The Distributional Impacts of Decarbonization Policies *

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Abstract

Decarbonization policies can impose highly uneven costs across workers, industries, and regions, making their distributional consequences central to both policy design and political feasibility. We quantify these effects using a dynamic spatial general-equilibrium model of the United States with 48 states and 33 sectors. The model integrates costly trade, input-output linkages, imperfect worker mobility, irreversible capital accumulation, and an electricity sector with renewable and fossil-fuel generation connected through an interstate transmission network. We compare two uses of the revenues from a 20% carbon tax: uniform rebates to workers and subsidies to renewable electricity. Both policies reduce fossil-fuel production by about 35% within five years and by 38–42% in the long run, but generate different trade-offs. Renewable subsidies produce a larger shift toward clean electricity and smaller aggregate consumption losses, whereas uniform rebates substantially reduce workers' welfare losses. Losses are concentrated in fossil-fuel-producing regions and carbon-intensive industries, and regional dispersion of impacts is substantially larger under the renewable subsidy. Workers initially employed in fossil fuels experience some of the largest lifetime welfare losses, but these losses vary substantially across locations because workers differ in their outside employment opportunities and the mobility costs they face.

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1 Introduction

Climate change has placed decarbonization at the center of economic policy. Carbon taxes, cap-and-trade systems, and subsidies for renewable energy are widely viewed as important instruments for reducing greenhouse-gas emissions. Yet these policies can also generate substantial distributional consequences. Carbon pricing raises the cost of fossil fuels and electricity, imposing larger burdens on firms and workers in carbon- and electricity-intensive sectors and in regions specialized in such activities.

At the same time, policies that encourage renewable energy create new opportunities for regions with favorable conditions for clean-energy production. Understanding who gains and who loses from alternative decarbonization policies is therefore critical for designing climate policies that are both economically efficient and politically sustainable.

These distributional consequences are particularly important because political constraints have become a major obstacle to ambitious climate policy. As Mehling (2018) puts it, "In the long run, the cost of doing nothing will almost certainly outweigh the cost of climate action—but the latter is real and will be allocated unevenly, creating winners and losers. That explains a growing preoccupation with the distribution of climate policy impacts." Such unevenly distributed costs can translate directly into political resistance. In the United States, for example, Senator Joe Manchin helped block a major component of the Biden administration's climate agenda while arguing that the proposed legislation to reduce carbon emissions would harm his constituents.[1] More generally, while the long-run benefits of reducing emissions are broadly shared, the economic costs of adjustment can be immediate and concentrated among particular industries, locations, workers, and owners of capital. Policies that mitigate these transitional losses may therefore play an important role in building and sustaining political support for decarbonization.

A growing reduced-form literature documents substantial heterogeneity in the incidence of environmental and climate policies across workers, firms, industries, and regions (e.g., Walker, 2013; Bigio et al., 2026; Bijnens, Hutchinson and Saint Guilhem, 2026). An important gap remains, however, between this evidence and the quantitative frameworks available for evaluating climate policies ex ante. As emphasized by Bilal and Stock (2026), understanding the climate transition requires models that capture not only aggregate effects but also the distribution of costs and benefits across workers, sectors, and regions. In an interconnected economy, policy effects extend beyond the workers, industries, and locations

[1] *The Washington Post*, May 22, 2022.

directly exposed to the intervention, propagating through trade and input-output linkages, worker mobility, capital accumulation, and electricity transmission. These same margins also shape the pace and pattern of adjustment over time. A quantitative general-equilibrium framework incorporating these spillovers and transition dynamics can therefore complement reduced-form evidence by allowing for the ex-ante evaluation and comparison of alternative climate-policy designs.

We develop such a framework and use it to study the distributional and transitional consequences of a carbon tax under alternative uses of its revenues. We focus on three main questions. First, which regions, sectors, and workers bear the largest costs of a carbon tax? Second, how quickly does the economy adjust to carbon pricing and the expansion of renewable energy? Third, how does the use of carbon-tax revenues affect the incidence and dynamic effects of the policy? In particular, how does using these revenues to subsidize renewable electricity, rather than rebating them uniformly to workers, affect the pace and distributional consequences of the energy transition? This question is particularly important because, although carbon taxes and renewable subsidies are often studied separately, they are frequently implemented as components of broader climate-policy packages.

Our framework is based on a dynamic spatial general-equilibrium model of the United States with 48 states and 33 economic sectors. Electricity is produced using two technologies, based respectively on renewable and fossil-fuel energy sources. The productivity of renewable-energy capital varies across the country according to local exposure to sunlight, wind, and hydro resources, while its marginal operating cost is assumed to be zero (as in Arkolakis and Walsh, 2023). Fossil-fuel-based electricity generation, by contrast, requires fossil-fuel inputs and, conditional on installed capital, exhibits decreasing returns to fossil-fuel use, generating upward-sloping and convex local electricity supply curves. Goods and services, including fossil fuels themselves, are produced using electricity, labor, intermediate inputs, and capital. The intermediate-input block of production allows for inter-sectoral linkages similar to Caliendo and Parro (2015).

Capital stocks evolve endogenously through investment decisions by forward-looking, region-sector-specific capital owners, including owners of renewable- and fossil-fuel-based electricity capital. Investment is irreversible: capital owners can accumulate their capital stocks but cannot undertake negative investment. This creates an additional source of dynamic adjustment, as changes in expected future returns affect investment across sectors, regions, and electricity technologies, while previously installed capital cannot be costlessly withdrawn.

States and sectors are connected through costly trade in goods and services, imperfect worker mobility across states and sectors, and interstate electricity transmission. These linkages propagate the effects of climate policy throughout the economy: changes in fossil-fuel prices affect production costs across sectors and locations, workers respond gradually to changes in regional and sectoral opportunities, investment responds to changes in expected returns, and differences in renewable-energy potential reshape the geography of electricity production. The government collects taxes and distributes the resulting revenues through transfers or subsidies, allowing us to study alternative ways of distributing carbon-tax revenues.

We calibrate the model to U.S. data on value added, expenditures, and factor payments from the Bureau of Economic Analysis (BEA); electricity generation, end-user expenditures, capital stocks, interstate flows, and prices from the Energy Information Administration (EIA); regional trade flows from the Commodity Flow Survey (CFS); and labor allocations and worker transitions across states and sectors from the American Community Survey (ACS) and Current Population Survey (CPS).

We use the calibrated model to quantify both the aggregate and distributional consequences of alternative decarbonization policies and to trace their effects throughout the transition. We find that a 20% carbon tax, implemented as a tax on fossil-fuel goods production, leads to a rapid and substantial decline in fossil-fuel production under either policy: national output falls by approximately 35% within five years and by 38–42% in the long run.

How carbon-tax revenues are used, however, generates an important trade-off. Subsidizing renewable electricity produces a much larger reallocation of generation toward renewable sources and a smaller long-run decline in aggregate consumption, whereas uniformly rebating revenues to workers substantially reduces workers' lifetime welfare losses. The transition paths also differ sharply. Under the renewable subsidy, rapid investment in renewable electricity generation initially depresses aggregate consumption but expands electricity capacity, lowers electricity prices, and subsequently generates a temporary consumption overshoot. Under the uniform rebate, by contrast, aggregate consumption initially rises as investment contracts sharply in fossil-fuel-intensive activities.

These aggregate effects mask substantial heterogeneity across locations, sectors, and factor owners. Losses are concentrated in fossil-fuel-producing states and carbon-intensive industries, and the renewable subsidy generates substantially greater cross-state dispersion in consumption and population changes. Real wages fall most sharply in the fossil-fuel sector, but workers' lifetime welfare losses depend importantly on both their initial sector and lo-

cation. Workers initially employed in fossil fuels experience some of the largest losses under either policy, with the magnitude of these losses varying substantially across states, reflecting differences in workers' outside employment opportunities and in the pattern of mobility costs they face. Capital owners also experience highly heterogeneous welfare effects, particularly under the renewable subsidy, which generates large losses for owners of fossil-fuel and fossil-fuel-based electricity capital while producing substantial gains for owners of renewable-generation capital. Despite substantial worker reallocation across regions and sectors, initial region and sector of employment remain important determinants of workers' lifetime welfare losses.

Our framework brings together two strands of the quantitative trade and spatial-economics literature. First, it builds on dynamic models of trade with costly worker mobility and capital adjustment, following Artuç, Chaudhuri and McLaren (2010), Dix-Carneiro (2014), Caliendo, Dvorkin and Parro (2019), Traiberman (2019), and Kleinman, Liu and Redding (2023). The trade, labor-market, and capital blocks of our model are most closely related to Caliendo, Dvorkin and Parro (2019) and Kleinman, Liu and Redding (2023). We depart from Kleinman, Liu and Redding (2023) by introducing irreversibility in capital accumulation: investment must be non-negative in every period, so that installed capital can decline only through depreciation. Relative to both frameworks, we additionally model the supply and demand for electricity and its imperfect transmission across space.

Second, our modeling of renewable- and fossil-fuel-based electricity generation builds on Arkolakis and Walsh (2023). A key departure is our treatment of electricity transmission. Building on Allen and Arkolakis (2022), we develop a novel network formulation of electricity transmission across space. Electricity flows endogenously across interconnected states subject to transmission costs, generating dispersion in both generator and end-user prices. Although electricity is a homogeneous good in our framework, the resulting demand system is isomorphic to an Armington system, greatly simplifying the solution of the model and providing a transparent mapping between the data and the key parameters governing electricity transmission.

Our paper also complements a growing empirical literature documenting the distributional and labor-market consequences of environmental and climate policies. Walker (2013) estimates the transitional earnings losses borne by workers affected by the Clean Air Act, while Bigio et al. (2026) and Bijnens, Hutchinson and Saint Guilhem (2026) provide recent evidence on the heterogeneous incidence of carbon pricing in Europe. These studies provide compelling evidence that the costs of environmental policies can be substantial and unevenly

distributed across workers, firms, and regions. Our approach complements this evidence by studying these distributional consequences in general equilibrium, accounting for the many channels through which a policy shock propagates through an interconnected economy—including trade and input-output linkages, worker mobility, capital accumulation, and the electricity transmission network. Moreover, whereas reduced-form evidence is necessarily disciplined by the historical policy variation observed in the data, our structural framework allows us to evaluate policies ex ante and to compare alternative combinations of carbon taxes, revenue redistribution, and renewable-energy subsidies that have not previously been implemented.

The paper proceeds as follows. Section 2 presents the model, including production, trade, labor mobility, and capital accumulation, and concludes with the definition of the dynamic equilibrium. Section 3 describes the datasets used to discipline the model, while Section 4 presents the calibration in detail. Section 5 analyzes the effects of a carbon tax under two alternative uses of the resulting revenues: a uniform rebate to workers and a subsidy to renewable electricity production. Section 6 concludes and discusses next steps in the project.

2 Model

2.1 Environment

We consider an economy with multiple locations, indexed by $\ell \in \mathcal{L} \equiv \{1, \ldots, \overline{\mathcal{L}}\}$, and multiple production sectors. Time is discrete and indexed by t. In each period, a mass $\overline{L}$ of hand-to-mouth workers chooses where to live and work. Each location also contains local capitalists who own the capital stocks used in sectoral production and electricity generation.

Production sectors are indexed by $j \in J \cup \{F\}$, where F denotes the fossil-fuel production sector, which plays a central role in our analysis. The set $J \equiv \{1, \ldots, \overline{J}\}$ contains all sectors other than fossil-fuel production and electricity generation.

Electricity is produced using two location-specific types of capital: renewable electricity capital—such as solar panels and wind turbines—denoted by $K_{\ell,ER}$, and fossil-based electricity capital—such as coal-fired power plants—denoted by $K_{\ell,EF}$. We refer to ER and EF as the renewable and fossil-based electricity sectors, respectively, and use E to denote the electricity sector as a whole. Electricity generated by the two sectors is assumed to be perfectly substitutable.

The government may impose sector-specific output taxes or subsidies, denoted by χ_j for

$j \in J \cup \{F, ER, EF\}$. Positive values of χ_j represent taxes, whereas negative values represent subsidies. Tax revenues, net of subsidy expenditures, are rebated to workers through lump-sum transfers b. The government balances its budget in every period.

