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ABSTRACT

This paper assesses the use of full-employment computable-general equilibrium (CGE) models to predict the labor-market effects of environmental policy. Specifically, it compares the predictions of a standard full-employment CGE model with those of a new search-CGE model with labor-search frictions and resulting unemployment (but that is otherwise identical to the full-employment model). The search-CGE captures key labor market details, including a distinction between the extensive margin of labor demand (the number of employees) and the intensive margin (the number of hours each employee works). We find that some key results are robust across the two models, such as the reallocation of labor across sectors in response to a carbon tax and the overall change in total labor demand. However, the full-employment model seriously overestimates the economy-wide net change in the number of jobs (by a factor of more than 2.5 for a carbon tax with revenues returned lump-sum to households, and by a factor of almost 3.5 when carbon tax revenues are used to reduce payroll taxes).

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1. Introduction

On June 1, 2017, in a speech announcing that the United States would exit the Paris agreement, President Trump cited estimates from a study by NERA Economic Consulting, claiming that "compliance with the terms of the Paris accord … could cost America as much as 2.7 million jobs in 2025."[1] However, that study (Bernstein et al. (2017)) relies on a computable general equilibrium (CGE) model of the US economy that, like almost all CGE models used for policy analysis, assumes full employment.[2] How can a full-employment model predict job losses? Can we trust those estimates? And given that full-employment CGE models are widely used to examine environmental policy, how should we view other estimates from those models?

Full-employment CGE models have numerous shortcomings for analyzing labor-market effects of policy. First, full-employment models assume that labor markets fully clear, and thus fail to account for frictional, structural, or cyclical unemployment. Second, full-employment models aggregate labor into total hours worked, and thus do not distinguish between the number of employees (the extensive margin) and the number of hours each employee works (the intensive margin). As a result, full-employment models can model changes in the total hours of work demanded by each sector, but not changes in the number of workers in each industry. Finally, changes in the total quantity of labor in full-employment CGE models are typically driven by changes in labor supply (a representative household choosing to work less through a labor-leisure choice). However, in the absence of any other way to generate "job loss" estimates, some CGE practitioners convert changes in labor quantity into "full-time equivalent" (FTE) jobs by dividing by a constant hours/FTE worker figure and report the change in FTE jobs as a "job loss" or "job gain." This implies that the percentage change in "jobs" under this method equals

[1] https://www.washingtonpost.com/news/the-fix/wp/2017/06/01/transcript-president-trumps-remarks-on-leaving-the-paris-climate-deal-annotated/?utm_term=.415fb02bb2b0.

[2] There are other issues related to the NERA study and its use to justify leaving the Paris accord. Indeed, a subsequent NERA press release stated that "NERA's study was not a cost-benefit analysis of the Paris Agreement, nor does it purport to be one" (http://www.nera.com/news-events/press-releases/2017/nera-economic-consultings-study-of-us-emissions-reduction-polici.html). Our paper focuses on the broader issue of using a full-employment model to estimate labor market effects of policy, and thus does not address those other issues.

the percentage change in total hours.[3]

The primary goal of this paper is to assess the use of full-employment models to predict the effect of environmental policies (or any other government policy) on both aggregate employment and employment across sectors. Specifically, we ask which results from such models are robust to the inclusion of a more realistic model of the labor market and which are not. To do this, we extend a multisector full-employment CGE model to include a labor-search friction as in Hafstead and Williams (2018). This change both introduces frictional unemployment and allows us to disaggregate total labor demand for each sector into workers and hours per worker. We impose a carbon tax as a sample environmental policy in both our search-CGE model and the otherwise identical full-employment CGE model. We then evaluate where the two models produce similar labor market outcomes and where they differ, with a focus on the key mechanisms driving the differences across models.

We find that estimated changes in the aggregate quantity of labor are very similar across models, suggesting that adding frictional unemployment does not significantly alter the aggregate result: the search-friction model picks up changes in involuntary unemployment, but these are offset by a somewhat smaller voluntary labor-supply response to policy, leaving the overall result almost unchanged. However, we find that FTE calculations significantly overestimate changes in the number of employed workers caused by environmental policies or tax policies, because the FTE approach misinterprets changes in hours per worker (which go in the same direction as the change in the aggregate number of workers) as a larger change in the number of workers. In our central case comparisons, we find that an FTE calculation from the full-employment model overestimates both the job loss from a carbon tax with lump-sum rebates and the offsetting job gain from using carbon tax revenues to reduce labor tax rates, in each case by a factor of over 2.5. Interestingly, the FTE approach still works reasonably well for estimating sector-level changes in jobs, because those sector-level changes are driven primarily by demand shifts across sectors, which are similar between models, and those

[3] For example, assume that a policy reduces total labor demand (in hours) in a given industry by 10 percent and that the industry employs 100,000 workers. The FTE calculation would imply job losses of 10,000. Note that this calculation implicitly assumes that all adjustment in total hours is on the number of workers by implicitly assuming that hours per worker are unchanged.

shifts are much larger in magnitude (for the typical sector) than changes in hours per worker.

This paper makes two main contributions relative to prior work. First, by showing which employment-related results from environmental CGE models are robust to a more realistic model of the labor market and which are not, the paper provides useful guidance for how much trust one should place in predictions from such models. And second, the paper substantially advances the development of search-friction environmental CGE models, moving beyond the highly stylized one- and two-sector models currently in the literature (e.g., those in Shimer 2013, Aubert and Chiroleu-Assouline 2017, and Hafstead and Williams 2018) to a more detailed many-sector model.

The next section of this paper describes both the search-CGE model and the parallel full-employment model. Section 3 explains the data and the calibration of the model. Section 4 compares the central-case results between the two models. Section 5 considers extensions to the baseline models, and Section 6 concludes.

2. Two Numerical Models

Our search-CGE model is an extension of the two-sector model in Hafstead and Williams (2018). The key element of this model is the inclusion of a search friction as in Pissarides (1985) and Mortensen and Pissarides (1994). The search friction introduces labor market dynamics and unemployment into the model. Firms incur costs (in the form of workers devoted to recruiting) of finding workers. When there is a match between a firm and an unemployed worker, they negotiate over the wage and hours, and the worker begins work in the next period. Workers become unemployed through an exogenous job destruction rate. In equilibrium, the job creation and job destruction processes determine the unemployment rate.

The search-CGE model extends the highly stylized two-sector Hafstead and Williams model in four significant respects. First, we add an explicit government sector that produces government services. Federal, state, and local governments employ more than 16 percent of all employees, and we allow for the government to face the same matching problem as private industries. Second, we disaggregate the private sector into

22 industries, and we allow those industries to vary along a wider range of dimensions, whereas in Hafstead and Williams (2018) the industries differ in size and pollution intensity, but are otherwise symmetric. Third, we allow for intermediate inputs into production, which allows us to examine not just how emissions taxes affect the taxed industry, but also effects on upstream and downstream sectors. This also allows us to model emissions reductions via substitution across intermediate inputs in the production function. Fourth, we introduce a foreign economy that engages in international trade with the domestic economy, allowing us to investigate the role of trade in the employment impacts of environmental models.

We compare that model to a parallel full-employment model. The full-employment is identical to the search-CGE model except for the search friction. In the full-employment model, the labor market always clears, with the wage adjusting such that the hours of labor the household wants to supply always equals total labor demand from firms. We maintain the same specification for government and the same production nest with intermediate inputs.

2.1. Search-CGE Model

2.1.1. Matching Process

The matching process follows Hafstead and Williams (2018), which in turn is a multisector generalization of Shimer (2010). The measure of workers is normalized to 1. The total number of workers in sector *j* is n_j.[4] Total employment is $\bar{n} = \sum_j n_j$ and the measure of unemployed workers, the unemployment rate, is $1-\bar{n}$. Let v_j denotethe number of recruiters employed in each sector. The total number of matches in each sector j, m_j, is a function of total recruiting effort in sector *j*, total recruiter effort in all industries, and the number of unemployed workers (who search indiscriminately across

[4] We use subscript *j* (and *k*) to refer to sectors generally (private or public). Subscript *i* refers to the private sector industries, and subscript *g* refers to the public sector.

sectors). Following Hafstead and Williams, we employ a multisector constant-returns-to-scale matching function,

$$m_j = \upsilon_j(1-\bar{n})^{\gamma_j}(v_j h_j)\left(\sum_k v_k h_k\right)^{-\gamma_j} \tag{1}$$

where υ_j and γ_j are the matching efficiency and match elasticity parameters and $v_j h_j$ represents the total recruitment effort (number of recruiters times hours worked) for sector *j*. Matches are increasing in the number of unemployed workers and the sector's own recruitment efforts but are decreasing in other sectors' recruitment efforts. In other words, matches in a given sector are increasing in supply (unemployed workers) and demand from that sector, but decreasing in the level of competition from other sectors for those workers. Note that if all sectors have the same υ_j and γ_j parameters, this matching function implies that the total number of job matches ($\sum_j m_j$) will be a Cobb-Douglas function of the number of unemployed workers and the aggregate level of recruiting effort.

Let H_j denote recruiter productivity in sector *j* (the number of sector-*j* workers that can be hired with one unit of recruiting effort), and let ϕ_j denote the probability an unemployed worker finds a job in sector *j*. By definition, the total number of matches must be equal to both recruitment effort times recruiter productivity, $m_j = (v_j h_j)H_j$, and the number of unemployed workers times the probability of finding a job, $m_j = (1-\bar{n})\phi_j$. Using equation (1), we can define sectoral recruiting productivity and the sectoral job finding probability as

$$H_j = \upsilon_j(\bar{\theta})^{-\gamma_j} \tag{2}$$

$$\phi_j = \upsilon_j \theta_j (\bar{\theta})^{-\gamma_j} \tag{3}$$

where $\theta_j = (v_j h_j)/(1-\bar{n})$ is the sector-specific ratio of recruiting effort to unemployed workers and $\bar{\theta} = \sum_j \theta_j$ represents the ratio of total recruiting effort to unemployed workers. The latter term is often referred to as labor market tightness in the search-and-matching literature: if the market becomes tighter on aggregate through either fewer unemployed workers or more recruitment effort, employers find it harder to fill jobs, whereas workers are more likely to find a job.

