportion of employment by each industry in those states. The final transfer ratio for each household is the sum across states of the products of state transfer shares and state employment shares from that industry.

III.F. Labor Market

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

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

Blanchflower and Oswald (1995) give estimates for η_1 of -0.1 across most nations, with remarkable consistency. This means that a 1% decrease in wages is associated with a 10% increase in the local unemployment rate.

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

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

III.G. Equilibrium

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

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

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

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

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

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

Up to now we have described the model under the assumption of perfect labor immobility, so that each industry's labor stock is fixed with its own unique wage. The alternative assumption that we consider is that of perfect labor mobility, where workers are free to move across sectors and there is just one economy-wide wage. We estimate the two models to compare the difference in changes in the counterfactual scenario. In the immobile case unemployment rates are different across sectors and are determined by using the sector-specific wage and the wage curve parameterized to that industry as described in the labor market section. In the perfectly mobile case there is just one wage and one unemployment rate across all sectors. When the mobile case is calculated, the unemployment rate is used to determine the amount of labor stock each household can supply (there is one household for each sector like in the immobile case) at the economy-wide wage. Each household supplies as much labor as it can under the unemployment rate and then these rates are summed to determine the aggregate labor supply. Equilibrium condition (23) changes to

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

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

IV. Data and Calibration

IV.A. Data Sources

The model is calibrated to fit an input-output matrix for the United States in 2007. This matrix comes from the Bureau of Economic Analysis (BEA) 2007 benchmark tables.[5] The BEA matrix contains

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

over 300 industry classifications, which we aggregate to 11 industries.[6] These industries fall into the two categories of our model: energy and materials. The industries are listed in Table 2. The energy sectors are oil and gas extraction, coal mining, electricity, and natural gas distribution. For electricity generation, we further divide it into two sub-industries: renewable and non-renewable electricity generation. Renewable electricity does not use fossil fuels as inputs, while non-renewable electricity does. The materials sectors are agriculture, chemical manufacturing, non-chemical (goods) manufacturing, services, construction, and (non-coal) mining. Manufacturing is split into two parts, chemical and non-chemical, because chemical manufacturing tends to have a much higher emission intensity than other manufacturing industries. 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 document "The Distribution of Federal Spending and Taxes in 2006" due to its high level of detail in expenditure and revenue categories[7]. 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.[8] These are then combined to create revenues by all levels of government.

IV.B. Calibration

[6] The BEA data do not disaggregate electricity generation into renewable and nonrenewable generation, so those two sub-industries are not presented in Table 2. Later in this section we describe our calibration strategy for electricity.

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

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

Calibration is done by first assuming that all prices are equal and solving backwards for a base case set of parameters. Some variables used to calibrate the model are changed to be able to fit the assumptions. Under balanced trade, there are no trade deficits, so all excess imports are added to final goods demands by consumers. Additionally, government spending is reduced to match revenues in the calibration step as well. After we solve for this base case set of parameters, we solve the model giving us a base case equilibrium. Policy experiments are then analyzed by solving for equilibrium under the policy changes, and evaluating the changes from the base case equilibrium.

Table 7 summarizes some of the important calibrated parameter values. The parameters for the nested production functions consist of elasticity parameters ρ_i^s, share parameters α_i^s, and shift parameters γ_i^s. The elasticity values are set based on existing literature. Elasticity of substitution between capital and labor ρ_i^{VA} for all industries is set at 0.3191, and elasticity between the value-added composite and the intermediate composite ρ_i^{Final} is set at 0.547 (Van der Werf 2008). Elasticity of substitution parameters for the intermediate composite ρ_i^I and energy and materials composites ρ_i^E and ρ_i^M are set at 0.1. This value is chosen to mimic the short-term elasticity of intermediate goods. We later vary these base-case elasticity values to explore robustness. The remaining production shift and share parameters, α_i^s and γ_i^s, are determined by solving to match the input-output matrix from the BEA. These parameters are unique to each industry, and so thus for space are not presented in Table 7. Based on Blanchflower and Oswald (1995), the elasticity parameter in the wage curve η_1 is set to –0.1, and the baseline unemployment rate is set to 5%.

Consumers' utility function is assumed to be Cobb-Douglas, and households are divided by industry. Parameters for the utility function are determined using shares of personal consumption expenditure in the BEA tables. This gives us parameters for all domestic and imported goods. Capital and labor supplies for households are determined from industry demands. We assume that in the calibrated equilibrium supply stocks are equal to industry demands, given unemployment. So supplies of labor for each industry-representative household are determined by finding demands for labor for that industry then dividing by one minus the unemployment rate.

Carbon emissions are a linear relation to output for the two polluting sectors (coal mining and oil and gas extraction), and to determine emissions in the model we simply find a carbon coefficient for each of them. Table 2 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.[9] Carbon coefficients are determined by calculating the per-unit carbon emissions by fuel source.

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%. 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.[10]

We decompose the electricity industry into two representative firms: one that uses non-renewable resources such as fossil fuels and one that uses renewable resources. The BEA tables do not provide information on this disaggregation, 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. Using shares of non-renewable and renewable sources, we create a non-renewable sector that uses the same inputs as the electricity sector from the BEA tables. The renewable sector uses no fossil fuel inputs, but rather uses more materials and value-added composites.

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

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

IV.C. Model Solution

We solve the model by finding the excess demands for all factors and imposing the zero-profit condition on firms. We then use an infinitely refining simplex algorithm to find a point where excess demands are approximately zero (Merrill 1973). This algorithm works by first creating a grid and then using a system of replacements to search the grid for an approximate solution. This is done by creating a "no-cycling" rule that requires each point on the simplex to be examined. When it finds an approximate solution, if it is larger than the tolerance, a finer grid is created around that point. Code is written in the open-source programming language Julia, and it is available upon request and posted on the authors' websites.

V. Simulation Results

We consider simulations of several different policy scenarios, which we compare to the base case simulations to see the effect on equilibrium outcomes, including unemployment and sectoral output. For each simulation, we run it under the two alternate assumptions about labor mobility: either labor is perfectly mobile across sectors, or labor is perfectly immobile across sectors (i.e. there are separate, fixed labor markets for each sector). For all models we assume that all industries start at a 5% unemployment rate, which is close to the natural rate of unemployment implied by most literature.

In our first set of policy scenarios, we consider a carbon tax. The base-case tax rate is set at $36 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.