2.2 Goods and Production

The economy contains five types of goods, organized in a nested production structure. Their outputs and prices are denoted as follows:

(i) Tradable location- and sector-specific intermediate goods produced using labor, capital, electricity, and sector-specific materials. Output of the intermediate good produced in location $\ell \in \mathcal{L}$ and sector $j \in J \cup \{F\}$ is denoted by $y_{\ell,j}$, and its price by $p_{\ell,j}$. These sector-specific intermediate goods are Armington-differentiated according to location.

(ii) Non-tradable location- and sector-specific Armington composites aggregating intermediate goods (i) across origin locations. The output of the Armington composite in location $\ell \in \mathcal{L}$ and sector $j \in J \cup \{F\}$ is denoted by $Q_{\ell,j}$, and its price by $P_{\ell,j}$.

(iii) Non-tradable location- and sector-specific materials aggregating Armington composites (ii) across sectors within each location. Sector-j-specific materials in location $\ell \in \mathcal{L}$, with $j \in J \cup \{F\}$, are denoted by $M_{\ell,j}$, and their price by $P^M_{\ell,j}$.

(iv) Non-tradable location-specific final goods aggregating location- and sector-specific Armington composites (ii) across sectors. Location-ℓ-specific output is denoted by Q_ℓ, and its price by P_ℓ, for $\ell \in \mathcal{L}$.

(v) Electricity, produced in each location using renewable and fossil-based technologies. We denote renewable and fossil-based electricity output in location ℓ by $y_{\ell,ER}$ and $y_{\ell,EF}$, respectively, with total electricity output given by $y_{\ell,E} = y_{\ell,ER} + y_{\ell,EF}$. Electricity is homogeneous across locations and production technologies and can be traded across locations. We denote by $P_{\ell,E}$ the price of electricity paid by households and intermediate-good producers in location ℓ, and by $p_{\ell,E}$ the price received by electricity producers located in ℓ.

We now describe the technologies used to produce each type of good.

2.2.1 Intermediate Local Goods Production

Tradable intermediate goods (i) in sector $j \in J \cup \{F\}$ and location $\ell \in \mathcal{L}$ are produced using electricity, labor, materials, and capital according to

$$y_{\ell,j,t} = \frac{z_{\ell,j}}{\left(\beta_j^E\right)^{\beta_j^E}\left(1-\beta_j^E\right)^{1-\beta_j^E}} E_{\ell,j,t}^{\beta_j^E}\left(L_{\ell,j,t}^{\beta_j^L} M_{\ell,j,t}^{\beta_j^M} K_{\ell,j,t}^{\beta_j^K}\right)^{1-\beta_j^E}, \tag{1}$$

where $z_{\ell,j}$ denotes total factor productivity (TFP) in sector j and location ℓ. The parameter β_j^E is the sector-specific expenditure share on electricity, while β_j^L, β_j^M, and β_j^K denote the expenditure shares in the Cobb–Douglas labor–material–capital bundle, satisfying

$$\beta_j^L + \beta_j^M + \beta_j^K = 1.$$

According to equation 1, sector j's expenditure share on the fuel composite is given by $\left(1-\beta_j^E\right)\beta_j^M \gamma_{j,F}$ and is fixed throughout. Therefore, this formulation abstracts from changes in technology induced by higher fossil fuel prices. If the researcher has access to data on technologies that are less dependent on fossil fuels or that emit less carbon, the framework could be extended to incorporate this margin of adjustment.

2.2.2 Armington Composites and Local Final Goods Production

Local final goods are produced in two stages. First, the non-tradable, location- and sector-specific composite goods (ii) are Armington aggregates of sector-j intermediate goods (i) sourced from all origin locations $\ell' \in \mathcal{L}$:

$$Q_{\ell,j,t} = \left(\sum_{\ell' \in \mathcal{L}} q_{\ell',\ell,j,t}^{\frac{\rho_j - 1}{\rho_j}}\right)^{\frac{\rho_j}{\rho_j - 1}}, \tag{2}$$

where $q_{\ell',\ell,j,t}$ denotes the quantity of sector-j intermediate goods shipped from origin location ℓ' and arriving in destination location ℓ in period t, and ρ_j is the sector-specific elasticity of substitution—$j \in J \cup \{F\}$.

These location- and sector-specific composite goods are allocated between final-good production, through $Q_{\ell,j,t}^f$, and sector-specific materials production, through $Q_{\ell,j,t}^m$, so that

$$Q_{\ell,j,t} = Q_{\ell,j,t}^f + Q_{\ell,j,t}^m.$$

We denote the price of one unit of the Armington composite good in (2) by $P_{\ell,j,t}$.

In the second stage, the non-tradable, location-specific final goods (iv) are produced by combining electricity $E_{\ell,t}$ and sector-specific composite goods $\left\{Q^f_{\ell,j,t}\right\}$ according to a Cobb–Douglas technology:

$$Q_{\ell,t} = E^{\mu_E}_{\ell,t} \prod_{j \in J \cup \{F\}} \left(Q^f_{\ell,j,t}\right)^{\mu_j}, \tag{3}$$

where μ_j are expenditure shares that are common across locations and satisfy

$$\sum_{j \in J \cup \{F,E\}} \mu_j = 1.$$

2.2.3 Materials

Materials are produced separately for each sector and location using a Cobb–Douglas aggregator over the local Armington sector-specific composite goods:

$$M_{\ell,j,t} = \prod_{n \in J \cup \{F\}} \left(\overline{Q}^m_{\ell,j,n,t}\right)^{\gamma_{j,n}}, \tag{4}$$

where $\overline{Q}^m_{\ell,j,n,t}$ denotes the quantity of the sector-n Armington composite good used in the production of $M_{\ell,j,t}$, and $\gamma_{j,n}$ is the expenditure share on inputs from sector n, satisfying

$$\sum_{n \in J \cup \{F\}} \gamma_{j,n} = 1.$$

Note that this structure creates inter-sectoral linkages, similar to Caliendo and Parro (2015).

Market clearing for the sector-j Armington composite good implies

$$Q^m_{\ell,j,t} = \sum_{n \in J \cup \{F\}} \overline{Q}^m_{\ell,n,j,t},$$

and therefore

$$Q_{\ell,j,t} = Q^f_{\ell,j,t} + \sum_{n \in J \cup \{F\}} \overline{Q}^m_{\ell,n,j,t}.$$

2.2.4 Electricity Production

The production of tradable electricity (v) largely follows Arkolakis and Walsh (2023). Renewable electricity is produced at zero marginal cost but is subject to a capacity constraint:

$$y_{\ell,ER,t} \leq z_{\ell,ER} K_{\ell,ER,t}^{\alpha_R}, \tag{5}$$

where $K_{\ell,ER,t}$ denotes the installed renewable capacity in location ℓ and period t, $z_{\ell,ER}$ is a productivity shifter, and $\alpha_R \in (0,1)$ is the elasticity of electricity production with respect to installed renewable capacity. The same installed renewable capacity can generate different amounts of electricity across locations because of differences in local conditions, such as solar exposure and wind intensity. Because renewable electricity has zero marginal cost, renewable generation is dispatched before fossil-fuel-based generation whenever renewable capacity is available.

Electricity generated from fossil fuels is produced according to

$$y_{\ell,EF,t} = z_{\ell,EF} K_{\ell,EF,t}^{\alpha_F} F_{\ell,t}^{1-\alpha_F}, \tag{6}$$

where $K_{\ell,EF,t}$ denotes the installed fossil-fuel-based capacity in location ℓ and period t, $F_{\ell,t}$ is the quantity of location-ℓ fuel composite used, $z_{\ell,EF}$ is a productivity shifter, and $\alpha_F \in (0,1)$ is the elasticity of electricity production with respect to installed fossil-fuel-based capacity.

2.3 Producer Behavior

2.3.1 Intermediate Local Goods

For each sector $j \in J \cup \{F\}$, let $p_{\ell,j,t}$ denote the gross price paid for an intermediate good produced in location ℓ. Because intermediate-good markets are competitive, the net-of-tax price received by the producer equals its marginal cost:

$$(1-\chi_{j,t})\, p_{\ell,j,t} = \frac{1}{z_{\ell,j}} P_{\ell,E,t}^{\beta_j^E} \left(c_{\ell,j,t}^{LMK}\right)^{1-\beta_j^E}, \qquad j \in J \cup \{F\}, \tag{7}$$

where $P_{\ell,E,t}$ is the price paid by users of electricity in location ℓ, and $c_{\ell,j,t}^{LMK}$ is the unit cost of the labor–materials–capital bundle. The latter is given by

$$c_{\ell,j,t}^{LMK} = \left(\frac{w_{\ell,j,t}}{\beta_j^L}\right)^{\beta_j^L} \left(\frac{P_{\ell,j,t}^M}{\beta_j^M}\right)^{\beta_j^M} \left(\frac{r_{\ell,j,t}}{\beta_j^K}\right)^{\beta_j^K}, \tag{8}$$

where $w_{\ell,j,t}$ is the wage rate, $P_{\ell,j,t}^M$ is the price of the material bundle, and $r_{\ell,j,t}$ is the capital rental rate in region ℓ and sector j.

Define the revenue of an intermediate-good producer in sector j and location ℓ as

$$R_{\ell,j,t} \equiv p_{\ell,j,t} y_{\ell,j,t}, \qquad j \in J \cup \{F\}. \tag{9}$$

Cost minimization implies that expenditure on electricity is given by:

$$P_{\ell,E,t} E_{\ell,j,t} = \beta_j^E \left(1 - \chi_{j,t}\right) R_{\ell,j,t}. \tag{10}$$

The remaining share $1 - \beta_j^E$ of net-of-taxes revenue is allocated across labor, materials, and capital according to:

$$w_{\ell,j,t} L_{\ell,j,t} = \left(1 - \beta_j^E\right) \beta_j^L \left(1 - \chi_{j,t}\right) R_{\ell,j,t}, \tag{11}$$

$$P_{\ell,j,t}^M M_{\ell,j,t} = \left(1 - \beta_j^E\right) \beta_j^M \left(1 - \chi_{j,t}\right) R_{\ell,j,t}, \tag{12}$$

$$r_{\ell,j,t} K_{\ell,j,t} = \left(1 - \beta_j^E\right) \beta_j^K \left(1 - \chi_{j,t}\right) R_{\ell,j,t}. \tag{13}$$

Within the material bundle, expenditure by sector j on the sector-n Armington composite satisfies

$$P_{\ell,n,t} \overline{Q}_{\ell,j,n,t}^m = \gamma_{j,n} P_{\ell,j,t}^M M_{\ell,j,t}, \qquad j, n \in J \cup \{F\}, \tag{14}$$

where $\overline{Q}_{\ell,j,n,t}^m$ denotes sector j's use of the sector-n composite as a material input.

2.3.2 Electricity

Given that renewable-based electricity is produced at zero marginal cost and is always dispatched first, conditional on installed capacity $K_{\ell,ER,t}$, the supply of renewable electricity in region ℓ is inelastic, so that $y_{\ell,ER,t} = z_{\ell,ER} K_{\ell,ER,t}^{\alpha_R}$ independently of the price faced by local generators.

If electricity producers in region ℓ face price $p_{\ell,E,t}$ and fossil-fuel based capital is positive,

i.e., $K_{\ell,EF,t} > 0$, the local supply of fuel-based electricity $y_{\ell,EF,t}$ is determined by the zero profit condition

$$(1-\chi_{EF,t})\, p_{\ell,E,t} = \frac{P_{\ell,F,t}}{1-\alpha_F} K_{\ell,EF,t}^{-\frac{\alpha_F}{1-\alpha_F}} \left(\frac{y_{\ell,EF,t}}{z_{\ell,EF}^{1/\alpha_F}} \right)^{\frac{\alpha_F}{1-\alpha_F}}, \tag{15}$$

where $P_{\ell,F,t}$ is the price of the local fuel composite. Total electricity generation in region ℓ is then given by $y_{\ell,E,t} = y_{\ell,ER,t} + y_{\ell,EF,t}$.