2.1.2. Households

As is standard in the search-and-matching literature, we use a representative household framework (see, for example, Merz 1995). A representative household is also standard in the full-employment CGE literature (see, for example, Goulder et al. 2016). In the search-CGE model, this framework assumes full insurance across workers such that the marginal utility of consumption is constant across workers regardless of past or current employment status. Workers in industry *j* work h_j hours and receive an hourly wage w_j. Hours and wages are bargained between employees and employers each period as described in Section 2.1.5, and therefore hours and wages are independent of length of employment. Unemployed workers work zero hours but receive unemployment compensation, b. In our policy simulations, unemployment compensation is held fixed in real terms such that any policy-induced change in employment is not due to changes in unemployment compensation. The households own the firms and have access to state-contingent claims, B, where Q denotes the price of an Arrow security that delivers one unit of consumption in the subsequent period. As is standard in both full-employment multisector CGE models and one-sector search-and-matching models, household utility is increasing in aggregate consumption, $\bar{C}$, and decreasing in hours worked. Here we use a separable utility function in aggregate consumption and hours,

$$U(\bar{C},h) = \log(\bar{C}) - \psi \frac{h^{1+\chi}}{1+\chi} \tag{4}$$

where ψ represents the labor disutility parameter and $(1/\chi)$ represents the Fritsch elasticity of labor supply. For simplicity, we assume that the disutility of labor does not vary across sectors.

Aggregate consumption is a constant elasticity of substitution (CES) composite of consumption of each industry-specific good, which itself is a composite of domestically produced and foreign-produced goods. Given this constant-returns-to-scale nest, demand for industry-specific consumption and the domestic-foreign mix of consumption for each good can be solved for independently of aggregate consumption. Given the domestic and foreign price for each good, p_i^d and p_i^f, and the exchange rate e, consumers choose an optimal domestic-foreign mix for each good to minimize the unit cost of the consumption, $\hat{p}_i$. Given the price of each consumption good, the household then chooses the mix of consumption goods to minimize the unit cost of aggregate consumption, $\overline{p}$.[5]

Given the distribution of workers at the beginning of the period, the bargained levels of wages and hours, the current level of assets, and the expected job-finding probability, households choose aggregate consumption and future assets to maximize life-time discounted utility

$$V(B,n_j)=\max_{\bar{C},B'}\left\{\sum_j U(\bar{C},h_j)+(1-\bar{n})U(\bar{C},0)+\beta E\left[V(B',n_j')\right]\right\} \tag{5}$$

subject to the budget constraint,

$$\overline{p}\bar{C}+QB'\leq\sum_j(1-\tau_L)n_jw_jh_j+(1-\bar{n})\overline{p}b+B+T \tag{6}$$

and the law of motion for employment by sector

$$n_j'=(1-\pi_j)n_j+\phi_j(1-\bar{n}),\ \forall\ j \tag{7}$$

where β is the discount factor, τ_L is the tax rate on labor income, T is government lump-sum transfers (taxes if negative), and π_j is the exogenous rate of job destruction in sector j each period.

The first-order condition with respect to future assets and the envelope condition with respect to current assets are

$$\begin{aligned}\lambda Q&=\beta V_B'\\ V_B&=\lambda\end{aligned} \tag{8}$$

respectively, where λ is the Lagrange multiplier on the budget constraint and V_B is the marginal value of an additional worker. Combining these first-order conditions, the Euler equation expresses the value of the Arrow security,

$$Q=\beta\frac{\lambda'}{\lambda}. \tag{9}$$

The first-order condition with respect to consumption determines aggregate consumption,

[5] See the appendix for a complete derivation of consumer good demand problem.

$$U_c = \overline{p}\lambda \tag{10}$$

where U_c denotes the derivative of utility with respect to consumption.

In search-and-matching models, a key variable is the value of employment in each sector to the household. This value is expressed as the difference between the value of a worker in sector *j* and the value of being unemployed,

$$V_{n_j} = U(\overline{C},h_j) - U(\overline{C},0) + \lambda\left[(1-\tau_L)w_j h_j - \overline{p}b\right] + (1-\pi_j)\beta EV'_{n_j} - \overline{\phi} \tag{11}$$

The value of employment is equal to the utility and compensation differentials between employed workers in sector *j* and unemployed workers, plus the continuation value of being employed in the next period, less the opportunity cost of being employed, $\overline{\phi} = \beta\sum_j \phi_j EV'_{n_j}$. This opportunity cost plays a key role in the wage-bargaining process described in Section 2.1.5, as workers are more likely to value a job in sector *j* if jobs in other sectors are harder to get or become less valuable as a result of environmental policy.

2.1.3. Private Industry

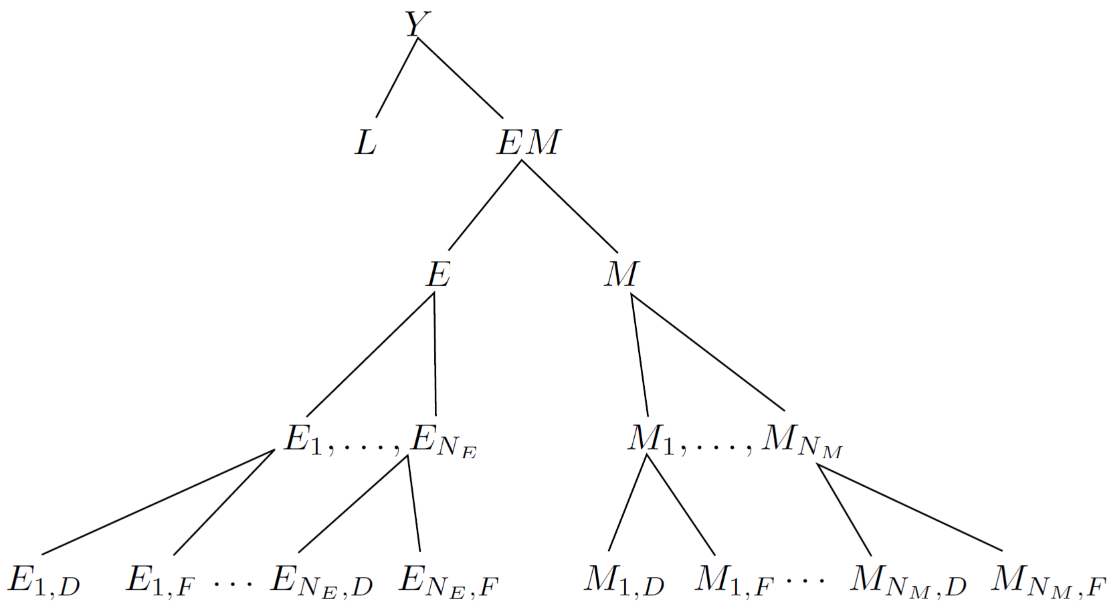
The private sector is represented by 22 distinct industries. In each industry, a representative firm produces a specific good using a nested CES production function that utilizes labor and intermediate inputs. The industries are listed in Table 1 in section 3.1. Each is classified as either an energy industry (E) or a materials industry (M). Oil&gas extraction, Coal mining, Electric power, Natural gas distribution, and Petroleum refining and coal products are all classified as energy industries, and the remaining industries, including government enterprises, are classified as materials industries.

Figure 1 displays the nested production function for each representative firm. At the bottom level, domestic and foreign intermediate inputs are aggregated into an intermediate input composite. The intermediate input composites are aggregated into energy and material input composites. Then these energy and material input composites are aggregated into an aggregate intermediate input composite. At the top level, labor and the aggregate intermediate input composite are combined to produce the final good. The outer nest of the production function is

$$y_i = f_i(h_i l_i, I_i) \tag{12}$$

where l_i is the number of workers devoted to production, the total number of workers less the number of recruiters, $l_i = n_i - v_i$, and I_i denotes the aggregate intermediate input composite.

Figure 1. Diagram of the Nested Production Function



Given the nested production structure, the representative firm chooses inputs at each level of the nest to minimize unit prices for each nest. Therefore, given the unit price for the aggregate intermediate input composite for each industry, $\overline{p}_i^I$, firms solve for the optimal inputs of labor and aggregate intermediate inputs independently of the choices at each lower nest. The complete description of cost-minimizing input decisions is described in the appendix.

Firms inherit a stock of workers each period, n_i. In each period, firms allocate workers between production and recruitment. Let $\overline{v}_i = v_i / n_i$ denote the recruiter ratio (the fraction of workers allocated to recruitment). Output can then be defined in terms of the stock of workers and the recruiter ratio, $y_i = f_i(h_i n_i (1-\overline{v}_i), I_i)$. Firms must trade off between more production today and making more new hires today (which enables more production in the future), taking as given the endogenous recruitment productivity, H_i.