For the carbon tax, we model three alternate ways to return the revenues. The first policy modeled is a carbon tax where revenues are returned in a lump-sum fashion to all households. In the assumption of perfect labor mobility, this goes to the lone representative household. In the assumption of perfectly immobile labor, the lump-sum revenues are returned to the sector-specific representative households in proportion to their share in total national income.

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 its reduced revenues are just equal to the carbon tax revenues.

The third policy modeled returns revenues in a way intended to offset the deleterious effects of the policy on the targeted industries. The third policy 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.

Lastly, we model the command-and-control policy, in which the exogenously-set emissions quantity restriction is set for each of the two polluting industries to equal the total emissions reduction found under the $36 carbon tax. Scarcity rents – the revenues from the shadow price on the emissions constraint – are returned lump-sum to consumers.

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.

V.A Uniform lump sum revenue return

Our model predicts reductions in emissions that are comparable with previous studies. The change in total emissions is shown in Figure 2, for various levels of the carbon tax rate. A $35 per ton carbon tax (which is comparable to what other models use) leads to a 45% reduction in carbon emissions. There is effectively no difference between the mobile and immobile models in this regard. As the graph shows, this is true across many carbon tax rates.

The labor market is of interest for this paper, and to interpret changes, we must be clear about the starting point. 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. While the two are close to each other, the immobile model predicts higher aggregate unemployment at every tax rate. The change in the unemployment rate is about 16% higher using the immobile labor assumption. So, under a $35 carbon tax, the unemployment rate increases from 5% to 5.40%, and under the immobile labor assumption the aggregate unemployment rate rises from 5% to 5.46%.

Although the aggregate unemployment rates are roughly 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 panel of

Figure 2 shows the differences between the two models for the oil and gas extraction and coal mining industries. Coal is clearly hit the hardest since it has the most carbon-rich product. At a $35 carbon tax the unemployment rate climbs to over 50%. This is much higher than the mobile labor market model predicts. The oil and gas extraction sector similarly sees a larger spike in unemployment under the immobile labor assumption, though a $35 tax only increases unemployment to about 13%.

Effects in other industries can be different as well. Price and final demand changes in response to a $35 per ton carbon tax are reported in Table 3. The change in prices are dampened in the immobile model as some industries can substitute towards cheaper labor trapped in their industry. While almost all industries see a reduction in output, the affected industries are obviously much worse. Heavily affected downstream industries also see larger reduction in output such as non-renewable electricity and natural gas distribution.

The electricity sector is of special interest, as ours is the first model that we know of to disaggregate non-renewable from renewable electricity production. Reductions in output are much larger for the non-renewable sector, since it uses fossil fuels as an input. The substitution towards renewables also shows up in the labor market. Labor demands are higher for the renewable electricity sector than for the non-renewable sector, and this effect widens as the tax on carbon increases. Figure 3 shows changes in labor demand in response to a carbon tax, for the mobile and immobile labor models, respectively. For a low tax rate, labor demand in the electricity sectors increases as other firms substitute away from fossil fuels toward electricity, and as the electricity sector substitutes toward value-added inputs and away from intermediate inputs. For a higher carbon tax, though, the change in labor demand becomes negative. Notably, at our base case $35 per ton carbon tax rate, we find a decrease in labor in the non-renewable sector and an increase in the renewable sector, for both the immobile and mobile labor models. Though the curves for the two models have the same shapes, the mobile model shows a much larger initial positive response as firms can pick up labor fleeing other industries. The mobile model also shows a larger disparity between the two, as workers can leave the non-renewable industry.

In summary, the results from the simulations with lump-sum revenue return demonstrate the importance of assumptions about labor mobility to the labor market outcomes. While there is virtually no difference in emissions between the simulations under the assumptions of perfect mobility and perfect immobility, there is a large difference in the labor demands across sectors, output and prices of goods across sectors, and a small difference in the aggregate unemployment rate. The change in the unemployment rate is about 16% higher under the assumption of perfect immobility than it is under the assumption of perfect mobility. This suggests that previous models that have assumed perfect cross-sectoral mobility, even when allowing for unemployment through labor market frictions, may slightly underestimate the impact of policy on labor markets.

V.B Uniform Labor Tax Cut

We now turn to another type of revenue return, which is cutting the labor tax rate instead of returning the revenue lump-sum. We consider a uniform cut to the labor tax across industries. Again, the reduction in emissions is largely the same between the two models, and about the same under the two revenue return schemes. Figure 4 shows emissions reduction for the mobile and immobile models under a labor tax cut revenue return.

Aggregate unemployment under the tax cut revenue can actually decrease, at least for a range of low carbon taxes. For a low carbon tax rate, the net effect of the tax swap is to reduce unemployment, since the distortion from the new carbon tax is less than the reduced distortion from the labor tax.[11] Under the immobile model the unemployment decrease is larger and exists at higher tax

[11] This is analogous to the "double dividend" literature, although here we are not examining welfare effects.

rates compared to the mobile model. This is an important difference between the two revenue return scenarios. For the lump-sum return, the unemployment *increase* is greater under the immobile labor assumption than under the mobile labor assumption, while for the uniform labor tax cut, the unemployment *decrease* is greater under the immobile labor assumption. Models that ignore labor mobility frictions can thus either under- or over-estimate the change in unemployment, depending on the revenue return method.

Looking at the coal mining and oil and gas extraction industries, the reduction in labor demands under the labor tax cut is roughly the same as under the lump sum revenue return, as seen in Table 3. For example, under the lump sum return and a $35 carbon tax, the oil and gas extraction industry reduces labor by 17.6%. For the same carbon tax rate, a labor tax cut return reduces labor by 17.3%. So, the economy-wide difference across the revenue return scenarios does arise in the taxed industries.

Untaxed industries show a different story. Figure 5 shows labor demand changes for the two electricity sectors. Labor demands in these sectors increase more under the labor tax rate cut than under the lump sum revenue return. Under the mobile labor market assumption, these sectors double their increase in labor as compared to the lump sum return. Under the immobile labor market assumption, we observe a larger range of tax rates which give an increase in labor demands. These increases are smaller than predicted by the mobile labor model.

The policy implications are that a tradeoff exists between the taxed and non-taxed industries. Although there are employment gains in other sectors, like electricity, the losses in the taxed industries are not changed very much between the two revenue return scenarios. This is likely because 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 1 percentage point. So, when coal mining is experiencing labor losses greater than 50%, a 1 percent tax cut does not do much to offset this.