Payments to renewable and fossil-fuel-based electricity capital satisfy

$$r_{\ell,ER,t} K_{\ell,ER,t} = (1-\chi_{ER,t})\, \alpha_R p_{\ell,E,t} y_{\ell,ER,t}, \tag{16}$$

$$r_{\ell,EF,t} K_{\ell,EF,t} = (1-\chi_{EF,t})\, \alpha_F p_{\ell,E,t} y_{\ell,EF,t}. \tag{17}$$

Optimal fuel use by fossil-fuel-based generators implies

$$P_{\ell,F,t} F_{\ell,t} = (1-\alpha_F)\,(1-\chi_{EF,t})\, p_{\ell,E,t} y_{\ell,EF,t}. \tag{18}$$

Because renewable electricity production exhibits decreasing returns to installed renewable capital, renewable generators earn profits equal to

$$\Pi_{\ell,ER,t} = (1-\chi_{ER,t})\,(1-\alpha_R)\, p_{\ell,E,t} y_{\ell,ER,t}. \tag{19}$$

2.4 Demand

2.4.1 Aggregate Income

Let $Inc_{\ell,t}$ denote disposable income in location ℓ. Disposable income consists of labor income, government transfers $T_{\ell,t}$, capital income, and renewable electricity profits:

$$\begin{aligned} Inc_{\ell,t} = & \sum_{j \in J \cup \{F\}} w_{\ell,j,t} L_{\ell,j,t} + T_{\ell,t} \\ & + \sum_{j \in J \cup \{F,ER,EF\}} r_{\ell,j,t} K_{\ell,j,t} + \Pi_{\ell,ER,t}. \end{aligned} \tag{20}$$

The formulation assumes that the capital stocks located in ℓ are owned by capitalists residing in ℓ. Consequently, the corresponding capital income accrues to disposable income in the same location.

2.4.2 Prices

The Armington-differentiated intermediate goods are subject to iceberg trade costs $\tau_{\ell,\ell',j} \geq 1$ when shipped from origin location ℓ to destination location ℓ', with

$$\tau_{\ell,\ell,j} = 1 \qquad \text{for all } \ell \in \mathcal{L} \text{ and } j \in J \cup \{F\}.$$

Therefore, the price in destination location ℓ' of a sector-j intermediate good produced in location ℓ is

$$p_{\ell,\ell',j,t} = p_{\ell,j,t}\tau_{\ell,\ell',j}. \tag{21}$$

It follows that, given the Armington aggregation structure, the price of the sector-j composite in location ℓ is

$$P_{\ell,j,t} = \left(\sum_{k\in\mathcal{L}} \left(p_{k,j,t}\tau_{k,\ell,j}\right)^{1-\rho_j}\right)^{\frac{1}{1-\rho_j}}, \qquad j \in J \cup \{F\}. \tag{22}$$

In turn, the price of the material bundle used by sector j in location ℓ is

$$P^M_{\ell,j,t} = \prod_{n\in J\cup\{F\}} \left(\frac{P_{\ell,n,t}}{\gamma_{j,n}}\right)^{\gamma_{j,n}}. \tag{23}$$

Finally, the price of the final good in location $\ell \in \mathcal{L}$ is

$$P_{\ell,t} = \prod_{j\in J\cup\{F,E\}} \left(\frac{P_{\ell,j,t}}{\mu_j}\right)^{\mu_j}. \tag{24}$$

2.4.3 Expenditure on Sectoral Composites

Workers and capitalists spend their disposable income on the local final good. Because final-good production is Cobb–Douglas, final expenditure in location ℓ on the sector-j composite or electricity E is

$$\mu_j Inc_{\ell,t}, \qquad j \in J \cup \{F, E\}.$$

For each non-fuel intermediate sector $j \in J$, total expenditure in location ℓ on the sector-j Armington composite is

$$X_{\ell,j,t} = \mu_j Inc_{\ell,t} + \sum_{n\in J\cup\{F\}} \gamma_{n,j} P^M_{\ell,n,t} M_{\ell,n,t}. \tag{25}$$

The first term represents the expenditure on the composite good from location ℓ and sector j embodied in the final good, while the second term represents demand for the sector-j composite as a material input.

The fossil-fuel composite is used in the production of the local final good, in the production of location-sector-specific materials, and by local fossil-fuel-based electricity generators. Total expenditure on the fossil-fuel composite in location ℓ is therefore given by:

$$X_{\ell,F,t} = \mu_F Inc_{\ell,t} + \sum_{n \in J \cup \{F\}} \gamma_{n,F} P^M_{\ell,n,t} M_{\ell,n,t} + P_{\ell,F,t} F_{\ell,t}. \tag{26}$$

Finally, total expenditure on electricity is given by

$$X_{\ell,E,t} = \mu_E Inc_{\ell,t} + \sum_{n \in J \cup \{F\}} P_{\ell,E,t} E_{\ell,n,t}. \tag{27}$$

The first term represents electricity demand embodied in local final-good production, while the second term represents electricity demanded by intermediate-good producers.

2.4.4 Demand for Intermediate Goods

For each sector $j \in J \cup \{F\}$, demand in destination location ℓ for an intermediate good sourced from origin location ℓ' is given by

$$q_{\ell',\ell,j,t} = X_{\ell,j,t} \frac{\left(p_{\ell',j,t} \tau_{\ell',\ell,j}\right)^{-\rho_j}}{P^{1-\rho_j}_{\ell,j,t}}, \tag{28}$$

where $X_{\ell,j,t}$ is given by equation (25) for all $j \in J$ and (26) for $j = F$. We now move to the description of the electricity market to obtain the demand faced by local producers of electricity.

2.5 Electricity Market and Transmission

A natural and straightforward approach to modeling electricity transmission across locations would be to treat electricity as an Armington good differentiated by its location of production. However, this approach encounters an important difficulty. Electricity can only be transmitted directly between locations connected by the transmission network. A conventional Armington specification would therefore imply prohibitively high (or infinite) bilateral transmission costs between locations that are not directly connected, such as New York and

Florida. Yet electricity generated in New York may ultimately be consumed in Florida after passing through a sequence of intermediate locations. Consequently, observed electricity flows—for example, from North Carolina to South Carolina—represent only one segment of a longer transmission path rather than the complete origin-to-destination flow. To address this issue, we develop a novel formulation that permits indirect trade in electricity across locations while remaining isomorphic to an Armington structure and implying a transparent mapping between the model and the observed transmission data.

Consider a transmission network with nodes, or locations, denoted by ℓ, k, m, and p. We henceforth use the terms node and location interchangeably. Each node ℓ is directly linked to a set of other nodes $\mathcal{N}_\ell$, which by definition excludes ℓ itself. Each node has a trader who purchases electricity from local generators and from traders in $\mathcal{N}_\ell$, and sells it to local households and producers as well as to traders in $\mathcal{N}_\ell$.

The market for electricity works as follows. Consider each year t as a continuum of seconds $s \in [0, 1]$. For expositional simplicity, we drop the year t subscript in what follows and reintroduce it at the end. Let $\kappa_{k,\ell}$ denote the time invariant component of the iceberg transmission cost of shipping electricity from node k to node ℓ. At each second s, transmission costs are subject to stochastic shocks $(\zeta_{k,\ell}(s))$, so that the **effective** transmission cost between nodes k and ℓ is given by

$$\frac{\kappa_{k,\ell}}{\zeta_{k,\ell}(s)}.$$

At the **beginning of each year**, traders set a **single** electricity price that applies at every second throughout the year. This price is fixed by contract and cannot be adjusted during the year. Traders choose their price **before** knowing the realization of shocks $\zeta_{k,\ell}(s)$ across locations and over time. Let $P_{\ell,E}$ denote the price charged by the trader at node ℓ to local consumers and producers and to traders in connected nodes, before transmission costs.

In every second s, the trader at location ℓ purchases from the lowest-cost source. Local competitive electricity generators sell electricity at price $p_{\ell,E}$ throughout the year. Much like traders, they set their price at the beginning of the year and cannot adjust it second by second. These local competitive electricity generators can only sell their electricity to the location-ℓ trader. Thus, in second s, the trader at ℓ faces cost

$$\frac{p_{\ell,E}\kappa_{\ell,\ell}}{\zeta_{\ell,\ell}(s)}$$

for local electricity, inclusive of the local delivery iceberg cost $\frac{\kappa_{\ell,\ell}}{\zeta_{\ell,\ell}(s)}$. Note that we allow

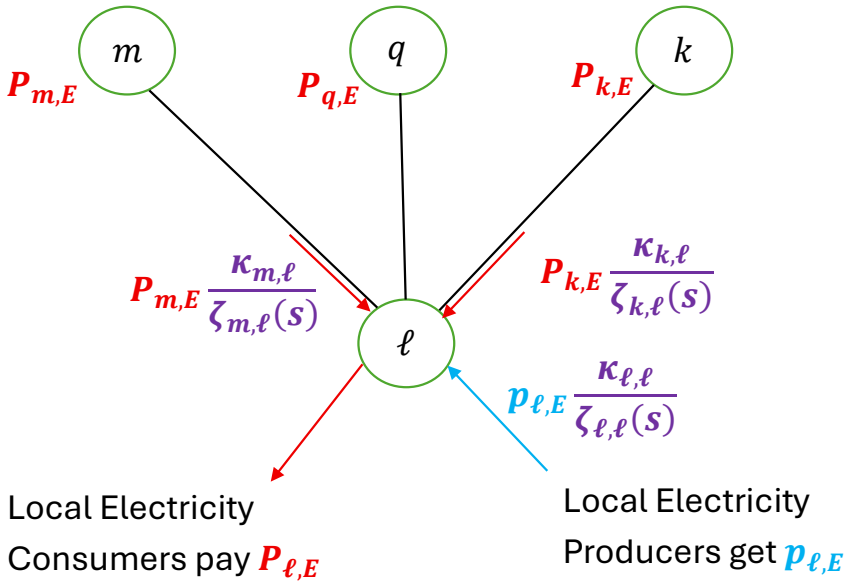


Figure 1: Illustration of the electricity transmission network.

$\kappa_{\ell,\ell} \neq 1$ due to the structure of transmission costs imposed in the calibration.

On the other hand, if the trader at ℓ sources from the network, it pays

$$\min_{k \in \mathcal{N}_\ell} \left\{ \frac{P_{k,E}\kappa_{k,\ell}}{\zeta_{k,\ell}(s)} \right\}$$

in second s. Therefore, the cost of procuring one unit of electricity for the trader at node ℓ in second s is given by:

$$C_{\ell,E}(s) = \min \left\{ \frac{p_{\ell,E}\kappa_{\ell,\ell}}{\zeta_{\ell,\ell}(s)}, \min_{k \in \mathcal{N}_\ell} \left\{ \frac{P_{k,E}\kappa_{k,\ell}}{\zeta_{k,\ell}(s)} \right\} \right\}.$$

The trader in location ℓ makes zero profits on average throughout the year and therefore sets

$$P_{\ell,E} = E_{\boldsymbol{\zeta}}[C_{\ell,E}(s)].$$

This environment is illustrated in Figure 1.

If the $\zeta_{k,\ell}(s)$ shocks are i.i.d. Fréchet with shape θ and scale $\Gamma\left(1+\frac{1}{\theta}\right)^\theta$ then

$$E_{\boldsymbol{\zeta}}[C_{\ell,E}(s)] = \left((p_{\ell,E}\kappa_{\ell,\ell})^{-\theta} + \sum_{k \in \mathcal{N}_\ell} (P_{k,E}\kappa_{k,\ell})^{-\theta} \right)^{-1/\theta}.$$

Hence, and reintroducing the time subscripts, the price $P_{\ell,E,t}$ charged by the trader in location ℓ and time t satisfies:

$$P_{\ell,E,t}^{-\theta} = (p_{\ell,E,t}\kappa_{\ell,\ell})^{-\theta} + \sum_{k\in\mathcal{N}_\ell} (P_{k,E,t}\kappa_{k,\ell})^{-\theta} \tag{29}$$

and depends on the price of local generators $p_{\ell,E,t}$, the price charged by immediately adjacent traders $P_{k,E,t}$ for $k \in \mathcal{N}_\ell$ and their direct time-invariant transmission costs $\kappa_{k,\ell}$.

Once we solve this system, we can then express the electricity price in location ℓ as

$$P_{\ell,E,t}^{-\theta} = \sum_{k\in\mathcal{L}} (\tau_{k,\ell,E}p_{k,E,t})^{-\theta}, \tag{30}$$

where $p_{k,E}$ denotes the producer price of electricity in location k, and $\tau_{k,\ell,E}$ is the effective iceberg transmission cost from origin k to destination ℓ. These effective transmission costs account for all feasible transmission paths through the network and therefore capture costs of shipping electricity from origin k to destination ℓ both directly and indirectly. Appendix B derives these transmission costs and shows how they can be computed from the primitive transmission costs $\kappa_{\ell,k}$. The appendix also derives the quantity that is shipped from k and that actually arrives in ℓ.

$$q_{k,\ell,E,t} = \frac{\tau_{k,\ell,E}^{-(\theta+1)} p_{k,E,t}^{-(\theta+1)}}{P_{\ell,E,t}^{-\theta}} X_{\ell,E,t}, \tag{31}$$

where $X_{\ell,E,t}$ is the total expenditure on electricity in location ℓ—see equation (27).