Firms choose the recruiter ratio and aggregate intermediate inputs to maximize the value of the firm; as the household owns the firms, future-period profits of all firms are discounted at the discount factor *Q* from the household problem (a no-arbitrage condition guarantees the same rate of return on ownership of private-sector firms). For each industry *i*, the Bellman equation is

$$J(n_i) = \max_{I_i, \overline{v}_i \geq 0} \left\{ p_i^d f_i(h_i n_i (1-\overline{v}_i), I_i) - (1+\tau_P) h_i n_i w_i - \overline{p}_i^I I_i + E\left[QJ(n_i') \right] \right\} \tag{13}$$

and the equation of motion for employment is

$$n_i' = (1-\pi_i) n_i + H_i \overline{v}_i h_i n_i . \tag{14}$$

where p_i^d represents the producer price for the good produced by industry *i*, and τ_P represents employer payroll taxes. Firms set total aggregate intermediate inputs to satisfy the first-order constraint,

$$p_i^d f_{I,i} = \overline{p}_i^I \tag{15}$$

where $f_{I,i}$ denotes the derivative of the outer-nest function with respect to aggregate intermediate inputs.

Firms add recruiters until the marginal cost of additional recruiting equals the benefit of recruiting $H_i h_i$ new workers for the following period; the first-order condition is

$$p_i^d f_{L,i} = H_i E\left[QJ'_{n_i} \right] \tag{16}$$

where $f_{L,i}$ represents the marginal value of an additional hour of production, and $E\left[QJ'_{n_i} \right]$ denotes the current period value of an additional worker in the following period. The value of an additional worker is equal to the marginal revenue of an additional worker, less the compensation, plus the expected value of the worker in the following period, conditional on the worker not separating from the firm. From the envelope condition with respect to the number of workers, the marginal value of an additional worker for a firm is

$$J_{n_i} = p_i f_{L,i} h_i - (1+\tau_P) w_i h_i + (1\text{-}\pi_i) E\left[QJ'_{n_i} \right] . \tag{17}$$

2.1.4. Government

The representative government serves two purposes. First, the government produces public goods. Second, the government collects labor and payroll taxes and pays unemployment benefits to unemployed workers. Public goods are produced using a nested production structure identical to that of the private firms. The outer nest of the government function is

$$g = f_g(h_g l_g, I_g) \tag{18}$$

where l_g is the number of workers devoted to production, the total number of workers less the number of recruiters, $l_g = n_g - v_g$, and I_g denotes the aggregate intermediate input composite. For simplicity, we assume that the level of total public goods production, g, is exogenously fixed.

Identically to the private firms, the government chooses inputs at each level of the nest to minimize intermediate input costs. Let $\overline{p}_g^I$ denote the unit price of intermediate inputs. Given a stock of workers n_g, the problem of the government is to choose recruitment and aggregate intermediate inputs to minimize the cost of providing the fixed level of public goods. The problem of the government can be written as

$$G(n_g) = \max_{I_g, \overline{v}_g \geq 0} \left\{ -(1+\tau_P) h_g n_g w_g - \overline{p}_g^I I_g + E\left[QG(n_g') \right] \right\} \tag{19}$$

subject to equation (18) and the law of motion for employment

$$n_g' = (1-\pi_g) n_g + H_g \overline{v}_g h_g n_g \ . \tag{20}$$

The government takes as given the endogenous recruiter productivity, H_g. The first-order condition for the government sector intermediate inputs is

$$p_g f_{I,g} = \overline{p}_g^I \tag{21}$$

where p_g^d refers to the shadow value on the domestic government constraint that public goods production must be (greater or) equal to g. The first-order condition with respect to government recruitment is

$$p_g^d f_{L,g} = H_g E\left[QG_n' \right] \tag{22}$$

Here, $f_{L,g}$ represents the marginal value of an additional hour of government production, and $E\left[QG'_n\right]$ denotes the current period value of an additional worker to the government in the following period.[6] The marginal value of an additional worker is

$$G_n = p_g^d f_{L,g} h_g - (1+\tau_P) h_g w_g + (1-\pi_g) E\left[QG'_n\right] \tag{23}$$

The government must satisfy a government budget constraint each period such that lump-sum transfers are equal to the difference between total tax revenue and total spending (on unemployment benefits, labor costs, and intermediate inputs costs)

$$T = \sum_j (\tau_L + \tau_P) h_j w_j n_j - (1-\overline{n})\overline{p}b - (1+\tau_P) h_g n_g w_g - \overline{p}_g^I I_g \tag{24}$$

2.1.5. Wage Bargaining

In each period, both private firms and the government enter a bargaining process with their workers (either those previously employed or those newly hired) to determine hours and wages. Following Hafstead and Williams (2018), we assume a Nash bargaining process in which employers and employees set working hours to maximize the surplus value of a match (the combined value of the worker to the firm and the job to the worker), and set the wage to split that surplus according to bargaining shares.[7] Maximizing the match surplus implies that the marginal value of an additional hour of work to the firm is equal to the disutility of an additional hour of work to the worker. Hours must satisfy the following condition for each sector (public and private):

$$(1-\tau_L)\lambda p_j^d f_{L,j} = (1+\tau_P)\psi h_j^{chi} \tag{25}$$

Following Hafstead and Williams, the equilibrium after-tax pay for a worker in sector j is

$$\begin{aligned}(1-\tau_L) h_j w_j = \frac{1-\tau_L}{1+\tau_P}(1-\eta)&\left[p_j^d f_{L,j} h_j + \sum_k p_k^d f_{L,k}\theta_k\right] \\ +\eta&\left[\frac{\psi}{\lambda}\frac{h_j^{1+\chi}}{1+\chi} + \overline{p}b\right]\end{aligned} \tag{26}$$

[6] Additional workers are valuable to the government to the extent that they ease the constraint that public goods production must be greater or equal to *g*.

[7] For a complete description of the bargaining problem, see Shimer (2010) for a one-sector model. The government Nash bargaining problem mirrors the private-sector problem, replacing market-clearing prices with the shadow value of the government production constraint.

where η refers to the bargaining power of the employer. The wage is increasing in the marginal revenue of an additional employee, how likely unemployed workers are to find jobs, the disutility of work, and the value of unemployment benefits. Those last two determine the flow value of unemployment. As shown by Hagedorn and Manovskii (2008), a high flow value of unemployment relative to after-tax earnings implies small relative changes in the wage and large relative changes in employment in response to changes in the marginal revenue of employment. As environmental policy affects the marginal revenue of employment in certain industries, this flow value will be important in determining the equilibrium employment response in the search-CGE model.

2.1.6. Foreign Economy

A single foreign economy represents the rest of the world (ROW). The foreign economy mirrors the domestic economy in all respects, although the scale of the ROW economy is larger. Workers match with jobs in 22 private-sector industries (each with a single representative firm) or the government sector. The representative household consumes a mix of foreign or domestic produced goods, chosen to minimize the cost of the aggregate consumption good, and chooses aggregate consumption to maximize household utility, conditional on wages, hours, and job-finding probabilities. The foreign sectors also utilize a mix of domestic and foreign goods as part of the intermediate input cost minimization problem. Firms choose recruitment and total intermediate inputs to maximize the value of the firm over time, conditional on the current stock of workers, wages, hours, and the recruiter productivity, and the government makes similar decisions to minimize the cost of providing a fixed quantity of public goods. Workers and firms bargain over hours and wages in the same manner as in the domestic economy.

The price of foreign goods is denoted by p_i^f. The exchange rate, *e*, converts domestic currency into the foreign currency such that the prices for domestic goods faced by the foreign agents are $p_i^d e$ and the prices for foreign goods faced by domestic agents are p_i^f / e. We assume balanced trade, with the exchange rate adjusting such that the values of imports and exports are equal in each period, as defined in the discussion of market-clearing below.

2.1.7. Market Clearing

Markets clear for each private good when total output equals consumption of domestically produced goods plus total intermediate input use plus government intermediate inputs plus exports. Let c_i^d denote the domestic household demand for goods produced by domestic sector *i*. Let $\overline{I}_i^d$ denote domestic intermediate input demand for goods produced by domestic sector *i* (as opposed to I_i, the aggregate intermediate input composite for sector *i*) and let $\overline{I}_i^g$ denote domestic government spending on intermediate inputs from domestic sector *i*. Finally let ex_i denote total exports (to both the foreign households and foreign industry) from domestic sector *i*. Domestic prices p_i^d adjust to clear domestic markets, with the condition

$$y_i = c_i^d + \overline{I}_i^d + \overline{I}_i^g + ex_i \tag{27}$$

for each sector *i*.[8]

Let c_i^f denote foreign household demand for foreign good *i*, $\overline{I}_i^f$ denote foreign intermediate input demand for goods produced by foreign industry *i*, $\overline{I}_i^{g,f}$ denote foreign government intermediate input demand for goods produced by foreign industry *i*, and im_i denote the domestic imports of foreign goods (by domestic household and domestic industry). Foreign prices p_i^f adjust such that foreign markets clear, with the condition

$$y_i^f = c_i^f + \overline{I}_i^f + \overline{I}_i^{g,f} + im_i \tag{28}$$

for each foreign industry *i*. The exchange rate adjusts to ensure balanced trade, where the total value of exports equals the total value of imports

$$\sum_i p_i^d ex_i = \sum_i (p_i^f / e)\, im_i \tag{29}$$

There is no market for public goods, but the constraint on the provision of the public good introduces a market-clearing-like condition: the shadow price p_g^d is "market-

[8] See the appendix for an exact derivation of elements in the market-clearing conditions.

clearing" if and only if the constraint $g = f_g(h_g n_g(1-\overline{v}_g), I_g)$ is binding. An identical condition holds for the foreign government with shadow price p_g^f.

2.2. Full-Employment Model

To aid in the comparison of our search-CGE models and full-employment models, we build a parallel full-employment CGE (or FE-CGE) model. In most respects the models are identical. Here we specify the key differences.