V.C Targeted Labor Tax Cut

This leads to another possible policy solution, which is our third revenue return scenario: a targeted tax cut. In this scenario, only the coal mining and oil and gas extraction industries receive a labor tax cut. It turns out that the tax revenue from the carbon tax is greater than the revenue from the labor tax in these two industries, so the post-policy labor tax actually becomes a subsidy. This subsidy is quite large, reaching over 50% under a $50 carbon per ton carbon tax. The result in the mobile labor market is that labor demands in these two industries increase rather dramatically. The oil and gas extraction industry more than doubles its labor supply, and the coal mining industry increases demands by about 20% at its peak. Figure 6 shows the change in unemployment under a targeted tax cut regime. The immobile labor model shows a much different result because these industries cannot expand past their allocated supplies. They simply exhaust all the labor in their respective industries.

Figure 6 shows aggregate unemployment under the targeted tax cut. Under both mobile and immobile labor, we see a decrease in aggregate unemployment for some carbon tax rates. In the mobile model, this decrease persists through most values of the carbon tax shown. This effect comes from two places. One is that these industries hire workers leaving unsubsidized industries. The immobile model has a much smaller unemployment decrease due to those industries not being able to expand their labor force. The second is that since we are both taxing and subsidizing these industries, the carbon tax has a weaker effect overall. Figure 6 also shows emissions reductions under a targeted tax rate return. The immobile model gives results like other revenue return schemes because the allocation of labor cannot shift to more carbon producing activities. The mobile market, however, shows a smaller reduction in emissions as subsidized labor makes production cheaper for fossil fuel industries.

This gives an important consideration for policy makers. While a subsidy to these industries would curb the issue of unemployment in these specific industries, it comes at the expense of larger policy goals, such as aggregate unemployment reduction and emissions abatement. A tax cut across all industries would yield a larger aggregate unemployment decrease, and emissions abatement would not change very much. However, unemployment in the taxed industries would still be quite high. It should give some hope, however, that a combined policy could better achieve these goals. It is likely that labor losses can be curbed at lower subsidies for these industries, and the surplus revenue can cut taxes in the wider economy.

V. D. Command-and-Control Policy

The last policy we consider is a command-and-control (CAC) policy, where each of the two polluting firms is given a quantity restriction. The regulator sets an amount of allowable pollution, 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 in which there is 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 an emissions reduction goal to each industry, which implies that there will be 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 20% 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 from this simulation are presented in Figure 7, with the upper panels showing the impact on unemployment rates in each sector, and the lower panels showing aggregate unemployment and shadow prices. The first thing to note is the much higher price in the oil and gas extraction industry is than in the coal industry. At a 20% emissions reduction, the shadow price of a ton of carbon in the oil and gas industry is $29.31, and in the coal mining industry it is only $1.42. Additionally, this policy has a moderate effect on the labor market, increasing the unemployment rate to 5.28% from a 20% reduction in emissions. This increase is almost twice as large as that under the the same amount of emissions reduction under a carbon tax. So, while this policy might put less strain on the coal mining industry, it comes at the cost of more inefficiency in the labor market.

The results for the immobile case give interesting policy implications for unemployment in the two sectors. Figure 7 shows shadow prices and unemployment rates for the two directly affected sectors. Under the immobile labor case shadow prices are slightly higher than in the mobile labor case. Additionally, unemployment is (as expected) higher in the two sectors than in the mobile labor case. However, when comparing to the tax with lump sum return, unemployment is higher in the oil and gas extraction sector and lower in the coal mining sector. At about 30% emissions reduction, the oil and gas extraction industry has about an 8% unemployment rate under a carbon tax, but that doubles under the CAC policy to 16%. The coal mining sector sees a dramatic reduction from 35% unemployment under the carbon tax to only 13% under the CAC policy. This indicates that a CAC policy that reduces each sector's emissions by different amounts could alleviate unemployment effects in the coal mining sector. Although this does come at the cost of increasing unemployment in the oil and gas extraction sector and unemployment overall.

One much larger trade-off to this policy is its effect on the overall economy. It is quite inefficient for both industries to reduce their emissions by the same amount since the coal mining sector has a lower marginal abatement cost. This shows up in the aggregate unemployment rate, which under the carbon tax with lump sum return was only about 5.1% in response to a 30% emissions reduction. Using this CAC policy, the aggregate unemployment rate jumps to about 5.8% under a 30% emission reduction. So, while we can reduce unemployment in the coal mining sector this comes at the cost of higher aggregate unemployment as well. There is also a substantial cost in terms of GDP. Table 6 shows the percent reduction in GDP for each policy scenario and labor mobility assumption. The reduction in GDP is almost 4 times larger under the CAC policy than under the various tax policies.

Given these costs, it is difficult to say what the optimal policy is. One could argue that making the unemployment rates across the two affected sectors is the best policy. Still another argument could be to start with equal reduction policies (as we have discussed here), then slowly increase the reductions required of the coal mining sector until the permit prices are equal across the two industries. Either way, separate quantity control policies may be an effective tool in alleviating the burden from sitting squarely on the coal mining sector's shoulders.

VI. Sensitivity Analysis

In this section we explain how the model was solved and some of the issues that arise in finding this equilibrium computationally. First, we give an overview of the algorithm and how we computed the equilibrium solution. We then present the issues of numeraire selection under nominal rigidities such as a carbon tax and wage curve specification. We also explore the influence of parameter assumptions on our conclusions.

VI.A. Robustness

We compare our outcomes under alternative values for various parameters assumed in the model. We consider first changes in technology and the elasticity of substitution for different nests of the production function. We then also consider a change in the parameters of our wage curve. As mentioned previously for most of our analysis we use Blanchflower et. al.'s estimate of -0.1, but structural estimates of matching models put this number closer to -1 (Boeters and Savard 2013). This would imply a smaller response to wage changes in magnitude.

Results for our robustness checks are presented in Table 8. The first lines show changes in technology substitution parameters. The predicted changes and levels are similar in magnitude and all move in the same direction. Changes in elasticity of intermediate goods and electricity seem to have the biggest impact on these variables. As expected, decreasing the elasticity parameter in our wage equation to -1 significantly lowers the impact of a carbon tax on unemployment.