Finally, Appendix B shows that the total electricity flowing through edge $(i \to j)$ is given by summing the expression above across all origins m and destinations $\ell \in \mathcal{L}$.

$$f_{i,j,E,t} = \sum_{m\in\mathcal{L}} \sum_{\ell\in\mathcal{L}} \left(\frac{\kappa_{j,j}\tau_{m,\ell,E}}{\tau_{m,i,E}\kappa_{i,j}\tau_{j,\ell,E}} \right)^{\theta} \frac{\tau_{m,\ell,E}^{-\theta} p_{m,E,t}^{-(\theta+1)}}{\sum_{k\in\mathcal{L}} (\tau_{k,\ell,E}\, p_{k,E,t})^{-\theta}} X_{\ell,E,t}. \tag{32}$$

As we will show in section 4.2, we will use data on producer prices $p_{\ell,E,t}$, consumer prices $P_{\ell,E,t}$, and flows $f_{i,j,E,t}$ to calibrate the transmission costs $\kappa_{\ell,k}$ and the parameter θ.

2.6 Taxes and Rebates

The government collects output-tax revenue from intermediate-good producers and electricity generators, with negative values of $\chi_{j,t}$ representing subsidies. In our simulations, we

consider two scenarios in which the government taxes fossil-fuel production (i.e., $\chi_{F,t} > 0$): the resulting revenues are either rebated lump sum to workers or used to subsidize renewable electricity generation.

In the first scenario, no other sector is taxed ($\chi_{j,t} = 0$ for $j \neq F$). The per-worker rebate is given by

$$b_t = \frac{\sum_{\ell \in \mathcal{L}} \chi_{F,t} p_{\ell,F,t} y_{\ell,F,t}}{\overline{L}}, \tag{33}$$

where $\overline{L}$ is the country's population, and government transfers to location ℓ are given by

$$T_{\ell,t} = b_t \left(\sum_{j \in J \cup \{F\}} L_{\ell,j,t} + L_{\ell,u,t} \right), \tag{34}$$

where $L_{\ell,u,t}$ denotes the number of unemployed workers in location ℓ at time t.

In the second scenario, worker rebates and transfers are set to zero ($b_t = T_{\ell,t} = 0$). Instead, fossil-fuel-tax revenues are used to subsidize renewable electricity generation. Because $\chi_{ER,t}$ denotes the tax rate on renewable electricity generation, a subsidy corresponds to $\chi_{ER,t} < 0$. The subsidy rate, $-\chi_{ER,t} > 0$, is set so that total subsidy payments equal fossil-fuel-tax revenues:

$$-\chi_{ER,t} = \frac{\sum_{\ell \in \mathcal{L}} \chi_{F,t} p_{\ell,F,t} y_{\ell,F,t}}{\sum_{\ell \in \mathcal{L}} p_{\ell,E,t} y_{\ell,ER,t}}. \tag{35}$$

2.7 Labor Supply

Workers employed in region ℓ and sector j at time t receive a wage $w_{\ell,j,t}$, as well as a tax rebate b_t that is uniform across sectors and locations. Workers may also choose not to work, in which case we say they have state u (for unemployed) and they earn no labor income (so that $w_{\ell,u,t} = 0$). All workers are hand-to-mouth and therefore spend their entire labor income and transfers on the final good in each period.

As in Artuç, Chaudhuri and McLaren (2010), at the end of each period, workers must decide on their location and sector for the next period. If a worker chooses to switch sectors, $j \to n$, migrate, $\ell \to k$, or both, they incur a deterministic switching cost $C_{\ell,j,k,n}$. In addition, in each period, workers receive an idiosyncratic shock to their switching costs, denoted $\varepsilon_{k,n,t}$. For notational convenience, we omit individual-specific subscripts, but these idiosyncratic shocks are independently and identically distributed across workers, time, sectors, and locations. They follow a $Gumbel(-\gamma \times \nu, \nu)$ distribution where γ is the Euler-Mascheroni constant and ν is the scale parameter. The dynamic problem of a worker initially placed in

location ℓ and sector j (including $j = u$) at time t is given by:

$$\begin{aligned}\widetilde{\mathcal{V}}_{\ell,j,t}\left(w_{\ell,j,t}, P_{\ell,t}, b_t, \boldsymbol{\varepsilon}_t\right) = \frac{w_{\ell,j,t} + b_t}{P_{\ell,t}} + \eta_{\ell,j} \\ + \max_{k\in\mathcal{L}, n\in J\cup F\cup u} \Bigg\{ \varepsilon_{k,n,t} - C_{\ell,j,k,n} \\ + \beta E_t\left[\widetilde{\mathcal{V}}_{k,n,t+1}\left(w_{k,n,t+1}, P_{k,t+1}, b_{t+1}, \boldsymbol{\varepsilon}_{t+1}\right)\right] \Bigg\},\end{aligned} \tag{36}$$

where $P_{\ell,t}$ is the price of the location-ℓ-specific final good, $\eta_{\ell,j}$ is a time-invariant, non-pecuniary value of being in location ℓ and sector j, β is the discount factor, and E_t is the expectation operator over future wages, prices, transfers, and idiosyncratic shocks, conditional on information available at time t.

We integrate over the idiosyncratic shocks to obtain the expected value function—henceforth referred to simply as the value function—and the associated transition rates. Applying this integration to equation (36) yields:

$$\begin{aligned}\mathcal{V}_{\ell,j,t}(w_{\ell,j,t}, P_{\ell,t}, b_t) = \frac{w_{\ell,j,t} + b_t}{P_{\ell,t}} + \eta_{\ell,j} \\ + \nu \log\left(\sum_{k\in\mathcal{L}, n\in J\cup\{F\}\cup\{u\}} \exp\left(\frac{-C_{\ell,j,k,n} + \beta E_t\left[\mathcal{V}_{k,n,t+1}(w_{k,n,t+1}, P_{k,t+1}, b_{t+1})\right]}{\nu}\right)\right)\end{aligned} \tag{37}$$

where the expectation operator E_t now refers only to expectations over the future path of wages, prices and transfers. Aggregating workers' decisions at the end of period t, we obtain that transition rates between t and $t+1$ take the convenient logit form:

$$m_{\ell,j,k,n,t} = \frac{\exp\left(\frac{-C_{\ell,j,k,n} + \beta E_t \mathcal{V}_{k,n,t+1}}{\nu}\right)}{\sum_{k'\in\mathcal{L}, n'\in J\cup\{F\}\cup\{u\}} \exp\left(\frac{-C_{\ell,j,k',n'} + \beta E_t \mathcal{V}_{k',n',t+1}}{\nu}\right)}, \tag{38}$$

with the arguments of $\mathcal{V}_{k,n,t+1}$ omitted for concision, and where $\ell, k \in \mathcal{L}$, and $j, n \in J \cup \{F\} \cup \{u\}$. These transition rates imply the following law of motion for labor supply:

$$L^S_{k,n,t+1} = \sum_{\ell\in\mathcal{L}, j\in J\cup\{F\}\cup\{u\}} m_{\ell,j,k,n,t} L^S_{\ell,j,t}, \tag{39}$$

where $L^S_{\ell,j,t}$ is the supply of labor to region ℓ, sector $j \in J \cup \{F\} \cup \{u\}$ at time t.

2.8 Capital Supply

The capital stock in location $\ell \in \mathcal{L}$ and sector $j \in J \cup \{F, ER, EF\}$ evolves according to

$$K_{\ell,j,t+1} = (1 - \delta_j)K_{\ell,j,t} + \xi_{\ell,j} Inv_{\ell,j,t}, \tag{40}$$

where $K_{\ell,j,t}$ denotes the capital stock available for production and $Inv_{\ell,j,t}$ denotes investment in location ℓ and sector j at time t, measured in units of the local final good. The parameter δ_j is the sector-specific depreciation rate, and $\xi_{\ell,j}$ is a location-sector-specific unit conversion rate between investment and capital. This conversion rate is particularly useful when capital is measured in physical units, such as MWh of installed electricity-generation capacity.

Because investment is measured in units of the local final good, the local aggregate resource constraint is

$$C_{\ell,t} + Inv_{\ell,t} = Q_{\ell,t}, \tag{41}$$

where $C_{\ell,t}$ is total consumption of the local final good in location ℓ (by workers and capital owners) and aggregate investment in location ℓ is

$$Inv_{\ell,t} = \sum_{j \in J \cup \{F,ER,EF\}} Inv_{\ell,j,t}. \tag{42}$$

We assume that capitalists are specific to a location-sector pair, are immobile, and can invest only in their own location and sector. The capitalist associated with location-sector pair (ℓ, j) chooses investment to maximize the present value of real net income:

$$\max_{\{K_{\ell,j,t+1}, Inv_{\ell,j,t}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \left(\frac{r_{\ell,j,t} K_{\ell,j,t}}{P_{\ell,t}} - Inv_{\ell,j,t} \right), \tag{43}$$

subject to the capital accumulation constraint (40) and investment irreversibility

$$Inv_{\ell,j,t} \geq 0, \tag{44}$$

taking the initial capital stock $K_{\ell,j,0}$ as given.

Let $\beta^t \widetilde{\mu}_{\ell,j,t}$ denote the multiplier on the period-t capital accumulation constraint (40). Write the nonnegative-investment constraint (44) as $-Inv_{\ell,j,t} \leq 0$, and let $\beta^t \widetilde{\lambda}_{\ell,j,t}$ denote its

multiplier, where $\widetilde{\lambda}_{\ell,j,t} \geq 0$. The Lagrangian of the capitalist's problem is given by

$$\mathcal{L} = \sum_{t=0}^{\infty} \beta^t \Bigg(\frac{r_{\ell,j,t} K_{\ell,j,t}}{P_{\ell,t}} - Inv_{\ell,j,t} \\ - \widetilde{\mu}_{\ell,j,t} \left(K_{\ell,j,t+1} - (1-\delta_j) K_{\ell,j,t} - \xi_{\ell,j} Inv_{\ell,j,t} \right) + \widetilde{\lambda}_{\ell,j,t} Inv_{\ell,j,t} \Bigg). \tag{45}$$

For $t \geq 1$, the first-order condition with respect to $K_{\ell,j,t}$ is

$$\beta^t \frac{r_{\ell,j,t}}{P_{\ell,t}} + \beta^t (1-\delta_j) \widetilde{\mu}_{\ell,j,t} - \beta^{t-1} \widetilde{\mu}_{\ell,j,t-1} = 0, \tag{46}$$

implying,

$$\widetilde{\mu}_{\ell,j,t} = \beta \left(\frac{r_{\ell,j,t+1}}{P_{\ell,t+1}} + (1-\delta_j) \widetilde{\mu}_{\ell,j,t+1} \right). \tag{47}$$

The first-order condition with respect to $Inv_{\ell,j,t}$ is

$$-1 + \xi_{\ell,j} \widetilde{\mu}_{\ell,j,t} + \widetilde{\lambda}_{\ell,j,t} = 0. \tag{48}$$

Together with the Kuhn–Tucker conditions

$$Inv_{\ell,j,t} \geq 0, \qquad \widetilde{\lambda}_{\ell,j,t} \geq 0, \qquad \widetilde{\lambda}_{\ell,j,t} Inv_{\ell,j,t} = 0, \tag{49}$$

this implies

$$\xi_{\ell,j} \widetilde{\mu}_{\ell,j,t} \leq 1, \tag{50}$$

and

$$Inv_{\ell,j,t} \left(1 - \xi_{\ell,j} \widetilde{\mu}_{\ell,j,t} \right) = 0. \tag{51}$$

Equivalently,

$$\xi_{\ell,j} \widetilde{\mu}_{\ell,j,t} = 1 \qquad \text{if } Inv_{\ell,j,t} > 0, \tag{52}$$

$$\xi_{\ell,j} \widetilde{\mu}_{\ell,j,t} \leq 1 \qquad \text{if } Inv_{\ell,j,t} = 0. \tag{53}$$

The infinite-horizon solution must satisfy the usual transversality condition. This condition is automatically satisfied along any stationary equilibrium with finite capital stocks and shadow values, since $\beta < 1$.