2.2.1. Households

A representative household chooses consumption, labor supply (in total hours worked), and savings to maximize an intertemporal utility function,

$$V(B) = \max_{\overline{C},\ell,B'} \left\{ \sum_j U(\overline{C},\ell) + \beta E\left[V(B')\right] \right\} \tag{30}$$

subject to the budget constraint

$$\overline{p}\overline{C} + QB' \le (1-\tau_L)w\ell + \text{B-T}. \tag{31}$$

The representative household has the same period utility function in aggregate consumption and labor supply and identical preferences over sector-specific goods.

With the exception of labor supply, the household first-order conditions in the full-employment model are identical to those in the search-CGE model. The first-order condition with respect to labor supply is

$$-U_\ell = w\lambda \tag{32}$$

2.2.2. Private Industries

Representative firms in the private industries have the same production nest as in the search-CGE model. Without specific workers in the full-employment model, the labor input l_i refers to total hours demanded by private industry *i*. The FE-CGE production function is

$$y_i = f_i(l_i, I_i)\,. \tag{33}$$

Given the wage w and optimal intermediate input price, $\overline{p}_i^I$, the first-order conditions for the representative firm from the static profit-maximization problem are

$$p_i^d f_{L,i} = (1+\tau_P)w \tag{34}$$

$$p_i f_{I,i} = \overline{p}_i^I\,. \tag{35}$$

2.2.3. Government

In the FE-CGE model, the government has the same production nest as in the search-CGE model. As with private industries, the labor input l_g denotes total hours demanded by the government sector. The government production function is

$$g = f_g(l_g, I_g)\,. \tag{36}$$

Given the wage and the optimal intermediate input price $\overline{p}_g^I$, the government chooses total labor input and the level of intermediate inputs to minimize the cost of achieving the production constraint. The first-order conditions from the static cost-minimization problem are

$$p_g^d f_{L,g} = (1+\tau_P)w \tag{37}$$

$$p_g^d f_{I,g} = \overline{p}_g^I \tag{38}$$

where again p_g^d denotes the shadow value on the production constraint. The government budget constraint does not include unemployment benefits; total lump-sum transfers are the difference between revenues and spending on inputs (including labor) to provide the public good,

$$T = \sum_j (\tau_L + \tau_P) l_j - (1+\tau_P) l_g - \overline{p}_g^I I_g \tag{39}$$

2.2.4. Market Clearing

The search-CGE market-clearing conditions also apply to the full-employment model. The FE-CGE model adds an additional market-clearing condition: labor market clearing.

The wage rate w adjusts such that total labor demand from all sectors (public and private) equals labor supply from the household,

$$\sum_j l_j = \ell \tag{40}$$

2.3. Emissions and Emissions Taxes

We account for carbon dioxide emissions at the point where domestic and foreign primary fossil fuels—Oil&gas extraction (og) and Coal mining (coal)– first enter as intermediate inputs into production. This accounting method implicitly includes both direct emissions from the combustion of these fuels by the purchasing industry and any emissions from the combustion of secondary fuel outputs sold further downstream to other industries or the household (households do not directly purchase primary fossil fuels). For example, the combustion of refined petroleum products is attributed to the petroleum refiner industry that purchases Oil&gas extraction as an input into production. This accounting method must therefore adjust for the import and export of secondary fuels, such as refined products, such that total emissions are consistent with data for US emissions related to consumption. Total emissions are

$$e = \sum_j \left[\mu_{og,j} I_{og,j} + \mu_{coal,j} I_{coal} \right] + e_{import} - e_{export} \tag{41}$$

where the set of emissions coefficients, μ, are calibrated to match combustion-related carbon dioxide emissions by source, and the emissions associated with the import or export of secondary fuels are represented by e_{import} and e_{export}, respectively. Emissions prices are introduced in proportion to the emissions coefficients on all purchases of primary fossil fuels as intermediate inputs and the imports of secondary fossil fuels.[9]

3. Data and Calibration

Primary data and parameters are combined in both models to create the primary dataset. Secondary parameters (i.e., CES share parameters) are then calibrated to re-create the

[9] Currently, we do not rebate secondary fuel producers for the export of secondary fuels that are combusted abroad.

benchmark year data in the absence of environmental policy. Here we briefly summarize the data sources and primary parameter calibration procedure.

3.1. Data

Both models are calibrated to 2015 data. Data on input use by sector, consumption by households, and labor input by sector are aggregated from the 2015 Bureau of Economic Analysis (BEA) Make and Use Tables from the Annual Industry Accounts.[10] Industry-specific separation rates are derived by averaging monthly total separation rates for each industry grouping in the Job Opening and Labor Turnover Survey from the Bureau of Labor Statistics. Table 1 displays these industry-specific separation rates. We calibrate emissions coefficients to match emissions data from the Energy Information Administration (EIA).

We assume that the foreign economy is symmetric to the domestic economy, but is three times larger than its domestic counterpart.

[10] https://www.bea.gov/industry/io_annual.htm
In some cases, the level of aggregation in the two models in this paper do not correspond one to one with the summary-level industry aggregation in the BEA annual data. In these cases, the detailed-level industry aggregation in the 2007 Benchmark Accounts is used to disaggregate the summary-level data. Inputs of Oil&Gas extraction and Coal mining are revised to be consistent with EIA data on energy inputs and prices by industry.

Table 1. Separation Rates and Labor Share by Industry

Industry	Separation rate	% of total labor compensation
Oil&gas extraction	4.6	0.16
Coal mining	4.6	0.04
Other mining	4.6	0.07
Mining support services	4.6	0.52
Electric power	3.2	0.66
Natural gas distribution	3.2	0.18
Petroleum refining and coal products	2.3	0.17
Water/sewage utilities	3.2	0.03
Agriculture	4.6	0.54
Construction	4.7	5.10
Durable manufacturing	2.0	5.85
Nondurable manufacturing (excl. refining)	2.3	2.95
Wholesale trade	2.4	4.66
Retail trade	4.7	4.95
Transportation and warehousing	3.2	3.17
Information	2.8	2.79
Finance, insurance, real estate (incl. housing)	2.3	8.37
Professional business services	5.2	18.34
Education and health	2.6	12.33
Leisure and hospitality	6.1	4.70
Other services	3.6	3.84
Government (incl. enterprises)	1.5	17.63

3.2. Common Primary Parameters

The time period in the model is one month. The discount factor is calibrated to be consistent with an annual interest rate of 4 percent. In both models, the Frisch elasticity of labor supply is set equal to 1. As discussed in Hall and Milgrom (2008), this represents a middle ground between estimates found for middle-aged men and other single-earner families (0.7) and higher elasticities found for young men and married women. In both models, the disutility of work parameter is calibrated to be consistent with the labor supply elasticity and data on total labor supplied. The tax on labor is set to 0.31, a rate that approximates the average marginal combined federal and state income tax rate plus the employee payroll tax contribution. The payroll tax is set to 0.06, representing the employer share of payroll taxes. We apply an elasticity of substitution across consumption goods to be a conservative 0.75 (full-employment CGE models like that of Goulder and Hafstead 2017 use a value of 1). Elasticities of substitution in production are taken from Jorgenson and Wilcoxen (1996).

3.3. Labor Market Parameters

For labor market parameters in the search-CGE model, we follow Hafstead and Williams (2018) by assuming relatively standard search-friction parameters. We start by using a steady state unemployment rate of 5 percent and a recruiter productivity (H_j) of 25 that is equal across all sectors, and fix hours in the public sector (h_g) such that employees spend one-third of their time working.[11] Following Hall and Milgrom (2008), we set the match elasticity equal to 0.5, and following Shimer (2010), we set the Nash bargaining parameter equal to 0.5.[12]

Conditional on these assumptions, we then implement a calibration procedure to solve for the disutility of work parameter (ψ), the level of unemployment benefits (b), the match efficiency parameter by sector (υ_j), and hours per worker in private sector (h_j) that are consistent with the model equations and asymmetric separation rates across sectors.[13]

4. Comparison of Model Results

Both the search-CGE and FE-CGE models are dynamic, but the FE-CGE model immediately converges to its steady state in the first period of the policy (because it

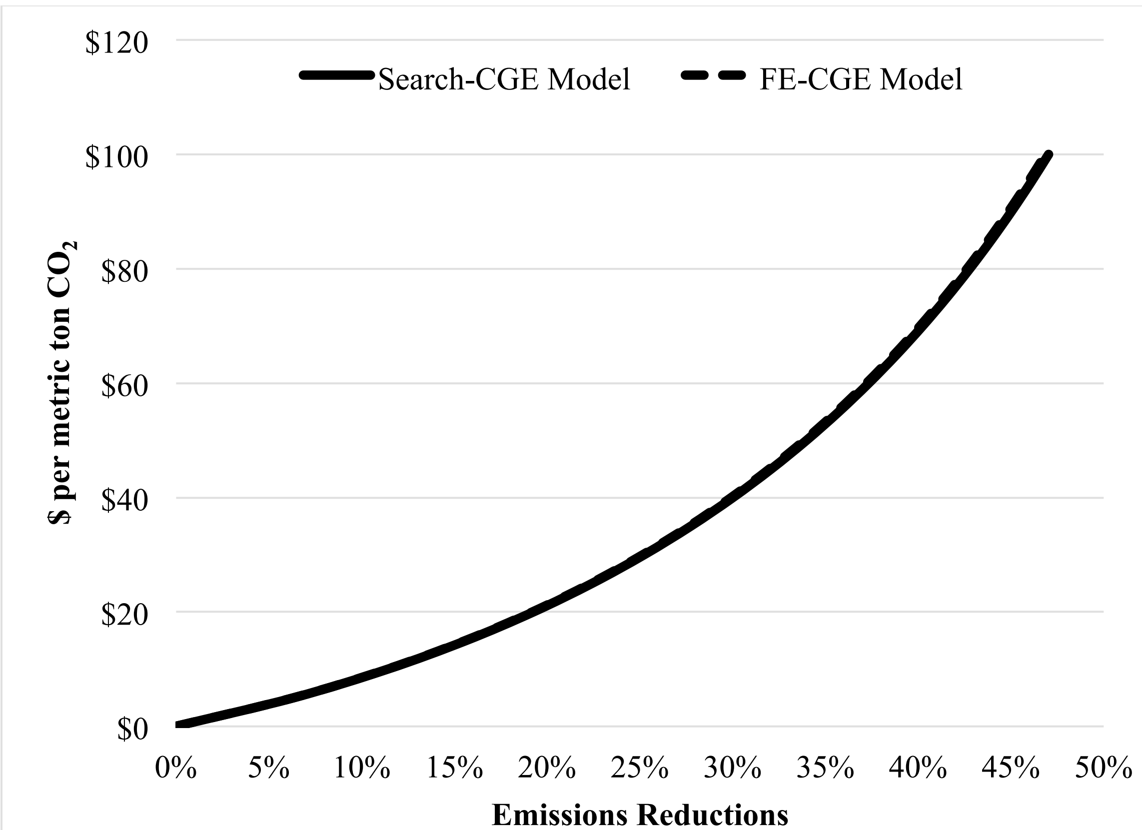
[11] Silva and Toledo (2009) estimate that the cost of recruiting a single worker is equal to approximately 12 percent of a worker's monthly wage. Adjusting for hours (one-third), this implies that one recruiter can hire 25/3 workers per month.