VI.B. Numeraire Assumptions

In this section we explore the effect of our modelling assumptions on our results. Specifically, we consider the numeraire and wage curve modeling choices. Our choice of numeraire may affect our equilibrium selection, due to the way we model carbon taxes and unemployment. While the numeraire choice usually does not matter, carbon taxes are typically modeled as a per unit tax based on the amount of carbon that is released upon use. This means that the tax is added to the price, and the assumption of homogeneity of demand is violated. Similarly, the wage curve represents a nominal rigidity and may allow our numeraire selection to influence equilibrium results.

We explore the effect of numeraire choice on equilibrium selection in Appendix tables A1 and A2. The first table shows the standard deviation in equilibrium quantities across numeraire assumptions. For example, the first row is the standard deviation (in percentage points) of predicted change in response to a $35 carbon tax for the oil and gas extraction industry. The second table is predicted changes in selected variables in response to a $35 carbon tax for each choice of numeraire price. While choice of numeraire can influence equilibrium selection, it likely does not impact our main conclusions.

VI.C. Wage Curve

Since we take our specifications for the wage curve from the empirical literature, there is a question of which wage to use in modeling – the net of tax wage or the gross wage. The difference is critically important since the difference can give difference signs of the effect. Figure 8 shows this difference when using the net of tax wage versus the gross wage. Using the gross wage predicts an increase in unemployment that is almost exactly the same as under the lump-sum return. This is simply because the reduction in wages is almost exactly the same under both cases. Using the net wage, however, predicts a *decrease* in unemployment from a tax rate cut. This is because as gross wages stay roughly the same, net wages increase due to the lower tax cut. The literature is currently unclear on which wage is appropriate to use, although most studies seem to use net wages.

There is some evidence that by including producer cost in the wage curve the double dividend can be eliminated (Conrad and Löschel 2005). Unfortunately, there does not seem to be a consensus about which wage to use, but for this analysis we continue using net-of-tax wages.

VII. Conclusion

We develop a computable general equilibrium model of United States climate policy that allows for involuntary unemployment and two alternate assumptions about cross-sectoral labor mobility: perfect mobility and perfect immobility. We consider the effect of a carbon tax on labor market outcomes including the unemployment rate, and we study how different assumptions about labor mobility affect these outcomes. Labor mobility does not have a substantive effect on emissions abatement, but it can have a large effect on labor market outcomes. The estimated increase in the unemployment rate when labor is modeled as perfectly immobile is up to 16% larger than the increase in the unemployment rate when labor is modeled as perfectly mobile. But, this result can flip when carbon tax revenues are returned as a labor tax cut rather than lump sum; in that case the change in the unemployment rate is negative and the immobile labor assumption yields a higher decrease in labor than the mobile labor assumption.

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 a more nuanced and realistic treatment of limited mobility. Our modeling of unemployment was a reduced-form wage curve, in contrast to other CGE models that have included more structural equilibrium unemployment specifications, like search and matching models. While it is possible that most of the intuitions and quantitative results from more complicated structural models can be captured with this reduced-form approach, it is also possible that our approach misses some important elements.

The 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: CGE studies of environmental policy with involuntary unemployment

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

Babiker and Eckaus (2007)	Japan, Europe, China, USA, Former Soviet Union (pre 1995) – Countries from GTAP database	Sector-specific with mobility rigidities	Wage floor	Permit system with reduction to Kyoto protocol levels	Small (0.5 – 1%) increases in unemployment, greater in China and India
Böhringer et al. (2008)	Germany	Homogeneous, perfectly mobile	Wage curve	Carbon tax	Unemployment can be 1% point higher under imperfect competition as compared to perfect competition
McKibbin and Wilcoxen (2008)	U.S., Japan, Australia, Europe, Other OECD, China, India, OPEC, EEFSU (Former Soviet Union)	Homogeneous, perfectly mobile	Overlapping contracts model	Carbon tax with border adjustment taxes (BAT)	Do not report results on unemployment rates
Hafstead et al. (2018)	United States	Homogeneous, perfectly mobile	Matching model with search frictions	Carbon tax	Carbon taxes cause sectoral shifts in labor, but little changes in aggregate unemployment.
This paper	United States	Labor either perfectly mobile or perfectly immobile (sector-specific)	Wage curve	Carbon tax with alternative revenue recycling schemes	Mobility affects unemployment

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

Table 2: Industry Production and Carbon Emissions

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

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

Table 3: Results from $35 per ton carbon tax with revenue return through lump sum transfer

	Price Changes		Final Demand Changes		Labor Demand Changes	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	0.13%	-0.28%	-15.19%	-14.17%	-17.63%	-7.08%
Coal Mining	11.72%	6.09%	-64.80%	-63.79%	-65.86%	-52.47%
Non-Renewable Electricity	1.77%	2.21%	-3.08%	-2.67%	-0.13%	-0.09%
Renewable Electricity	-0.31%	0.18%	-1.05%	-0.70%	0.36%	0.04%
Natural Gas Distribution	3.21%	3.57%	-4.43%	-3.94%	-0.12%	-0.01%
Mining	0.38%	-0.03%	-1.74%	-0.48%	-9.34%	-3.16%
Agriculture	0.08%	-0.53%	-1.45%	0.01%	-8.15%	-2.81%
Construction	0.41%	2.52%	-1.58%	-2.87%	8.36%	1.58%
Manufacturing	1.20%	1.53%	-2.49%	-1.99%	-0.38%	-0.09%
Chemicals	0.53%	0.45%	-1.88%	-0.96%	-4.90%	-1.53%
Services	-	-	-1.35%	-0.51%	-2.44%	-0.80%
Govt	0.32%	4.09%	-0.36%	-3.94%	8.37%	0.52%

Notes: This table provides changes in final demands, labor demands, and prices for each industry in response to a $35 carbon tax.

Table 4: Results from $35 per ton carbon tax with revenue return through aggregate tax cut

	Output Price		**Output Quantity**		**Labor Quantity**	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	0.21%	-0.19%	-15.10%	-13.93%	-17.35%	-6.17%
Coal Mining	11.73%	6.25%	-64.83%	-63.65%	-65.86%	-52.37%
Non-Renewable Electricity	1.83%	2.29%	-2.93%	-2.39%	0.25%	0.41%
Renewable Electricity	-0.27%	0.26%	-0.88%	-0.42%	0.76%	0.53%
Natural Gas Distribution	3.27%	3.65%	-4.29%	-3.67%	0.24%	0.48%
Mining	0.41%	0.00%	-1.56%	-0.16%	-9.07%	-2.48%
Agriculture	0.11%	-0.52%	-1.27%	0.36%	-7.84%	-2.10%
Construction	0.40%	2.50%	-1.39%	-2.57%	8.80%	2.18%
Manufacturing	1.20%	1.54%	-2.29%	-1.67%	-0.04%	0.40%
Chemicals	0.55%	0.50%	-1.70%	-0.65%	-4.58%	-0.94%
Services	-	-	-1.14%	-0.16%	-2.11%	-0.24%
Govt	0.27%	3.48%	-0.31%	-3.36%	8.60%	2.28%

Notes: This table provides changes in final demands, labor demands, and prices for each industry in response to a $35 carbon tax. Revenue is returned via an aggregate labor tax cut (i.e. a cut for all industries).