In a steady state, equation (47) becomes

$$\widetilde{\mu}_{\ell,j} = \beta \frac{r_{\ell,j}}{P_\ell} + \beta(1-\delta_j)\widetilde{\mu}_{\ell,j}, \tag{54}$$

and hence

$$\widetilde{\mu}_{\ell,j} = \frac{\beta}{1-\beta(1-\delta_j)} \frac{r_{\ell,j}}{P_\ell}. \tag{55}$$

If $Inv_{\ell,j} > 0$, complementary slackness implies

$$\xi_{\ell,j}\widetilde{\mu}_{\ell,j} = 1. \tag{56}$$

Substituting equation (55) yields

$$\frac{r_{\ell,j}}{P_\ell} = \left(\frac{1}{\beta} - (1-\delta_j)\right) \frac{1}{\xi_{\ell,j}}. \tag{57}$$

If $Inv_{\ell,j} = 0$, the optimality condition is instead

$$\xi_{\ell,j}\widetilde{\mu}_{\ell,j} \leq 1. \tag{58}$$

Moreover, the steady-state capital accumulation equation implies

$$\delta_j K_{\ell,j} = \xi_{\ell,j} Inv_{\ell,j}. \tag{59}$$

2.9 Equilibrium

Consider a path of taxes/subsidies $\{\chi_{j,t}\}_{j\in J\cup\{F,ER,EF\}}$ for $t = 0, ..., \infty$. We assume the economy is initially in a steady state given taxes/subsidies $\{\chi_{j,0}\}_{j\in J\cup\{F,ER,EF\}}$ and that the path of taxes is revealed at the end of $t = 0$, *after* workers have decided their regions and sectors of employment at $t = 1$ and *after* capitalists have made their investments. Therefore, labor allocations and capital stocks at $t = 1$ are set at $t = 0$ levels. There is no aggregate uncertainty, so workers and capitalists have perfect foresight about future equilibrium variables. We take aggregate nominal income in the U.S., $\sum_{\ell\in\mathcal{L}} Inc_{\ell,t}$, as the numeraire.

Conditional on initial conditions $\{K_{\ell,j,0}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F,ER,EF\}}$, $\{L_{\ell,j,0}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F\}\cup\{u\}}$, a dynamic equilibrium in this economy is given by paths of (a) wages $\{w_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F\}}$; (b) capital

rental rates $\{r_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F,ER,EF\}}$; (c) intermediate goods prices $\{p_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F\}}$, electricity producer prices $\{p_{\ell,E,t}\}_{\ell\in\mathcal{L}}$; (d) labor allocations $\{L_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F\}\cup\{u\}}$; (e) investments $\{Inv_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F,ER,EF\}}$; (f) capital allocations $\{K_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F,ER,EF\}}$; (g) production $\{y_{\ell,j,t}\}_{\ell\in\mathcal{L},j\in J\cup\{F,ER,EF\}}$ and shipments $\{q_{k,\ell,j,t}\}_{k,\ell,\in\mathcal{L},\, j\in J\cup\{F\}}$ and $\{q_{k,\ell,E,t}\}_{k,\ell,\in\mathcal{L}}$; and (h) transfers b_t such that:

1. Prices $\{P_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F\}}$, $\left\{P^M_{\ell,j,t}\right\}_{\ell\in\mathcal{L},\, j\in J\cup\{F\}}$, $\{P_{\ell,t}\}_{\ell\in\mathcal{L}}$ and $\{P_{\ell,E,t}\}_{\ell\in\mathcal{L},}$ are given by equations (22), (23), (24) and (30) respectively.

2. Given wages, prices, and transfers b_t, workers solve the Bellman equations (37) implying transition rates given by (38).

3. Labor supply $\left\{L^S_{k,n,t}\right\}$ across locations $k \in \mathcal{L}$ and sectors $n \in J \cup \{F\} \cup \{u\}$ satisfies equation (39), except for $t = 1$. Given our assumptions on timing:

$$L^S_{k,n,1} = L^S_{k,n,0}\ \forall k, n.$$

4. Capital rental rates $\{r_{\ell,j,t}\}_{\ell\in\mathcal{L},j\in J\cup\{F,ER,EF\}}$ and Lagrange multipliers $\{\widetilde{\mu}_{\ell,j,t}\}_{\ell\in\mathcal{L},j\in J\cup\{F,ER,EF\}}$ satisfy the first order conditions given by equation (47) and complementary slackness conditions

$$\widetilde{\mu}_{\ell,j,t}\xi_{\ell,j} - 1 \leq 0 \text{ and } Inv_{\ell,j,t}\left(\widetilde{\mu}_{\ell,j,t}\xi_{\ell,j} - 1\right) = 0.$$

   Given our assumptions on timing, $\{K_{\ell,j,1}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F,ER,EF\}}$ is pre-determined. The equations above must hold starting at $t = 1$. We also invoke a terminal condition where $\widetilde{\mu}_{\ell,j,T}$ and $\frac{r_{\ell,j,T}}{P_{\ell,T}}$ come from the final steady state.

5. Capital stocks $\{K_{\ell,j,t}\}_{\ell\in\mathcal{L},\, j\in J\cup\{F,ER,EF\}}$ evolve according to equation (40). As with labor, capital at $t = 1$ is determined at $t = 0$ and so:

$$K_{\ell,j,1} = K_{\ell,j,0}.$$

6. Aggregate income in region $\ell \in \mathcal{L}$ is given by equation (20).

7. If the government rebates tax revenues to workers, transfers are given by equations (33) and (34). Otherwise, $T_{\ell,t} = b_t = 0$ and the government instead subsidizes renewable electricity generation using equation (35).

8. Input demands $L_{\ell,j,t}$, $M_{\ell,j,t}$, $K_{\ell,j,t}$, and $E_{\ell,j,t}$ for locations $\ell \in \mathcal{L}$ and $j \in J \cup \{F\}$ satisfy equations (11), (12), (13) and (10) respectively.

9. The demand for electricity capital satisfies equations (16) and (17), and the demand for fuel from fossil-fuel based electricity producers is given by equation (18).

10. Shipments $\{q_{k,\ell,j,t}\}$ for $k, \ell \in \mathcal{L}$ and $j \in J \cup \{F\}$ are given by equation (28). For electricity, they are given by equation (31).

11. Renewable electricity production $y_{\ell,ER,t}$ is given by equation (5) with equality. If $K_{\ell,EF,t} > 0$, fuel-based electricity production $y_{\ell,EF,t}$ satisfies the zero profit condition (15), otherwise, $y_{\ell,EF,t} = 0$. Total electricity production $\{y_{\ell,E,t}\}$ for $\ell \in \mathcal{L}$ is given by:

$$y_{\ell,E,t} = y_{\ell,ER,t} + y_{\ell,EF,t}.$$

12. Markets clear:

- **Labor markets** clear at the (ℓ, j) level for all ℓ and $j \in J \cup \{F\}$.

$$L_{\ell,j,t} = L^S_{\ell,j,t}$$

  Labor supply $L^S_{\ell,j,t}$ is determined by equation (39), while labor demand $L_{\ell,j,t}$ is determined by equation (11).

- **Capital markets** clear at the (ℓ, j) level for all ℓ and $j \in J \cup F, ER, EF$. The supply of capital at time t is determined by equation (40) and must equal capital demand. For $j \in J \cup F$, capital demand is determined by equation (13), while for $j \in ER, EF$ it is determined by equations (16) and (17), respectively.

- **Goods and electricity markets** clear for all $\ell \in \mathcal{L}$ and all $j \in J \cup \{F, E\}$:

$$\sum_{k \in \mathcal{L}} q_{\ell,k,j,t}\, \tau_{\ell,k,j} = y_{\ell,j,t},$$

  where $y_{\ell,j,t}$ is given by equation (1) for $j \in J \cup \{F\}$ and $y_{\ell,E,t} = y_{\ell,ER,t} + y_{\ell,EF,t}$.

3 Data

3.1 Locations and Sectors

We use the 48 contiguous U.S. states as our geographic units, grouping the District of Columbia with Maryland and excluding Alaska and Hawaii. We consider 33 sectors defined according to the 2022 North American Industry Classification System (NAICS). A complete list of sectors, $J \cup \{F\}$, is provided in Table A.1 in Appendix A. Our reference year is 2017, and, whenever possible, we use five-year averages over 2015–2019 to improve measurement precision.

3.2 Production, Employment and Trade

State- and sector-specific value added comes from the Bureau of Economic Analysis (BEA) Regional Economic Accounts. We pool data from 2015 to 2019 and treat the resulting values as 2017 levels. Sector-specific gross output, value added, and wage bills come from the 2017 BEA Use Table. We also use the 2017 BEA Supply and Use Tables to construct the sectoral input-output linkages ($\gamma_{j,n}$), production cost shares (β_j^E, β_j^L, β_j^M, β_j^K), and final expenditure shares (μ_j) used in the model.

We use the BEA Fixed Assets Accounts to calculate sector-specific depreciation rates. For each year from 2015 to 2019, we divide annual depreciation by the historical-cost net stock of private fixed assets and use the five-year average as the 2017 depreciation rate δ_j for $j \in J \cup \{F, ER, EF\}$. Given the lack of depreciation rates specific to renewable- and fossil-fuel-based electricity production, we impose $\delta_{ER} = \delta_{EF}$.

We use the American Community Survey (ACS) to measure state- and sector-specific labor allocations and worker flows across states and sectors. We complement the ACS data on region-to-region-sector worker flows with sector-to-sector worker flows from the Current Population Survey (CPS). To increase precision, we pool annual ACS and CPS samples from 2015 to 2019 and construct five-year averages, which we treat as 2017 values.

Sector-specific interstate trade flows come from the U.S. Census Bureau's Commodity Flow Survey (CFS). The CFS is released every five years; to reduce measurement noise, we average data from the 2012 and 2017 waves and treat the resulting values as 2017 levels. These data provide the interstate trade flows used in the calibration.

3.3 Electricity Production and Usage

We use 2017 data from the Energy Information Administration (EIA) to construct state-level measures of installed electricity generation capacity and electricity generation by production technology (renewable or fossil-fuel based), as well as prices received by electricity generators, prices paid by end users, and total end-user expenditures.

Renewable sources of electricity include solar, wind, geothermal, hydroelectric, and nuclear; non-renewable sources include coal, natural gas, petroleum, other biomass and gases, and wood and wood-derived fuels.

Form EIA-860 provides nameplate capacity by electricity type and state, which maps directly into $K_{\ell,ER}$ and $K_{\ell,EF}$. The Power Plant Operations Report (Form EIA-923) provides net generation by energy type and state, which maps into $y_{\ell,ER}$ and $y_{\ell,EF}$. For both capacity and generation, we aggregate electric utilities and independent power producers and exclude combined heat-and-power plants that produce energy for in-house use.

We compute $p_{\ell,E}$ as revenues from state-specific wholesale electricity sales (Schedule 7A) divided by the corresponding quantity of wholesale electricity sold (Schedule 6), measured in \$/MWh. Finally, we obtain 2017 state-level end-user electricity prices $P_{\ell,E}$ and electricity expenditures $X_{\ell,E}$ from the EIA mandatory annual census (Form EIA-861).

3.4 Electricity Transmission

We use EIA Form 930 to measure directional electricity flows between balancing authorities (BAs). We construct average annual flows using hourly data from July 2015 through June 2019. Because BA territories do not generally coincide with state borders, Form EIA-930 does not directly provide state-to-state electricity flows. We therefore use 2017 Form EIA-860 data to associate power plants with counties and BAs and assign each county to its dominant BA—the BA accounting for the largest share of installed nameplate capacity. We use this mapping to allocate BA-to-BA electricity flows across states and construct directional state-to-state flows or, when not feasible, directional flows between groups of states. Further details are provided in Appendix A.2.1.

These flow data, together with producer and end-user electricity prices $p_{\ell,E}$ and $P_{\ell,E}$ and local electricity expenditures $X_{\ell,E}$, provide the basis for disciplining the interstate electricity transmission parameters $\kappa_{\ell,k}$ and θ.