[12] In models without taxes, setting the bargaining parameter equal to the match elasticity ensures the Hosios condition such that the equilibrium level of unemployment is efficient from the social planner's perspective. However, in the presence of preexisting taxes on labor, the Hosios condition does not hold even when these parameters are equal.

[13] This calibration strategy implies that hours per worker vary across sectors because of differences in marginal products of labor and that the marginal value of employment in each sector (V_{n_j}) varies across sectors.

includes no labor adjustment frictions, and neither model incorporates capital). Therefore, we compare only the steady states of the two models. Figure 2 displays how carbon emissions respond to carbon prices (with carbon-pricing revenue returned via lump-sum rebates) across the two models. The two lines are identical, and the differences in labor markets do not affect the elasticity of emissions reductions with respect to the carbon price.

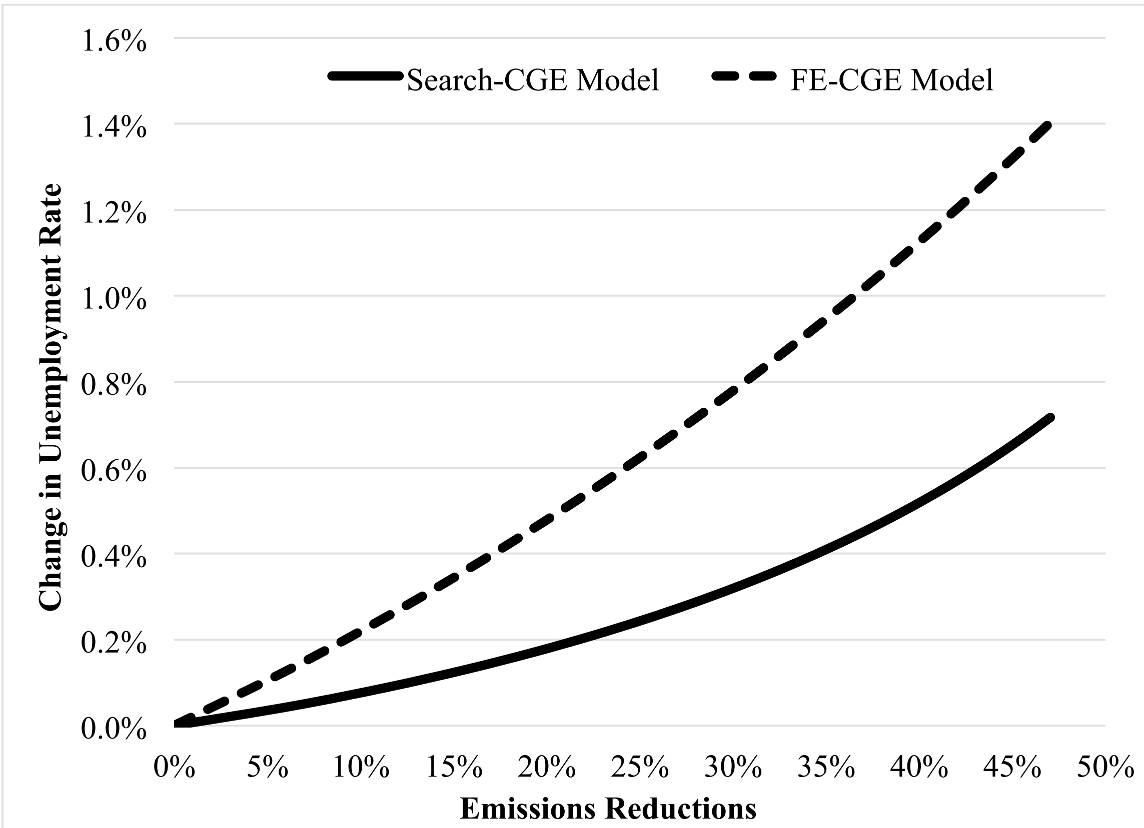
Figure 2. Emissions Reductions by Carbon Price, Lump-Sum Rebates



4.1. Aggregate Employment Impacts

Figure 3 displays one of the central results of our paper: the change in the unemployment rate caused by imposing carbon taxes (with lump-sum rebates) in the two models, and how that varies with stringency (expressed as the level of emissions reductions with respect to reference case emissions). Because the FE-CGE model does not model unemployment, we compute this change based on a FTE-type calculation (similar to the approach in other studies that address employment changes using a full-employment model). First, we calculate the change in FTE jobs that is equivalent to the change in the total quantity of labor from the FE-CGE model. Then we convert that into an implied change in the unemployment rate, holding fixed the size of the labor force and assuming a 5 percent baseline unemployment rate.

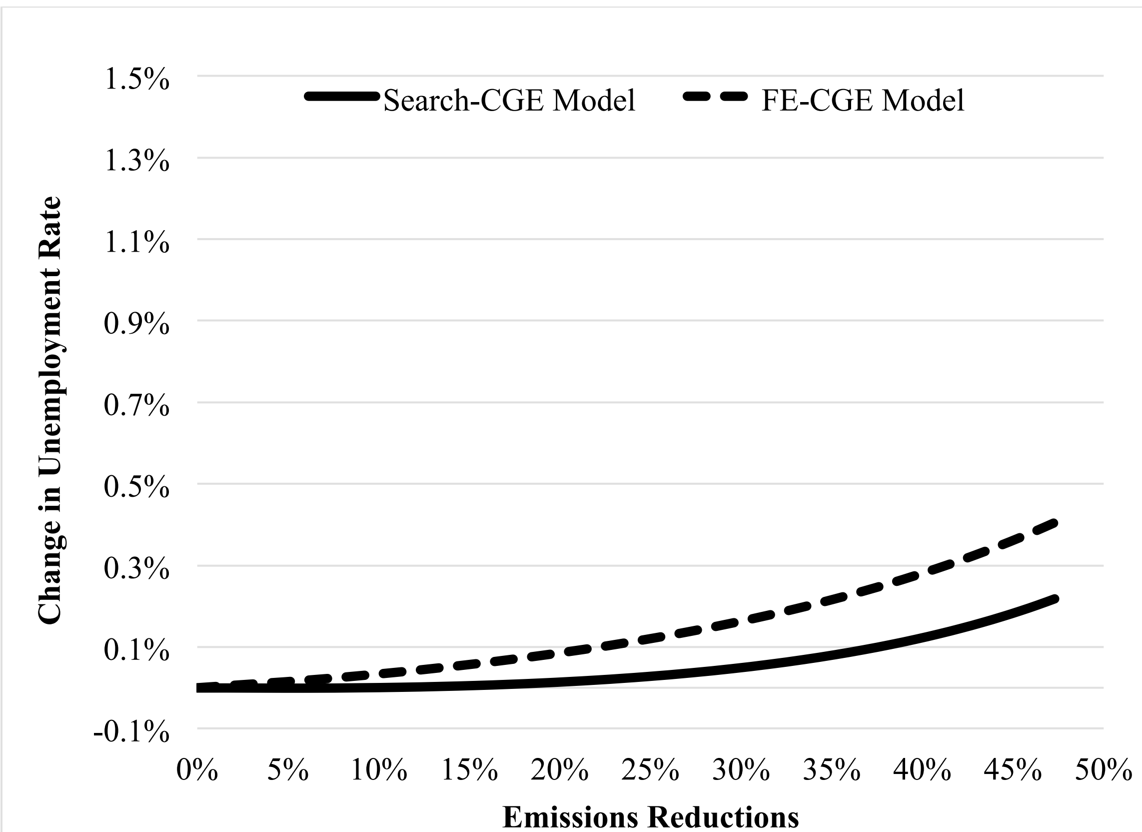
Figure 3. Change in Unemployment Rate by Level of Stringency, Lump-Sum Rebates



In each model, unemployment rises as the environmental policy becomes more stringent, but the FE-CGE model dramatically overestimates the change in the unemployment rate relative to the search-CGE model at all levels of stringency. For example, at 20 percent emissions reductions, the FE-CGE implies an increase in the unemployment rate of about 0.5 percentage points, whereas the search-CGE model implies an increase of 0.2 percentage points—the FE-CGE model estimates an increase 2.5 times greater than the search-CGE model's estimate. On an absolute basis, the difference between the two estimates is increasing with stringency, though the ratio of the two is decreasing with stringency.