Table : **Results from $35 per ton carbon tax with revenue return through targeted tax cut**

	Output Price		**Output Quantity**		**Labor Quantity**	
	Mobile	Immobile	Mobile	Immobile	Mobile	Immobile
Oil & Gas Extraction	-10.6%	-1.3%	-5.6%	-13.3%	175.9%	5.3%
Coal Mining	-10.1%	-10.5%	-61.6%	-61.4%	2.6%	3.2%
Non-Renewable Electricity	1.4%	2.1%	-1.7%	-2.4%	0.0%	0.0%
Renewable Electricity	-0.3%	0.2%	0.0%	-0.5%	-0.3%	0.1%
Natural Gas Distribution	1.3%	3.4%	-1.6%	-3.6%	-1.0%	0.0%
Mining	0.0%	-0.1%	-0.4%	-0.3%	-4.8%	-2.9%
Agriculture	0.1%	-0.5%	-0.5%	0.2%	-6.3%	-2.6%
Construction	0.2%	2.3%	-0.5%	-2.5%	2.4%	1.8%
Manufacturing	0.6%	1.4%	-0.9%	-1.7%	-0.9%	-0.1%
Chemicals	0.0%	0.4%	-0.4%	-0.7%	-3.3%	-1.4%
Services	-	-	-0.3%	-0.3%	-2.0%	-0.7%
Govt	0.5%	3.3%	-0.5%	-3.2%	2.5%	1.9%

Notes: This table provides changes in final demands, labor demands, and prices for each industry in response to a $35 carbon tax. Revenue is returned via a targeted labor tax cut, such that only workers in polluting industries are given the tax cut. At this level, the cut to the tax rate becomes a subsidy, hence the large influx of workers to the oil and gas extraction sector.

Table 5: Average effect across numeraire selection

	Output Price	**Output Quantity**	**Labor Quantity**
Oil & Gas Extraction	-1.40%	-15.64%	-17.93%
Coal Mining	10.11%	-65.54%	-66.54%
Non-Renewable Electricity	0.23%	-3.17%	0.06%
Renewable Electricity	-1.87%	-1.09%	0.59%
Natural Gas Distribution	1.70%	-4.57%	0.15%
Mining	-1.17%	-1.79%	-9.42%
Agriculture	-1.48%	-1.48%	-8.17%
Construction	-1.18%	-1.36%	9.11%
Manufacturing	-0.38%	-2.48%	-0.13%
Chemicals	-1.03%	-1.94%	-4.84%
Services	-1.59%	-1.34%	-2.31%
Govt	-1.31%	1.33%	10.60%

Table 6: Reduction in GDP from each policy regime from 30% reduction in emissions

	Mobile	Immobile
Tax with lump-sum return	0.58%	0.55%
Tax with offsetting aggregate tax cut	0.43%	0.30%
Tax with offsetting targeted tax cut	0.31%	0.44%
Command and Control	2.65%	2.86%

Notes: This table summarizes the impact on GDP due to a 30% reduction in emissions across our different regimes. The first three rows are different revenue return regimes for a carbon tax. The final row is a command-and-control policy with the same emissions reductions on both industries.

Table 7: Parameter values

Parameter name	Description	Value	Source
ρ	Elasticity of substitution among intermediate goods	0.1	We chose this to mimic short term elasticity of intermediate goods
ρ_{VA}	Elasticity of substitution between capital and labor	0.319	Van der Werf (2008)
ρ_{PROD}	Elasticity of substitution between value added components and intermediate goods	0.547	Van der Werf (2008)
ρ_{ELEC}	Elasticity of substitution between renewable and non-renewable electricity	0.5	This was chosen as a value between Leontief and Cobb-Douglas production technology.
η_1	Elasticity of unemployment to wages	-0.1	Blanchflower and Oswald (1995)
u	Baseline unemployment rate	5%	Estimate of natural rate of unemployment
	Percent of revenues dedicated to government spending	65%	CBO budget documentation https://www.cbo.gov/publication/44924
	Tax revenues as percent of GDP	16.5%	
	Tax rate on labor	26.9%	BEA factor payments and CBO documentation
	Tax rate on capital	11.4%	BEA factor payments and CBO documentation

Table 8: Robustness checks

	Mobile			Immobile		
	Unemployment	GDP Loss	Abatement	Unemployment	GDP Loss	Abatement
Base case	5.40%					
rho on intermediate = 0.5	5.41%	1.76%	48.67%			
rho on intermediate = 0.9	6.00%	2.46%	53.40%			
rho on VA = 0.75	5.55%	1.66%	45.09%			
rho on totProd = 0.75	5.55%	2.50%	50.90%			
rho on elec = 0.9	6.01%	2.46%	53.41%			
unemployment elasticity = 1	5.14%	1.97%	52.97%			

Notes: This table is predictions for specified variables after implementation of a $35 carbon tax. Unemployment is the resulting unemployment rate, GDP loss is the resulting fall in GDP, and abatement is the percentage of emissions abated. Predictions of these variables are produced under different parameter assumptions shown on the left.