Table 1: Parameters Calibrated Externally

Parameter	Description	Value	Source
ρ_j, $j \in J$	Armington elasticity	5	Standard
ρ_F	Armington elasticity for fuel	10	Broda and Weinstein (2006)
χ_j, $j \in J \cup \{F, ER, EF\}$	Output taxes in the baseline	0	—
α_R	Elasticity of renewable electricity production w.r.t. K_{ER}	0.73	Johnson (2014)
α_F	Capital share in fossil-fuel electricity production	0.7	Arkolakis and Walsh (2023)
β	Intertemporal discount factor	0.95	Standard

4 Calibration

Our calibration imposes a series of parameter values that are standard in the literature. The Armington elasticity ρ_j is imposed to be equal to 5 for sectors $j \in J$, a value standard in the international trade literature. We impose $\rho_F = 10$, reflecting greater substitutability among sources of fuels (Broda and Weinstein, 2006). In our baseline calibration, we set output taxes χ_j to 0. We follow Arkolakis and Walsh (2023) and set the capital share in fossil-fuel electricity production α_F to 0.7 (the fuel share is $1 - \alpha_F$). We set $\alpha_R = 0.73$ so that the model matches the long-run elasticity of renewable electricity output with respect to electricity prices, equal to 2.67, as estimated by Johnson (2014). The intertemporal discount factor is set to the standard value of 0.95. These parameters are summarized in Table 1.

We calibrate the following set of parameters using the structure of the model:

a) Trade costs: $\{\tau_{\ell,k,j}\}_{\ell,k\in\mathcal{L},j\in J\cup\{F\}}$.

b) Transmission costs: $\{\kappa_{k,\ell}\}_{k\in\mathcal{L},\ell\in\mathcal{L}}$ and θ.

c) Production function coefficients and capital stocks: $\left\{\beta_j^L\right\}_{j\in J\cup\{F\}}$, $\left\{\beta_j^M\right\}_{j\in J\cup\{F\}}$, $\left\{\beta_j^K\right\}_{j\in J\cup\{F\}}$ $\left\{\beta_j^E\right\}_{j\in J\cup\{F\}}$.

d) Final goods production coefficients: $\{\mu_j\}_{j\in J\cup\{F,E\}}$.

e) Armington-differentiated intermediate good productivities: $\{z_{\ell,j}\}_{\ell\in\mathcal{L},j\in J\cup\{F\}}$.

f) Renewable and fuel-based electricity productivities: $\{z_{\ell,ER}\}_{\ell\in\mathcal{L}}$ and $\{z_{\ell,EF}\}_{\ell\in\mathcal{L}}$.

g) Labor supply parameters: ν, $\{C_{\ell,j,k,n}\}_{\ell,k\in\mathcal{L},j,n\in J\cup\{F\}\cup\{u\}}$ and $\{\eta_{\ell,j}\}_{\ell\in\mathcal{L},j\in J\cup\{F\}\cup\{u\}}$.

In the remainder of this section, we briefly describe each set of parameters, with additional details provided in Appendix C. For calibration purposes, we assume that the economy in 2017 is in steady state.

4.1 Trade Costs

We use the Commodity Flow Survey (CFS) and the Head and Ries (2001) formula to obtain trade costs across all pairs of locations. Under symmetric trade costs, and given the sector-specific trade elasticity, ρ_j, trade costs can be calculated from observed flows as:

$$\tau_{\ell,k,j} = \left(\frac{X_{k,\ell,j}}{X_{k,k,j}}\frac{X_{\ell,k,j}}{X_{\ell,\ell,j}}\right)^{\frac{1}{2\left(1-\rho_j\right)}}, \tag{60}$$

where $X_{\ell,k,j}$ are total trade flows in sector j from location ℓ to location k.

A number of sectors are not surveyed by the CFS, especially in tradable services (see Appendix Table A.1). To impute trade costs in these sectors, we first regress sector-specific log trade costs constructed using equation (60) on origin and destination fixed effects and log distance between origin ℓ and destination k, allowing the coefficient on log distance to vary across sectors:

$$\log\left(\tau_{\ell,k,j}\right) = \zeta_j \log\left(distance_{\ell,k}\right) + \phi_\ell + \psi_k + \varepsilon_{\ell,k,j}.$$

To guarantee symmetry, we impose $\phi_\ell = \psi_\ell$ for all ℓ in the above specification. [2]

For sectors not covered by the CFS, we set the trade cost elasticity to distance to $\zeta_j = -1.6/(1-\rho_j)$, following Eckert (2019), who estimates the distance elasticity for service sectors.[3] We then impute trade costs in these sectors using

$$\log\left(\tau_{\ell,k,j}\right) = \zeta_j \log\left(distance_{\ell,k}\right) + \widehat{\phi}_\ell + \widehat{\phi}_k.$$

[2] We also exclude observations with $\tau_{\ell,k,j} = 1$ and $\tau_{\ell,k,j} = \infty$.

[3] Eckert (2019) estimates the elasticity of $\tau_{\ell,k,j}^{1-\rho_j}$ to distance between regions ℓ and k, separately for goods and services, for different decades; 1.6 is its average estimate.

4.2 Electricity Transmission Costs

We exploit equations (30) and (32) to calibrate transmission costs $\kappa_{k,\ell}$ and the volatility parameter θ. Intuitively, conditional on θ, equation (30), together with observed producer and end-user electricity prices, disciplines transmission costs $\kappa_{k,\ell}$. Conditional on these transmission costs, equation (32), together with observed electricity flows, producer prices, and local electricity expenditures, disciplines θ. In practice, we jointly estimate $\kappa_{k,\ell}$ and θ by minimizing the distance between predicted and observed electricity prices $P_{\ell,E}$ and flows $f_{\ell,k,E}$. We provide further details below.

Bilateral transmission costs are parameterized as:

$$\kappa_{\ell,k} = \begin{cases} \exp(\gamma_\ell), & \text{if } \ell = k, \\ \exp(\gamma_\ell + \gamma_k), & \text{if } k \in \mathcal{N}_\ell, \\ \infty, & \text{if } k \notin \mathcal{N}_\ell \cup \{\ell\} \end{cases} . \tag{61}$$

That is, provided locations ℓ and k are connected through the network, the transmission cost from ℓ to k depends on an ℓ-specific term and a k-specific term. Conditional on θ, this structure allows us to identify transmission costs from cross-location variation in observed electricity producer prices $p_{\ell,E}^{Data}$ and end-user prices $P_{\ell,E}^{Data}$.

For a candidate parameter vector (γ, θ), we construct $\kappa_{\ell,k}$ according to equation (61), compute

$$\widetilde{\kappa}_{k,\ell} \equiv \begin{cases} \kappa_{k,\ell}^{-\theta}, & \text{if } k \in \mathcal{N}_\ell \cup \{\ell\} \\ 0, & \text{if } k \notin \mathcal{N}_\ell \cup \{\ell\} \end{cases},$$

and set

$$\widetilde{\tau}'_E = (I - \widehat{\kappa})^{-1} Diag\left(\widetilde{\kappa}\right),$$

where

$$\widehat{\kappa} = \widetilde{\kappa} - Diag\left(\widetilde{\kappa}\right).$$

Finally, we set $\tau_{\ell,k,E} = \widetilde{\tau}_{\ell,k,E}^{-1/\theta}$.

Given data on producer prices $p_{\ell,E}^{Data}$, the corresponding model-implied consumer price in state ℓ is given by

$$P_{\ell,E}^{Model} = \left(\sum_{k \in \mathcal{L}} \tau_{k,\ell,E}^{-\theta} \left(p_{k,E}^{Data} \right)^{-\theta} \right)^{-1/\theta}.$$

According to the model, electricity flows between *directly* connected locations i and j are

given by:

$$f_{i,j,E}^{Model} = \sum_{m \in \mathcal{L}} \sum_{\ell \in \mathcal{L}} \left(\frac{\kappa_{j,j} \tau_{m,\ell,E}}{\tau_{m,i,E} \kappa_{i,j} \tau_{j,\ell,E}} \right)^{\theta} \frac{\tau_{m,\ell,E}^{-\theta} (p_{m,E}^{Data})^{-(\theta+1)} X_{\ell,E}^{Data}}{\sum_{k \in \mathcal{L}} (\tau_{k,\ell,E} p_{k,E}^{Data})^{-\theta}},$$

where $X_{\ell,E}^{Data}$ denotes observed end-user expenditure on electricity in location ℓ, obtained from the EIA. This expression captures the fact that, among the total electricity flow from location i to a directly connected location j, some electricity may originate in other locations $m \in \mathcal{L}$ and ultimately be consumed in downstream locations $\ell \in \mathcal{L}$. Thus, for example, part of the electricity flow observed between New York and Pennsylvania may have originated in Maine and may ultimately be consumed in Florida.

The expression above defines state-to-state electricity flows, $f_{i,j,E}^{Model}$, for each pair of directly connected locations $i, j \in \mathcal{L}$. Unfortunately, not all flows observed in the EIA data can be unambiguously mapped into state-to-state flows. For example, the EIA reports electricity flows between the Independent System Operators for New England and New York, denoted ISNE and NYIS, respectively. The reported data measure aggregate electricity transmission between New England and New York, but do not separately identify Connecticut–New York, Massachusetts–New York, and Vermont–New York flows.

For this reason, to exploit as much of the information contained in the EIA data as possible, we construct aggregate electricity flows between *groups* of states.[4]

Let $\mathcal{G}$ denote a partition of $\mathcal{L}$ into groups of states. In the example above, New York forms a group consisting of a single state, whereas the relevant New England group comprises Connecticut, Massachusetts, and Vermont.

For any two groups $g, g' \in \mathcal{G}$, we define the directional electricity flow from g to g', $F_{g,g',E}^{Model}$, as the sum of all state-to-state flows from locations in g to directly connected locations in g':

$$F_{g,g',E}^{Model} = \sum_{i \in g} \sum_{j \in g'} f_{i,j,E}^{Model}.$$

[4]As explained in Section 3.4, the EIA reports electricity flows between balancing authorities, whose territories do not coincide with state borders. For a more detailed discussion of this issue, see Appendix A.2.1.

The estimates of (γ, θ) solve

$$
\begin{aligned}
(\widehat{\gamma}, \widehat{\theta}) = \arg\min_{\gamma,\theta} \quad & \sum_{\ell \in \mathcal{L}} \omega_\ell \left(\frac{P_{\ell,E}^{Model} - P_{\ell,E}^{Data}}{P_{\ell,E}^{Model} + P_{\ell,E}^{Data}} \right)^2 \\
& + \frac{1}{2} \sum_{g \in \mathcal{G}} \sum_{g' \in \mathcal{G}} \left(\frac{F_{g,g',E}^{Model} - F_{g,g',E}^{Data}}{F_{g,g',E}^{Model} + F_{g,g',E}^{Data}} \right)^2 \\
& + \left(\frac{\sum_{g \in \mathcal{G}} \sum_{g' \in \mathcal{G}} F_{g,g',E}^{Model} - \sum_{g \in \mathcal{G}} \sum_{g' \in \mathcal{G}} F_{g,g',E}^{Data}}{\sum_{g \in \mathcal{G}} \sum_{g' \in \mathcal{G}} F_{g,g',E}^{Model} + \sum_{g \in \mathcal{G}} \sum_{g' \in \mathcal{G}} F_{g,g',E}^{Data}} \right)^2 .
\end{aligned}
$$

The loss function therefore minimizes a weighted distance between model-predicted and observed end-user electricity prices and between model-predicted and observed directional electricity flows.[5] As explained above, the first component of the loss function—the price deviations—primarily disciplines the transmission costs $\kappa_{k,\ell}$, while the second—the electricity-flow deviations—primarily disciplines θ. The final component penalizes discrepancies between the aggregate level of the selected model-implied flows and their empirical counterparts, serving as a safeguard against solutions in which electricity flows are systematically too high or too low.

4.3 Production Function Coefficients

Production function coefficients are calibrated from expenditure shares constructed from the BEA data. Labor, materials, and electricity shares (β_j^L, β_j^M, and β_j^E) are computed using sector-specific data on the wage bill, gross output, value added, and electricity expenditures. Capital shares are obtained residually as $\beta_j^K = 1 - \beta_j^L - \beta_j^M$. Input-output linkage parameters $\gamma_{j,n}$ are calibrated from the BEA input-output matrix. Details are provided in Appendix C.3 (see steps 1 to 5).