Figure 4 makes the same comparison, but with carbon pricing revenue returned via payroll tax cuts instead of lump-sum transfers.[14] Under both models, the change in the unemployment rate is very small if the carbon tax revenue is used to finance reductions in payroll taxes. But again, the FE-CGE model significantly overestimates the employment response to the tax cuts relative to the search-CGE model. In the search-CGE model, the unemployment impact is essentially zero across a range of stringencies. At 20 percent reductions, the unemployment rate increases by slightly more than 0.01 percentage points in the search-CGE model, versus an increase much closer to 0.1 percentage points in the FE-CGE model.

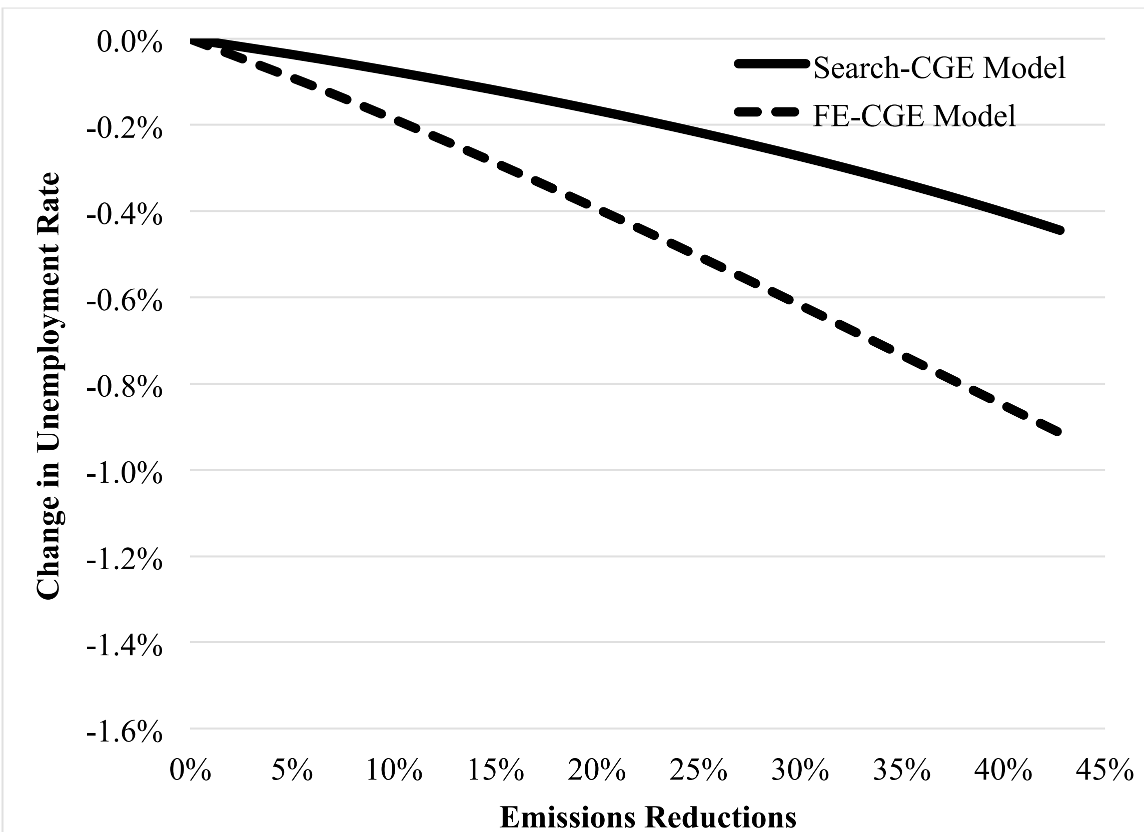
Figure 4. Change in Unemployment Rate by Level of Stringency, Labor Tax Cuts



[14] We define revenue neutrality in each model such that the real value of lump-sum transfers is unchanged from the benchmark calibration. This definition uses revenues to offset both decreases in labor and payroll tax revenues and increases in government spending (on inputs in both models and unemployment benefits in the search-CGE model). Alternatively, we could define revenue neutrality such that revenues are unchanged, with a decline in lump-sum transfers to offset increased government spending. Results with this alternative specification are quantitatively similar.

Figure 5 shows the difference between the responses of the unemployment rate to the environmental policy under lump-sum rebates and under payroll tax cuts, or, in other words, how the payroll tax cuts affect the unemployment rate. These results demonstrate that the revenue-recycling effect on unemployment is much smaller in the search-CGE model than in the FE-CGE model. Therefore, the FE-CGE model, relative to the search-CGE model, overestimates how much unemployment responds to both carbon pricing and payroll tax changes.

Figure 5. Difference in Change in Unemployment Rate between Lump-Sum Rebate and Labor Tax Cuts, by Level of Stringency



4.2. Employment Impacts across Sectors

To investigate the source of the differences in aggregate unemployment impacts across models, we now disaggregate the results along two dimensions, breaking out each of the

23 sectors, and dividing the change in labor supply in the search-CGE model into the change in number of workers and change in hours per worker. Table 2 displays those disaggregated results for a $40 carbon tax with lump-sum rebates.[15]

Table 2. Long-Run Changes in Workers, Hours per Worker, and Total Labor Input

$40 Carbon Tax with Lump-Sum Rebates

	Search-CGE Model			**FE-CGE Model**
Sector	**Number of workers**	**Hours per worker**	**Labor input**	**Labor input**
Oil&gas extraction	–25.25%	–0.66%	–25.72%	–25.59%
Coal mining	–36.38%	–0.66%	–36.77%	–36.67%
Other mining	–3.13%	–0.66%	–3.73%	–3.58%
Mining support services	–20.27%	–0.66%	–20.77%	–20.64%
Electric power	–5.48%	–0.64%	–6.06%	–5.90%
Natural gas distribution	–5.03%	–0.64%	–5.62%	–5.47%
Petroleum refining and coal products	–9.09%	–0.63%	–9.65%	–9.51%
Water/sewage utilities	–0.66%	–0.64%	–1.27%	–1.12%
Agriculture	–1.56%	–0.66%	–2.18%	–2.01%
Construction	–1.23%	–0.66%	–1.85%	–1.70%
Durable manufacturing	–1.38%	–0.62%	–1.98%	–1.80%
Nondurable manufacturing (excl. refining)	–1.30%	–0.63%	–1.90%	–1.72%
Wholesale trade	–0.70%	–0.63%	–1.31%	–1.13%
Retail trade	0.58%	–0.66%	–0.05%	0.11%
Transportation and warehousing	–2.16%	–0.64%	–2.77%	–2.61%
Information	0.13%	–0.63%	–0.48%	–0.32%
Finance, insurance, real estate (incl. housing)	0.04%	–0.63%	–0.57%	–0.39%
Professional business services	–0.52%	–0.67%	–1.14%	–1.00%
Education and health	0.75%	–0.63%	0.13%	0.31%
Leisure and hospitality	0.42%	–0.68%	–0.22%	–0.08%
Other services	0.40%	–0.64%	–0.22%	–0.06%
Government enterprises	–0.12%	–0.61%	–0.73%	–0.55%
General government	0.75%	–0.61%	0.14%	0.15%
All sectors	–0.34%	–0.64%	–0.95%	–0.82%

15 A $40 carbon tax with lump-sum rebates is similar to the carbon dividend policy outlined by the Climate Leadership Council, an organization with founding members that include Republican statesmen such as James Baker and George Schultz.

A number of key results emerge from Table 2. First, the search-CGE model predicts a more negative change (larger drop or smaller increase) in total labor demand in every industry than the FE-CGE model, although the differences are small. The search-CGE model effectively adds an additional margin along which labor can respond, thus making the total quantity of labor more responsive to the carbon tax. Second, the FE-CGE model predicts a more negative change in employment (larger drop or smaller increase) in each sector than the search-CGE model (assuming that one interprets the FE-CGE change in labor demand as a change in the number of employees, as is common in the CGE literature). This difference arises because hours per worker fall in every industry in the search-CGE model. By implicitly assuming no change in hours per worker in the interpretation of the FE-CGE model results, CGE practitioners overestimate the change in the number of workers. As a result, the overall drop in employment is overestimated as well. This same issue causes the two models to produce different estimates for the sign of the change in jobs in a substantial fraction of industries: the FE-CGE model predicts an employment increase in only one private-sector industry (retail trade) and the government sector; in the search-CGE model, employment increases in 6 of the 22 private-sector industries and the government sector.[16]

However, in other respects, the two models generate relatively similar results. The rough ranking of industries (from relatively large job losses to small losses or gains) is essentially the same between the two models, because both models pick up the same underlying effect of substitution away from carbon-intensive goods. And the magnitude of the difference in the estimated change in jobs for any given industry is relatively small. Thus, if the goal is simply to identify relative shifts in employment, or to get a rough estimate of the effect on a particular industry, it doesn't make much difference which model one uses. But because the FE-CGE model yields systematically more negative effects on employment in every industry, they add up to a substantial difference in the aggregate estimates, even if those differences are relatively small for each industry taken by itself.

[16] The government's production of services is held fixed. With low elasticities of substitution, the government displays only a small change in total labor demand. However, the government must increase employment to offset the reduction in hours per worker that is relatively constant across sectors.

The differences across models are generally due to the assumption in the FE-CGE model that all adjustments occur on the extensive margin. In the benchmark search-CGE model, the intensive margin hours per worker response is responsible for approximately two-thirds of the total labor response to the carbon tax with lump-sum rebates. In Section 5, we investigate the robustness of these results.