Figure 1: Nested Production Structure

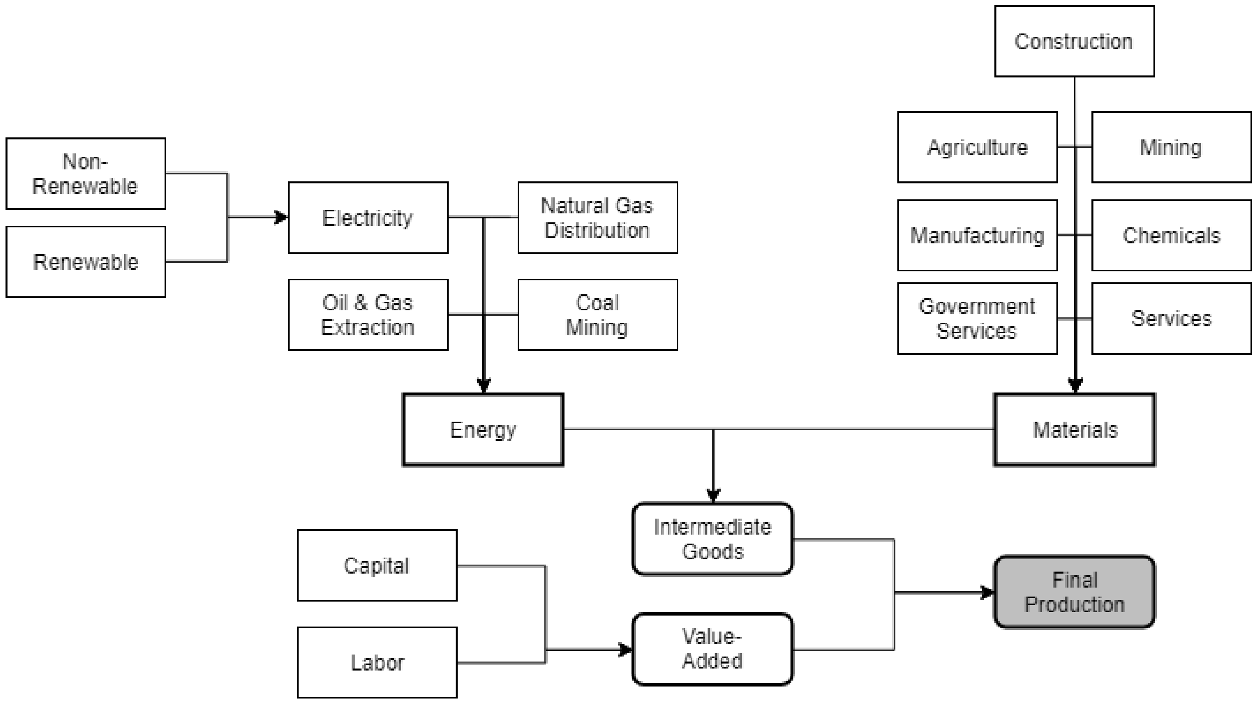
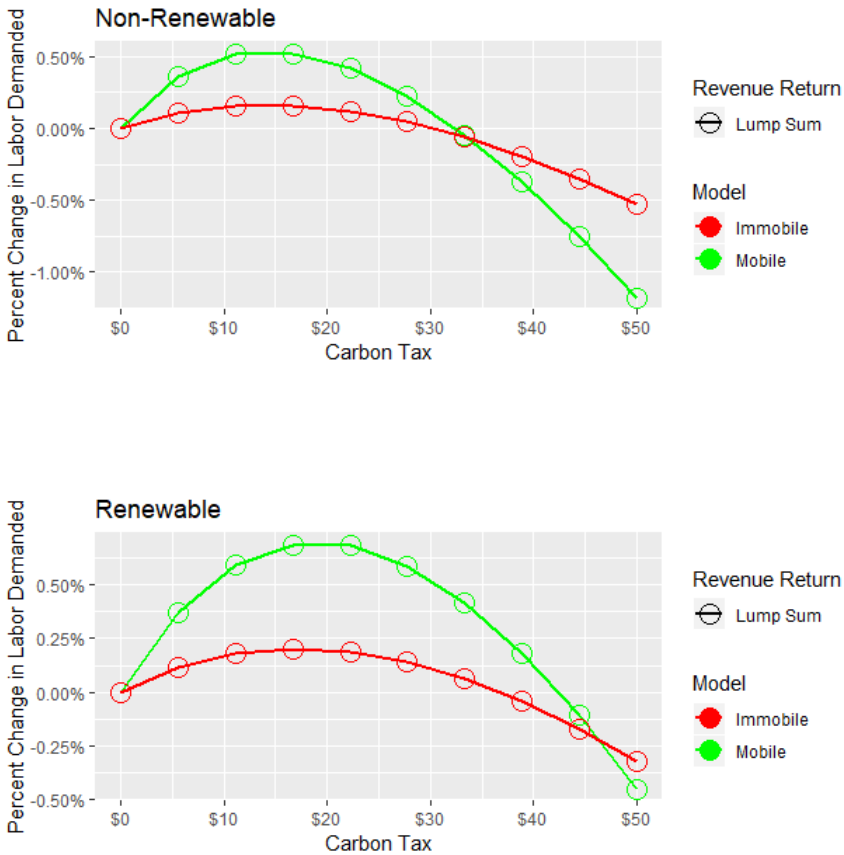