BEA value added is measured at the region-sector level. Together with the calibrated shares β_j^L, β_j^M, β_j^K, and β_j^E, these data allow us to recover intermediate goods producers' payments to labor, materials ($X_{\ell,j}^M$), capital, and electricity ($X_{\ell,j}^E$) at the state-sector level. In particular, we recover capital payments $r_{\ell,j} K_{\ell,j}$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$. We then use the structure of the model, equation (57), and the normalization $\xi_{\ell,j} = 1$ to recover capital stocks $K_{\ell,j}$, which are not directly observed in the data. Details are provided in step 22 of

[5] Let $VA_\ell = \sum_{j \in J \cup F} VA_{\ell,j}^{BEA}$ denote total value added in state ℓ. The state-specific weight is $\omega_\ell = \frac{|\mathcal{L}| \sqrt{VA_\ell / \sum_{r \in \mathcal{L}} VA_r}}{\sum_{s \in \mathcal{L}} \sqrt{VA_s / \sum_{r \in \mathcal{L}} VA_r}}$.

Appendix C.3.

4.4 Intermediate Goods Productivities

At this point, we have region-sector-specific value added from the BEA ($VA^{BEA}_{\ell,j}$), expenditure shares (β^E_j, β^M_j, $\gamma_{n,j}$), region-sector expenditures on materials and electricity ($X^M_{\ell,j}$, $X^E_{\ell,j}$), trade costs $\tau_{\ell,k,j}$, Armington elasticities ρ_j, reduced-form electricity transmission costs $\tau_{\ell,k,E}$, and the transmission-cost volatility parameter θ. We use these objects to recover final-expenditure shares μ_j and intermediate-good productivities $z_{\ell,j}$.

We proceed iteratively. Given an initial guess for producer prices $p_{\ell,j}$, we recover local income Inc_ℓ and national-level aggregate income. Together with sector-level BEA data on gross output and electricity expenditures, these objects allow us to recover the final-expenditure shares μ_j. We then use the following equations implied by the model to update producer prices:

$$p^{new}_{\ell,j} = \left(\frac{\frac{VA^{BEA}_{\ell,j}}{\left(1-\beta^E_j\right)\left(1-\beta^M_j\right)}}{\sum_{k\in\mathcal{L}} \left(\mu_j Inc_k + \sum_{n\in J\cup F} \gamma_{n,j} X^M_{k,n}\right) \frac{\left(\tau_{\ell,k,j}\right)^{1-\rho_j}}{P^{1-\rho_j}_{k,j}}} \right)^{\frac{1}{1-\rho_j}} \qquad \text{for } j \in J,$$

$$p^{new}_{\ell,F} = \left(\frac{\frac{VA^{BEA}_{\ell,F}}{\left(1-\beta^E_F\right)\left(1-\beta^M_F\right)}}{\sum_{k\in\mathcal{L}} \left(\mu_F Inc_k + \sum_{n\in J\cup F} \gamma_{n,F} X^M_{k,n} + \left(1-\alpha_F\right) p_{k,E} y_{k,EF}\right) \frac{\left(\tau_{\ell,k,F}\right)^{1-\rho_F}}{P^{1-\rho_F}_{k,F}}} \right)^{\frac{1}{1-\rho_F}},$$

and

$$p^{new}_{\ell,E} = \left(\frac{y_{\ell,E}}{\sum_{k\in\mathcal{L}} \left(\mu_E Inc_k + \sum_{n\in J\cup F} X^E_{k,n}\right) \frac{\tau^{-\theta}_{\ell,k,E}}{P^{-\theta}_{k,E}}} \right)^{-\frac{1}{\theta+1}}.$$

We iterate on these equations until producer prices converge. Given the resulting producer prices $p_{\ell,j}$, we compute local prices P_ℓ, local material prices $P^M_{\ell,j}$, and local electricity prices $P_{\ell,E}$. Using region-sector employment from the American Community Survey, we then recover wages $w_{\ell,j}$. Finally, using the steady-state version of the capitalists' Euler equation, we recover rental rates $r_{\ell,j}$.

We then construct unit costs according to

$$\overline{c}_{\ell,j} = P_{\ell,E}^{\beta_j^E} \left(c_{\ell,j}^{LMK}\right)^{1-\beta_j^E},$$

and recover intermediate-good productivities as

$$z_{\ell,j} = \frac{\overline{c}_{\ell,j}}{p_{\ell,j}}.$$

The details of this procedure are outlined in steps 10 to 15 of Appendix C.3.

4.5 Electricity Productivities

Given data on fossil-fuel and renewable electricity production, $y_{\ell,EF}$ and $y_{\ell,ER}$, and the corresponding capital stocks, $K_{\ell,EF}$ and $K_{\ell,ER}$, together with model-implied values for the local producer price of electricity, $p_{\ell,E}$, and the local price of the fossil-fuel composite, $P_{\ell,F}$, we recover renewable and fossil-fuel electricity productivity using:

$$z_{\ell,ER} = \frac{y_{\ell,ER}}{K_{\ell,ER}^{\alpha_R}},$$

and

$$z_{\ell,EF} = \frac{\left(y_{\ell,EF}\right)^{\alpha_F}}{K_{\ell,EF}^{\alpha_F}\left[\left(1-\alpha_F\right)\frac{p_{\ell,E}}{P_{\ell,F}}\right]^{1-\alpha_F}}.$$

See details in step 21 of Appendix C.

4.6 Labor Supply Parameters

4.6.1 Worker Flows

Before describing how we calibrate the labor supply parameters, we need to discuss how we obtain worker flows across regions and sectors. Unfortunately, there is no publicly available data on the full matrix of worker flows across region and industry pairs. However, we combine data from the ACS and the CPS to impute such flows in a way that guarantees that the economy is initially in steady state—an assumption we impose in our calibration procedure. Appendix C.2 contains a complete description of the algorithm we employ. It bears a resemblance to *raking* in the statistics literature.

4.6.2 Migration Elasticity

We follow Artuç and McLaren (2015) who estimate ν as a semi-elasticity of worker flows with respect to wage differentials. We correct this estimate to account for differences in the granularity of choices workers face as well as differences in baseline wages.

4.6.3 Mobility Costs and Sector-Specific Utilities

Impose $C_{\ell,j,\ell,j} = 0$ (no cost of not moving) for all $\ell \in \mathcal{L}$ and $j \in J \cup F$, $C_{\ell,j,\ell,u} = 0$ (no cost of moving locally to unemployment) and $\eta_{\ell,u} = 0$ (unemployment gives zero utility) for all regions ℓ. We obtain for all ℓ, j:

If $m_{\ell,j,\ell,j} > 0$ and $L_{\ell,j}^{ACS} > 0$:

$$\eta_{\ell,j} = -\frac{\nu}{\beta} \log\left(\frac{m_{\ell,j,\ell,u}}{m_{\ell,j,\ell,j}}\right) - \nu \log\left(\frac{m_{\ell,u,\ell,u}}{m_{\ell,j,\ell,u}}\right) - \left(\frac{w_{\ell,j} + b}{P_\ell}\right)$$

If $m_{\ell,j,\ell,j} = 0$ or $L_{\ell,j}^{ACS} = 0$:

$$\eta_{\ell,j} = -\infty.$$

We can then recover mobility costs using:

If $m_{\ell,j,\ell,j} > 0$, $L_{\ell,j}^{ACS} > 0$ and $m_{\ell,j,k,n} > 0$:

$$\begin{aligned} C_{\ell,j,k,n} = &-\frac{\nu}{1-\beta} \log\left(\frac{m_{\ell,j,k,n}}{m_{\ell,j,\ell,j}}\right) - \frac{\nu\beta}{(1-\beta)} \log\left(\frac{m_{k,n,k,n}}{m_{\ell,j,k,n}}\right) \\ &+ \frac{\beta}{1-\beta}\left(\frac{w_{k,n} + b}{P_k} - \frac{w_{\ell,j} + b}{P_\ell}\right) + \frac{\beta}{1-\beta}\left(\eta_{k,n} - \eta_{\ell,j}\right), \end{aligned}$$

else

$$C_{\ell,j,k,n} = +\infty.$$

4.7 Calibration Results

We calibrate a large set of parameters, so we report summary statistics and visualizations for selected subsets. Table 2 reports summary statistics for the parameters governing the production of intermediate and final goods, as specified in equations 1 and 3. The expenditure share on electricity ranges from 0.003 in Finance and Insurance to 0.033 in Paper

Manufacturing, highlighting substantial heterogeneity across sectors in their exposure to electricity prices. Weighting sectors by their revenue shares, the average labor share is 0.310, the average materials share is 0.406, and the average capital share is 0.275.

The fourth row summarizes sectors' direct exposure to the carbon tax through their use of fossil-fuel inputs. The fossil-fuel sector itself has the greatest exposure, with an expenditure share of 0.38, followed by Transportation, with an expenditure share of approximately 0.10. Row 6 summarizes sectoral weights in final demand. Health Care receives the largest weight, at approximately 0.14, while Primary Metal Manufacturing receives the smallest. Finally, the last row summarizes capital depreciation rates across sectors. Real Estate has the lowest depreciation rate, at 3% per year, whereas Computer and Electronic Manufacturing has the highest, at 20%.

Table 2: Parameters Governing Intermediate- and Final-Goods Production

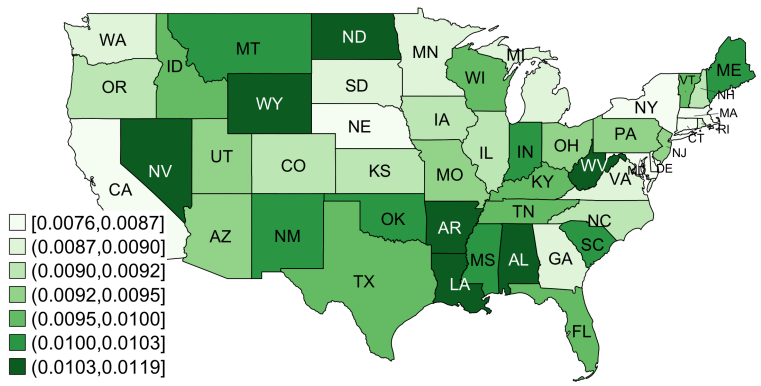
Parameter	Minimum	Maximum	Revenue-weighted mean
1. β_j^E	0.003 (Sector 25)	0.033 (Sector 8)	0.009
2. $(1-\beta_j^E)\beta_j^L$	0.037 (Sector 26)	0.697 (Sector 6)	0.310
3. $(1-\beta_j^E)\beta_j^M$	0.131 (Sector 6)	0.543 (Sector 8)	0.406
4. $(1-\beta_j^E)\beta_j^M\gamma_{jF}$	0.000 (Sector 16)	0.376 (Sector 1)	0.024
5. $(1-\beta_j^E)\beta_j^K$	0.124 (Sector 30)	0.620 (Sector 26)	0.275
6. μ_j	0.000 (Sector 13)	0.138 (Sector 30)	–
7. δ_j	0.032 (Sector 26)	0.216 (Sector 16)	–

Notes: Minimums and maximums in rows 1–6 are computed across sectors $j \in J \cup \{F\}$. The means in rows 1–5 use sectoral revenues $p_j y_j$ as weights; no mean is reported for the final-demand weights in row 6. Row 7 reports only the minimum and maximum depreciation rates across $j \in J \cup \{F, ER, EF\}$; renewable and fossil electricity use the common calibrated electricity depreciation rate. See Table A.1 for sector definitions.

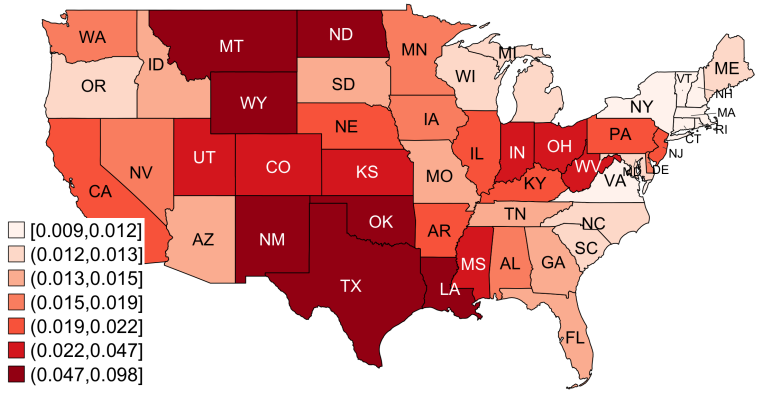
Figures 2a and 2b compute region-specific averages of electricity and fossil-fuel expenditure shares, respectively, to visualize geographic variation in exposure to electricity and fossil-fuel prices. States such as Louisiana and West Virginia are among those most exposed to electricity prices, while Texas, Oklahoma, and Louisiana are among those where production is most exposed to fossil-fuel prices. In some of these states, the average fossil-fuel expenditure share approaches 10%. Figure 2c depicts the input-output matrix $\gamma_{j,n}$ defined in equation (4). As expected, the matrix is strongly concentrated along the diagonal, reflecting the importance of within-sector intermediate inputs.