Table 3. Long-Run Changes in Workers, Hours per Worker, and Total Labor Input
$40 Carbon Tax with Labor Tax Cuts

	Search-CGE Model			**FE-CGE Model**
Sector	**Number of workers**	**Hours per worker**	**Labor input**	**Labor input**
Oil&gas extraction	–24.86%	–0.15%	–24.97%	–24.95%
Coal mining	–36.09%	–0.15%	–36.18%	–36.16%
Other mining	–2.69%	–0.15%	–2.83%	–2.81%
Mining support services	–19.87%	–0.15%	–19.98%	–19.96%
Electric power	–5.05%	–0.14%	–5.18%	–5.15%
Natural gas distribution	–4.68%	–0.14%	–4.81%	–4.79%
Petroleum refining and coal products	–8.77%	–0.14%	–8.89%	–8.87%
Water/sewage utilities	–0.28%	–0.14%	–0.42%	–0.39%
Agriculture	–1.07%	–0.15%	–1.21%	–1.18%
Construction	–0.83%	–0.15%	–0.97%	–0.94%
Durable manufacturing	–0.90%	–0.14%	–1.04%	–1.00%
Nondurable manufacturing (excl. refining)	–0.79%	–0.14%	–0.93%	–0.90%
Wholesale trade	–0.25%	–0.14%	–0.39%	–0.36%
Retail trade	1.03%	–0.15%	0.89%	0.92%
Transportation and warehousing	–1.74%	–0.14%	–1.88%	–1.85%
Information	0.54%	–0.14%	0.39%	0.42%
Finance, insurance, real estate (incl. housing)	0.51%	–0.14%	0.37%	0.40%
Professional business services	–0.12%	–0.15%	–0.26%	–0.24%
Education and health	1.22%	–0.14%	1.08%	1.11%
Leisure and hospitality	0.82%	–0.15%	0.68%	0.70%
Other services	0.84%	–0.15%	0.69%	0.72%
Government enterprises	0.34%	–0.14%	0.20%	0.23%
General government	0.29%	–0.14%	0.15%	0.15%
All Sectors	–0.05%	–0.15%	–0.19%	–0.17%

Table 3 makes the same comparison, but for the case in which carbon tax revenue is used to cut payroll taxes (rather than returned lump-sum as in Table 2). Most of the qualitative results remain the same. Again, the search-CGE model predicts a larger absolute change in total labor demand in each sector due to the addition of the search friction (though the difference is quantitatively small). And again, because the FE-CGE model interprets all changes in labor demand as changes in the number of workers, the FE-CGE model predicts a more negative change in jobs in every industry than the search-CGE model.

In this case, though, the two models agree on the sign of job changes in each industry: each model predicts increases in employment in seven private-sector industries and the government sector. And while the search-CGE estimate of the drop in hours per worker is much smaller under payroll tax reductions than under lump-sum rebates (because the payroll tax cut raises the after-tax marginal value of working another hour, thus offsetting most of the effect of the carbon tax), the same is true for the extensive margin, and thus the relative importance of the intensive margin actually increases. The change in hours is responsible for about 75 percent of the economy-wide change in total labor input. As a result, the FE-CGE model predicts a decrease in the number workers that is nearly 3.5 times greater than the search-CGE prediction.

5. Sensitivity Analysis

To assess the robustness of our model comparison results, we look at how sensitive they are to changes in a variety of parameter and modeling assumptions. First, we test standard CGE parameters such as the elasticities of labor supply and household consumption, the production elasticity between labor and intermediate inputs, and trade elasticities. Second, we vary key search parameters such as the wage-bargaining shares, the match elasticity, and recruiter productivity. Finally, we test whether altering our assumption for constant real unemployment benefits affects the key results.

Three major observations emerge from the sensitivity analysis. First, sensitivity analysis on standard CGE parameters shows that the FE-CGE model consistently yields higher estimates of the aggregate long-run unemployment impact of carbon pricing than the search-CGE model, regardless of the value of standard CGE parameters. The bargaining process in the search-CGE model allows for adjustments in hours and wages that ultimately mitigate the decreased demand for labor caused by the carbon-pricing policy. This intuition is also reflected in the sensitivity analysis on key search parameters: alternative specifications that reduce the size of the bargaining set tend to lead to higher estimated unemployment impacts in the search-CGE model in response to carbon-pricing-induced reductions in labor demand. In the case of bargaining power, higher employer bargaining power sufficiently restricts the wage and hours response to the carbon tax such that the FE-CGE model underestimates the unemployment impact relative to the search-CGE model. Finally, the search-CGE results are sensitive to how unemployment benefits are modeled. Using a fixed replacement rate, as opposed to a fixed real benefit level, significantly decreases estimated effects on unemployment in the search-CGE model, leading to a much larger difference from the FE-CGE model estimates.

5.1. Standard CGE Parameters

Table 4 displays the change in long-run unemployment from a $40 carbon tax across a range of standard CGE parameters for both models and recycling options. The elasticity of labor supply captures the response of hours worked to changes in the real wage rate. Although higher labor supply elasticities increase the responsiveness of hours worked to changes in the real wage rate in both the search-CGE and FE-CGE models, this has opposite effects on the change in unemployment in the two models. In the search-CGE model, if workers are more willing to change their hours of work, more of the adjustment will be on the intensive margin (hours worked), and thus less is needed on the extensive margin (employment). On the other hand, increasing the labor supply elasticity in the FE-CGE model causes the representative household to be more responsive to the real wage, leading to a larger reduction in labor supply. Because the FTE calculations interpret changes in representative agent labor supply as a change in employment, increasing the elasticity of labor supply results in an increased reduction in FTE employment, resulting in a higher estimated unemployment rate.

Unemployment impacts of emissions taxes are largely independent of both the household elasticity for consumption and production elasticity between labor and intermediate inputs in both search-CGE and FE-CGE models. As the elasticities increase, the increase in the unemployment rate slightly declines across both models and revenue recycling designs, compared with the central case. For the consumption elasticity, the income effect outweighs the substitution effect: making it easier to substitute from high-pollution-intensity consumption goods to low-pollution-intensity consumption goods further decreases high-pollution-intensity employment, but this decline is offset by a higher real income for the household. For the production elasticity of substitution between labor and intermediate inputs, an increased elasticity slightly decreases the impacts of a $40 carbon tax by shifting production inputs away from more expensive dirty intermediate inputs to labor. An increase in the substitution effect thus helps offset decreases in demand caused by the carbon tax.

Trade elasticities represent how easily consumers and producers can substitute between domestic and foreign-made goods or inputs.[17] Higher trade elasticities increase the negative impacts of an emissions tax on high-pollution-intensity industries because it becomes easier to substitute to imported dirty goods, further reducing domestic production and labor demand in those industries. However, this is offset by larger gains in clean industries. As a result, the overall change in the unemployment rate is relatively insensitive to the trade elasticity in both the search-CGE and FE-CGE models.

[17] In our alternative trade elasticity simulations, we increase both the domestic consumer and producer elasticities between domestic and foreign goods and the foreign consumer and producer elasticities between domestic and foreign goods.

Table 4. Sensitivity Analysis on Standard CGE Parameters ($40/ton carbon tax)

Change of unemployment rate from reference case (5%)		Lump-sum rebate: Search-CGE Model	Lump-sum rebate: FE-CGE Model	Labor tax cut: Search-CGE Model	Labor tax cut: FE-CGE Model
Central case		0.320%	0.777%	0.047%	0.158%
Labor supply elasticity	50% higher ($1/\chi = 1.5$)	0.260%	0.909%	0.041%	0.194%
	50% lower ($1/\chi = 0.5$)	0.406%	0.540%	0.052%	0.102%
Household elasticity for consumption	50% higher ($\sigma^c = 1.125$)	0.308%	0.752%	0.043%	0.150%
	50% lower ($\sigma^c = 0.375$)	0.333%	0.804%	0.051%	0.168%
Production elasticity for labor and int. inputs	50% higher ($\sigma^y = 0.75$)	0.311%	0.768%	0.039%	0.150%
	40% lower ($\sigma^y = 0.3$)	0.327%	0.784%	0.054%	0.165%
Trade elasticity	50% higher ($\sigma^{df} = 2.25$)	0.343%	0.753%	0.091%	0.200%
	50% lower ($\sigma^{df} = 0.75$)	0.194%	0.843%	–0.130%	–0.027%

5.2. Labor Market Parameters

Table 5 displays the change in long-run unemployment caused by a $40 carbon tax for the search-CGE model across alternative search-CGE labor market parameter values. For comparison, we display results from the FE-CGE even though that model doesn't include search parameters, and therefore those results do not change.

Bargaining power determines how the surplus from a job match is split between employees and employers. If employer bargaining power is high ($\eta > 0.5$), then (all else equal) a policy-induced reduction in the marginal value of a worker (J_n) leads to a larger decline in recruitment effort, increasing the employment response. Conditional on the relative flow value of unemployment, increased bargaining power also limits both the wage and hours responses to the policy. Less flexible hours increase the employment response to policy by increasing the extensive margin response, and less flexible wages decrease the reallocation of workers from relatively dirty industries to relatively clean industries. In our high-bargaining-power specification, the increase in unemployment is greater than the increase in unemployment in the FE-CGE model. This is the only specification that deviates from our central result that the FE-CGE model overestimates unemployment impacts relative to the search-CGE model.