Figure 2: Results for lump sum transfer

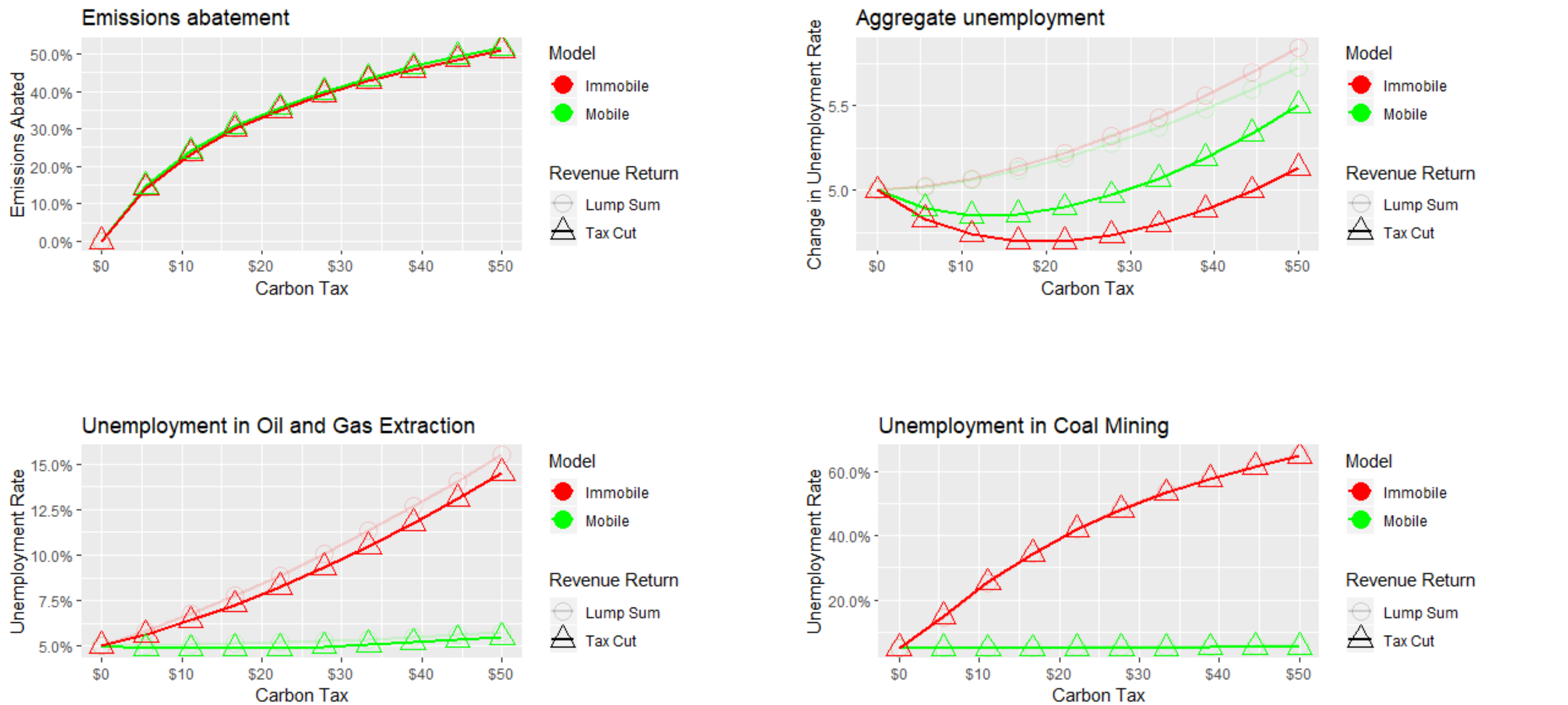
Notes: These graphs show the results for a carbon tax of varying levels with a lump sum transfer return to individuals. The first panel shows the predicted amount of emissions abatement on the vertical axis. The second panel shows the predicted change in the aggregate unemployment rate from the base level (5%). The bottom two panels show the change in the unemployment rate for the two polluting industries in our model.

Figure 3: Labor demand changes in electricity sectors under lump sum transfer



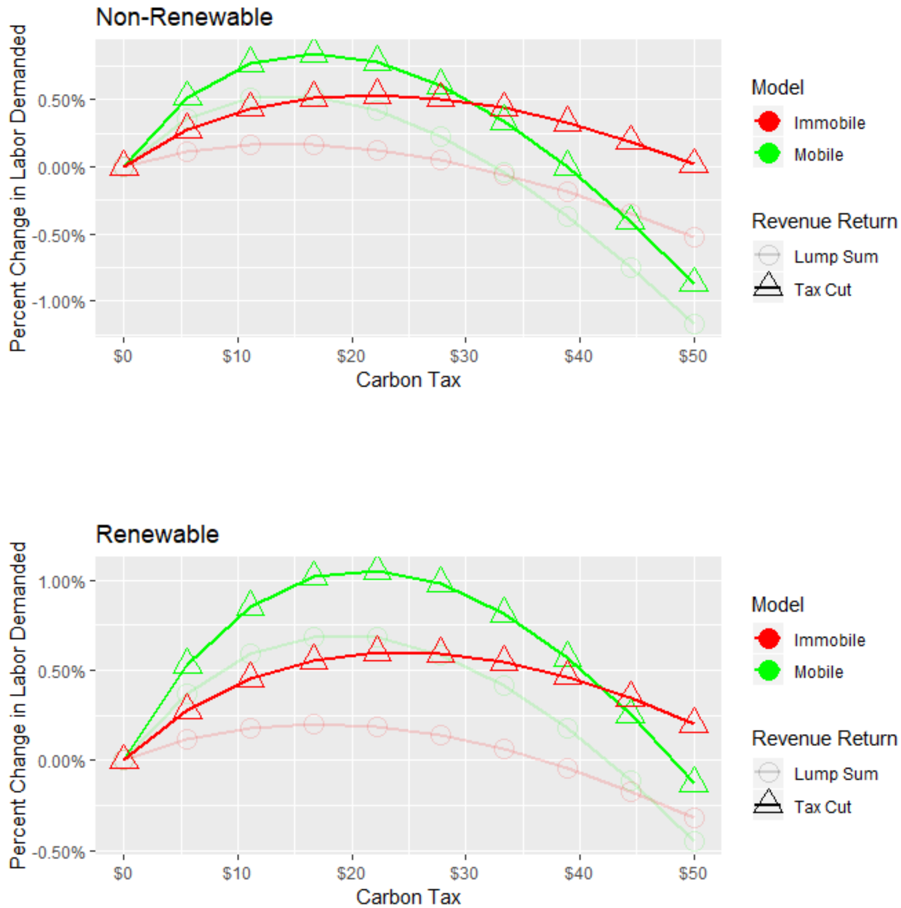
Notes: These graphs show the change labor demands for the non-renewable and renewable electricity sectors from differing levels of a carbon tax. The vertical axis is the percent change from the baseline case. Revenue here is returned lump sum to the households in the model.