Table 5. Sensitivity Analysis on Labor Market Parameters ($40/ton carbon tax)

Change of unemployment rate from reference case (5%)		Lump-sum rebate: Search-CGE Model	Lump-sum rebate: FE-CGE Model	Labor tax cut: Search-CGE Model	Labor tax cut: FE-CGE Model
Central case		0.320%	0.777%	0.047%	0.158%
Nash bargaining parameter	50% higher (η = 0.75)	0.962%	0.777%	0.143%	0.158%
	50% lower (η = 0.25)	0.078%	0.777%	0.010%	0.158%
Match elasticity	50% higher (γ_j = 0.75)	0.159%	0.777%	0.021%	0.158%
	50% lower (γ_j = 0.25)	0.477%	0.777%	0.073%	0.158%
Recruiter productivity	50% higher (H_j = 37.5)	0.501%	0.777%	0.074%	0.158%
	50% lower (H_j = 12.5)	0.137%	0.777%	0.019%	0.158%

The matching elasticity indicates how the number of job matches will change with a given change in recruiting effort. Increasing the elasticity increases the ability of the low-pollution-intensity industries to hire workers who lost jobs in the high-pollution-intensity industries. As a result, the unemployment impact decreases when match elasticity increases.

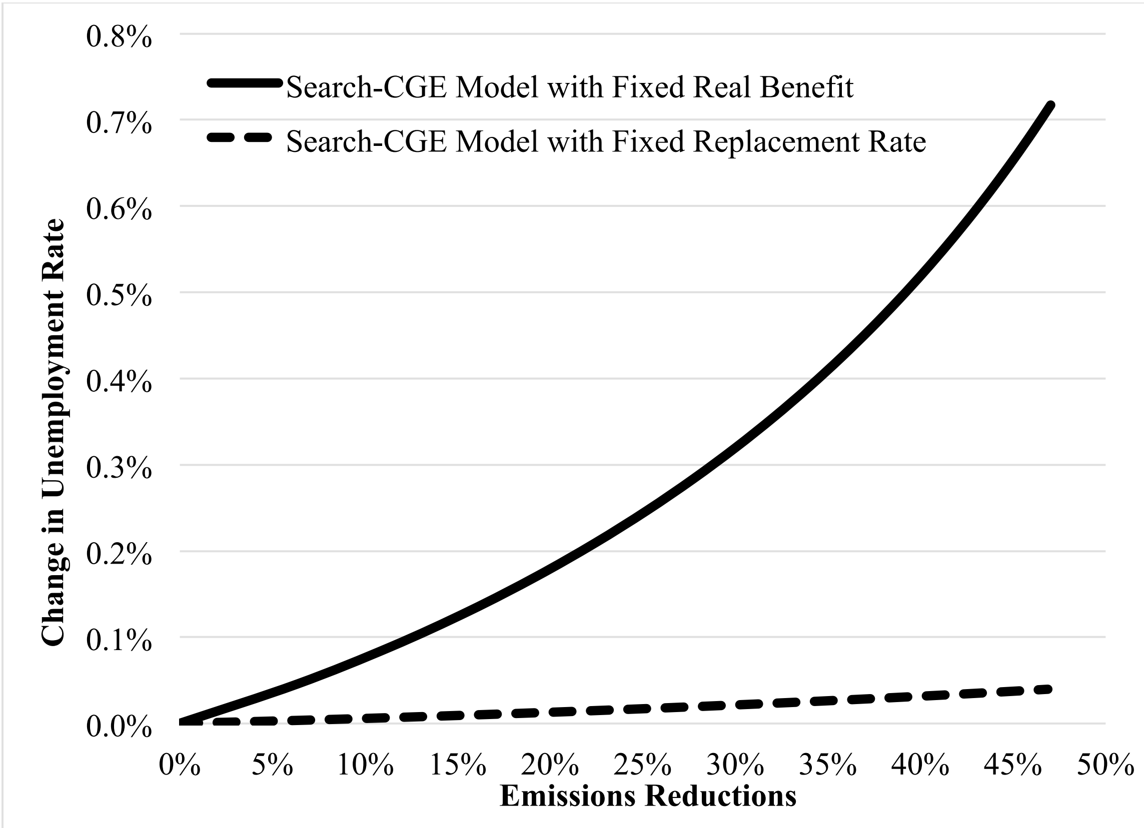
Recruiter productivity is an endogenous function of matching efficiency, the ratio of total recruiter effort to the number of unemployed workers (labor market tightness), and match elasticity, but in the calibration process, we calibrate the match efficiencies to be consistent with prespecified benchmark recruitment productivities. Higher benchmark productivities imply higher match efficiencies; higher match elasticities imply that job matches are more sensitive to changes in labor market tightness and that any given change in the value of a job match will have a greater effect on the level of unemployment. In other words, higher match efficiency implies lower recruiting costs, and thus it requires a larger change in labor-market tightness to offset any given change in the value of a match. As a result, the unemployment impact increases when recruiter productivity/match efficiency is higher. Further, as recruitment productivity approaches infinity, recruiting costs converge to zero and the search-CGE model results will converge to the FE-CGE model results.

5.3. Unemployment Benefits

In the search-CGE model, unemployed workers receive nominal unemployment benefits $\overline{p}b$ each period, implying real benefits equal b. In the calibration procedure, b is calibrated to be consistent with our data and other calibration assumptions. The value of b in the search-CGE model is 0.369; this value implies a benchmark replacement rate of about 38.9 percent (nominal unemployment benefits as a percentage of nominal average after-tax earnings). This value is larger than the 25 percent value used by Hall and Milgrom (2008) but closely matches the value used in other studies, such as Amaral and Tasci (2013).[18] In the search-CGE model, real benefits b are held fixed, and therefore the replacement rate increases with the carbon tax (a higher carbon tax rate implies a higher price level and lower average after-tax real wages). In the $40 carbon tax case, for example, the replacement rate increases to 42.7 percent.

[18] As shown in Hafstead and Williams (2018), the benchmark replacement rate is a function of the elasticity of labor supply. If we increase the elasticity of labor supply, the calibrated replacement rate would fall. Hafstead and Williams found that Frisch elasticity of 2 was consistent with a replacement rate of 25 percent in a similar model.

Figure 6. Change in Unemployment Rate by Level of Stringency under Two Unemployment Benefit Assumptions, Lump-Sum Rebates



Alternatively, the search-CGE model could hold the replacement rate fixed and allow the real value of unemployment benefits b to vary in response to the carbon tax. Figure 6 displays the unemployment rate for carbon taxes with lump-sum rebates across a range of stringencies under both unemployment benefit assumptions. At all levels of stringency, the search-CGE model with fixed replacement rate predicts significantly less unemployment than our benchmark search-CGE model with fixed real benefits. The fixed replacement rate effectively lowers the value of unemployment benefits and therefore lowers the flow value of unemployment. This reduced value of unemployment increases the value of a job (V_n) and reduces equilibrium wages. As a result, relative to the fixed benefit search-CGE model, the fixed replacement rate search-CGE model leads to smaller carbon-tax-induced increases in the unemployment rate because wages are more flexible.

Thus, if replacement rates were held fixed, then FE-CGE models would overestimate the employment impacts of a carbon tax by an even greater magnitude.

This exercise also demonstrates the importance of unemployment benefit assumptions when the wage bargain depends on the value of unemployment benefits, a result that is potentially quite important for the rapidly growing body of research on environmental policy–employment modeling.

6. Conclusions

The political debate over environmental policy puts tremendous importance on how policy affects jobs. Climate activists argue that environmental policies will create new "green jobs," while opponents deride such policies as "job-killers." In the absence of better tools, some economists have converted estimated changes in aggregate labor hours from widely used full-employment environmental CGE models into estimates of changes in FTE jobs—even though such models neither model the number of jobs nor consider involuntary unemployment.

This paper looks at how robust the conclusions from such models are to more realistic models of the labor market. It extends the Hafstead and Williams (2018) search-friction model from a highly stylized two-sector model to a more detailed environmental CGE model and compares results from that model with those of an otherwise equivalent full-employment CGE model. We find that estimates of the aggregate changes in labor quantity and the shifts across industries are relatively robust to this change: while results differ between the two models, the magnitude of those differences is modest. However, the full-employment model estimates the net change in the aggregate number of employed workers to be roughly 2.5 times the estimate from the search-friction model, because the full-employment model misinterprets voluntary changes in hours worked per worker as changes in the number of jobs.

These results demonstrate that one should exercise great caution in using estimates of the aggregate change in the number of jobs from full-employment models. However, they also suggest that the full-employment assumption is not a substantial problem for estimates of sector-level job changes or changes in total labor hours.

Aside from implying that FTE job loss estimates seriously overstate effects on jobs, our results also suggest that carbon taxes have relatively small net effects on employment: the search-friction model finds that a $40 carbon tax with lump-sum rebates would decrease total jobs by about 0.34 percent. If revenues were used to reduce labor taxes (payroll or personal wage taxes), the same $40 carbon tax would decrease total jobs by about 0.05 percent.

These results are generally robust across alternative specifications, though there are a few exceptions. Higher employer bargaining power would increase the search-CGE net employment effect, and holding the unemployment benefit replacement rate constant (as opposed to the real level of benefits, as in our base specification) would decrease the search-CGE net employment effect.

However, while this research showed which employment results are robust to differences in assumptions between the two models we considered, it cannot evaluate which model is more likely to generate accurate predictions. In the absence of other information, we would argue that the search-friction model's far less unrealistic microfoundations are likely to yield better estimates, but that is ultimately an empirical question, and that empirical question is difficult to answer. As shown by Hafstead and Williams (2018), general-equilibrium effects cause a fundamental identification problem for empirical work on these issues, so reduced-form empirical work will generally be seriously biased. Thus one useful direction for future research would be to bring together empirical work with general-equilibrium modeling, such as that in this paper, both to improve empirical estimates and to test some of the predictions of general-equilibrium employment models.

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