Figure 4: Results for aggregate tax cut



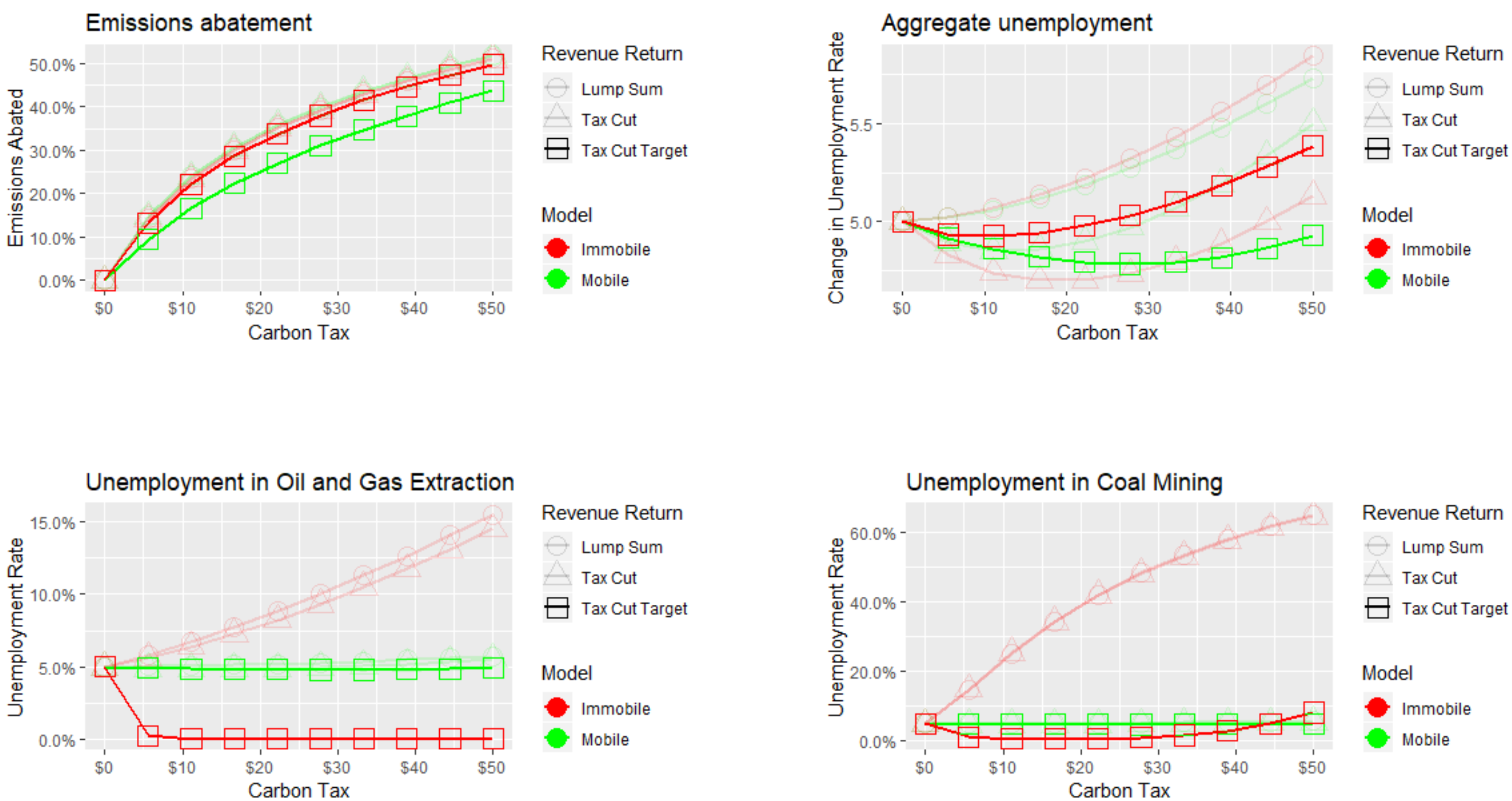
Notes: These graphs show the results for a carbon tax of varying levels with revenues returned by a cut the labor tax rate for all industries. The first panel shows the predicted amount of emissions abatement on the vertical axis. The second panel shows the predicted change in the aggregate unemployment rate from the base level (5%). The bottom two panels show the change in the unemployment rate for the two polluting industries in our model. Faded lines are results from previous graphs for comparison.

Figure 5: Labor demand changes in electricity sector under aggregate tax cut



Notes: These graphs show the change labor demands for the non-renewable and renewable electricity sectors from differing levels of a carbon tax. The vertical axis is the percent change from the baseline case. Revenue here is returned via an aggregate tax cut (i.e. an equal cut for all sectors).

Figure 6: Results from targeted tax cut



Notes: These graphs show the results for a carbon tax of varying levels with revenues returned by a cut the labor tax rate for the polluting industries. The first panel shows the predicted amount of emissions abatement on the vertical axis. The second panel shows the predicted change in the aggregate unemployment rate from the base level (5%). The bottom two panels show the change in the unemployment rate for the two polluting industries in our model. Faded lines are results from previous graphs for comparison.

Figure 7: Results from command and control policy

Notes: These graphs show the results for a command and control policy, where abatement levels are set by the government. The first panel shows the shadow price calculated on emissions on the vertical axis. The second panel shows the predicted change in the aggregate unemployment rate from the base level (5%). The bottom two panels show the change in the unemployment rate for the two polluting industries in our model. Faded lines are results from the carbon tax with lump sum return for comparison.

Appendix

Table A1: Variance in equilibria due to numeraire selection

Sector	Variance in Labor Demands	Variance in Capital Demands
Oil & Gas Extraction	1.058	0.756
Coal Mining	0.991	0.890
Non-Renewable Electricity	0.575	0.180
Renewable Electricity	0.556	0.160
Natural Gas	0.381	0.028
Mining	0.725	0.377
Agriculture	0.725	0.369
Construction	0.236	0.677
Manufacturing	0.374	0.034
Chemicals	0.615	0.240
Services	0.547	0.159
Government	3.724	4.302

Note: This table presents the variance in outcomes for sectoral labor and capital demands across simulations with different numeraire assumptions.

Table A2: Predicted change in capital demands for Oil and Gas Extraction under different numeraire choices

Sector Chosen as Numeraire	Change in Capital Demand in Oil and Gas Extraction Sector
Oil & Gas Extraction	-18.00%
Coal Mining	-20.96%
Non-Renewable Electricity	-18.17%
Renewable Electricity	-17.54%
Natural Gas	-18.63%
Mining	-17.68%
Agriculture	-17.52%
Construction	-17.24%
Manufacturing	-17.60%
Chemicals	-17.71%
Services	-17.25%
Government	-16.88%

Note: This table presents the predicted change in capital demand in the oil and gas extraction sector from a carbon tax under 12 different numeraire assumptions.

Table A3: Predicted change in emissions under different numeraire choices

Numeraire Price	Coal Mining	Oil and Gas Extraction
1	-76.47%	-24.06%
2	-78.31%	-26.58%
3	-76.44%	-24.13%
4	-75.95%	-23.56%
5	-76.79%	-24.55%
6	-76.03%	-23.67%
7	-75.86%	-23.50%
8	-75.45%	-23.14%
9	-75.81%	-23.50%
10	-76.04%	-23.68%
11	-75.53%	-23.18%
12	-74.99%	-22.72%

Note: This table presents the predicted change in carbon emissions from the oil and gas extraction sector and the coal mining sector from a carbon tax, under two different ways of modeling the carbon tax (ad valorem and per unit) and under 11 different numeraire assumptions.