Figure 2d displays the parameters γ_ℓ, for $\ell \in \mathcal{L}$, that enter the specification of transmission costs in equation (61). The implied transmission costs tend to be larger for connections

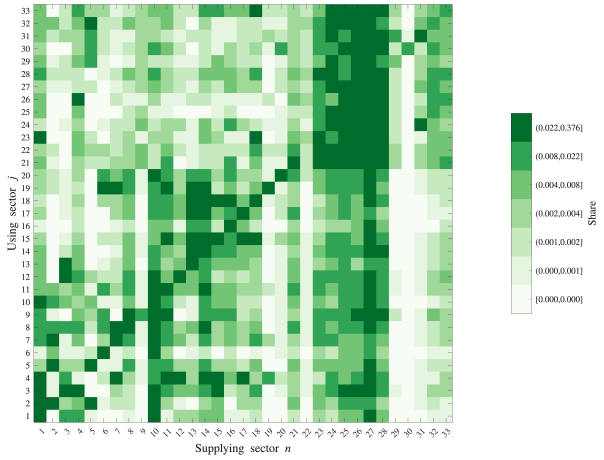
involving Nevada, Oregon, Montana, and much of New England. We calibrate the dispersion parameter governing transmission costs to $\theta = 2.36$.



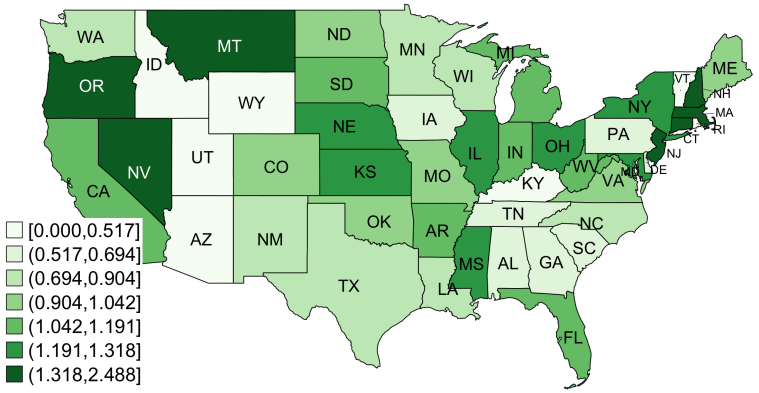
(a) Regional Electricity Intensity



(b) Regional Fuel-Input Intensity



(c) Material-Input Intensity



(d) Electricity Network Parameters

Figure 2: Regional Electricity, Fuel, and Material-Input Characteristics

Notes: Panel (a) shows the location-specific weighted average of electricity expenditure shares, $\sum_{j\in J\cup\{F\}} \frac{VA^{BEA}_{\ell,j}}{\sum_{j\in J\cup\{F\}} VA^{BEA}_{\ell,j}} \beta^E_j$, where the weights correspond to each sector's share of local value added. Panel (b) shows the location-specific weighted average of fossil-fuel expenditure shares, $\sum_{j\in J\cup\{F\}} \frac{VA^{BEA}_{\ell,j}}{\sum_{j\in J\cup\{F\}} VA^{BEA}_{\ell,j}} (1-\beta^E_j)\beta^M_j \gamma_{j,F}$. Panel (c) shows the input-output matrix $\gamma_{j,n}$ defined in equation (4). See Table A.1 for sector definitions. Panel (d) shows γ_ℓ, which governs transmission costs κ for each location ℓ; see equation (61).

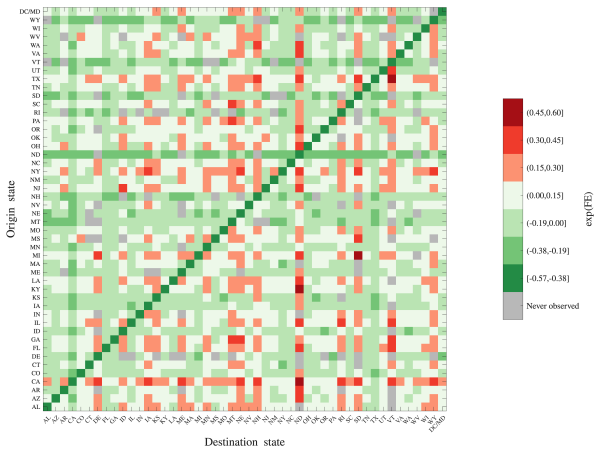
The dispersion of worker idiosyncratic preference shocks is calibrated at $\nu = 6.52$. We decompose off-diagonal worker mobility costs $C_{\ell,j,k,n}$ between origin region-sector pair (ℓ, j) and destination region-sector pair (k, n) as

$$\log\left(C_{\ell,j,k,n}\right) = FE_{\ell,k} + FE_{j,n} + res_{\ell,j,k,n},$$

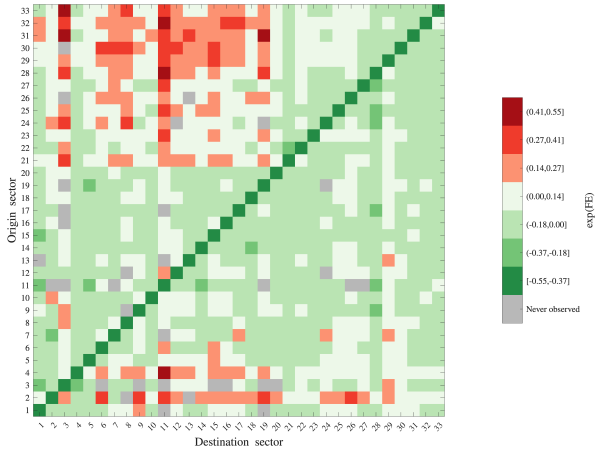
where $FE_{\ell,k}$ captures the region-pair component of mobility costs, $FE_{j,n}$ captures the sector-pair component, and $res_{\ell,j,k,n}$ denotes the residual. Figure 3a displays a heat map of $FE_{\ell,k}$ and reveals substantial dispersion in mobility costs across region pairs. For example, moving from North Dakota to New Mexico is relatively easy, whereas moving from Kentucky to North Dakota is relatively costly. Figure 3b shows the corresponding dispersion across sector pairs. Moving from Mining to Fossil Fuels is relatively easy, whereas moving from Accommodation and Food Services to Plastics and Rubber Manufacturing is particularly costly.

Table 3 reports summary statistics for the preference parameters $\eta_{\ell,j}$. Decomposing $\eta_{\ell,j}$, normalized by the aggregate real wage, into additive location and sector fixed effects shows that DC–Maryland has the lowest location effect, while Iowa has the highest. These estimates should not be interpreted literally as rankings of how desirable different locations are. The preference parameters give the model flexibility to simultaneously match observed wages and transition rates across regions and sectors. In particular, the relatively low preference shifter for DC–Maryland simply reflects the higher wages in that area, which are not solely explained by high productivity and high mobility frictions. Compensating differentials give the model the additional flexibility needed to match the relatively high wages in that location.

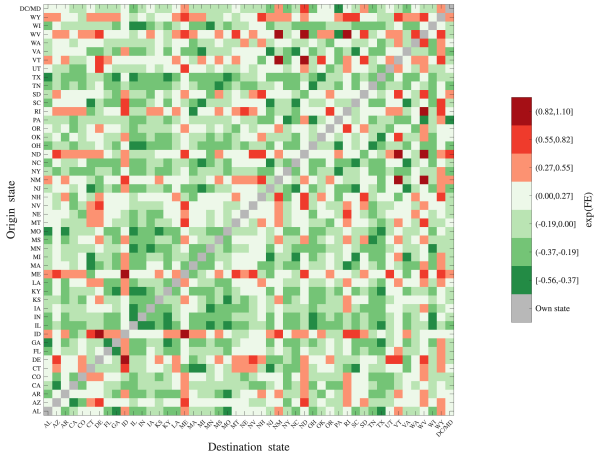
Preference fixed effects are substantially more dispersed across sectors than across locations. Fossil Fuels has the lowest estimated sector preference fixed effect, while Educational Services has the highest. Again, this dispersion should not be interpreted as reflecting only intrinsic worker preferences. It also partly compensates for systematic differences in wages across sectors: Fossil Fuels is relatively high paying, whereas Educational Services is relatively low paying.



(a) Mobility costs: region-pair effects



(b) Mobility costs: sector-pair effects



(c) Trade costs: region-pair effects

Figure 3: Worker Mobility and Trade Costs

Notes: Panels (a) and (b) are based on the decomposition of off-diagonal worker mobility costs, $\log(C_{\ell,j,k,n}) = FE_{\ell,k} + FE_{j,n} + res_{\ell,j,k,n}$, where $FE_{\ell,k}$ and $FE_{j,n}$ capture the region-pair and sector-pair components of mobility costs, respectively. Panel (a) displays $\exp(FE_{\ell,k})$ relative to its mean across cells, while Panel (b) displays $\exp(FE_{j,n})$ relative to its mean across cells. See Table A.1 for sector definitions. Panel (c) is based on the decomposition of off-diagonal trade costs, $\log(\tau_{\ell,k,j}) = FE_{\ell,k} + FE_j + res_{\ell,k,j}$, where $FE_{\ell,k}$ and FE_j capture the region-pair and sector-specific components of trade costs, respectively. It displays $\exp(FE_{\ell,k})$ relative to its mean across cells.

Table 3 summarizes the dispersion in productivity $z_{\ell,j}$, $z_{\ell,ER}$, and $z_{\ell,EF}$ across sectors and locations. For non-electricity sectors, Wyoming has the lowest estimated regional productivity, while California has the highest. In renewable electricity, Delaware is the least productive state and Illinois the most productive. In fossil-fuel-based electricity, DC–Maryland has the lowest estimated productivity, while Nebraska has the highest.

Table 3: Preference and Productivity Parameters

Parameter	Minimum	Maximum	Mean
Panel A: Preference Parameters (η)			
Region fixed effects	-3.625 (DC/MD)	2.902 (Iowa)	-0.545
Sector fixed effects	-15.553 (Sector 1)	6.618 (Sector 29)	2.590
Panel B: Intermediate Goods Productivities z			
Region fixed effects	0.686 (Wyoming)	1.233 (California)	1.009
Sector fixed effects	0.287 (Sector 29)	3.359 (Sector 26)	1.195
Panel C: Electricity Production Productivities			
z_{ER}	5.310 (Delaware)	119.664 (Illinois)	59.888
z_{EF}	5.230 (DC/MD)	95.892 (Nebraska)	13.237

Notes: Panel A decomposes $\eta_{\ell,j}/\overline{w} = FE_\ell + FE_j + res_{\ell,j}$ and reports statistics for the region fixed effects FE_ℓ and sector fixed effects FE_j, where $\overline{w}$ denotes the average real wage in the U.S. Means in this panel are employment-weighted. Panel B applies an analogous decomposition with $\log(z_{\ell,j})$ on the left-hand side. Region fixed effects are reported as $\exp(FE_\ell)$, while sector fixed effects are reported as $\exp(FE_j)$. Means in Panels B and C are unweighted. See Table A.1 for sector definitions.

Figure 3c displays the region-pair component of trade costs and reveals substantial geographic heterogeneity. Shipping goods from West Virginia and North Dakota tends to be relatively costly, whereas shipping from Indiana to Illinois is relatively inexpensive. Unreported results also show substantial heterogeneity across sectors: shipping goods produced in Electrical Equipment is relatively inexpensive, while shipping Agricultural goods is relatively costly.

5 Counterfactual Exercises

The framework developed in Sections 2 to 4 can accommodate a wide range of climate-policy interventions. We use it here to study the distributional consequences of specific carbon-tax policies: who gains and who loses, where those gains and losses are concentrated, how workers and capital owners adjust over time, and how alternative uses of carbon-tax revenues shape these effects. We do not seek to characterize the optimal carbon tax or to conduct a

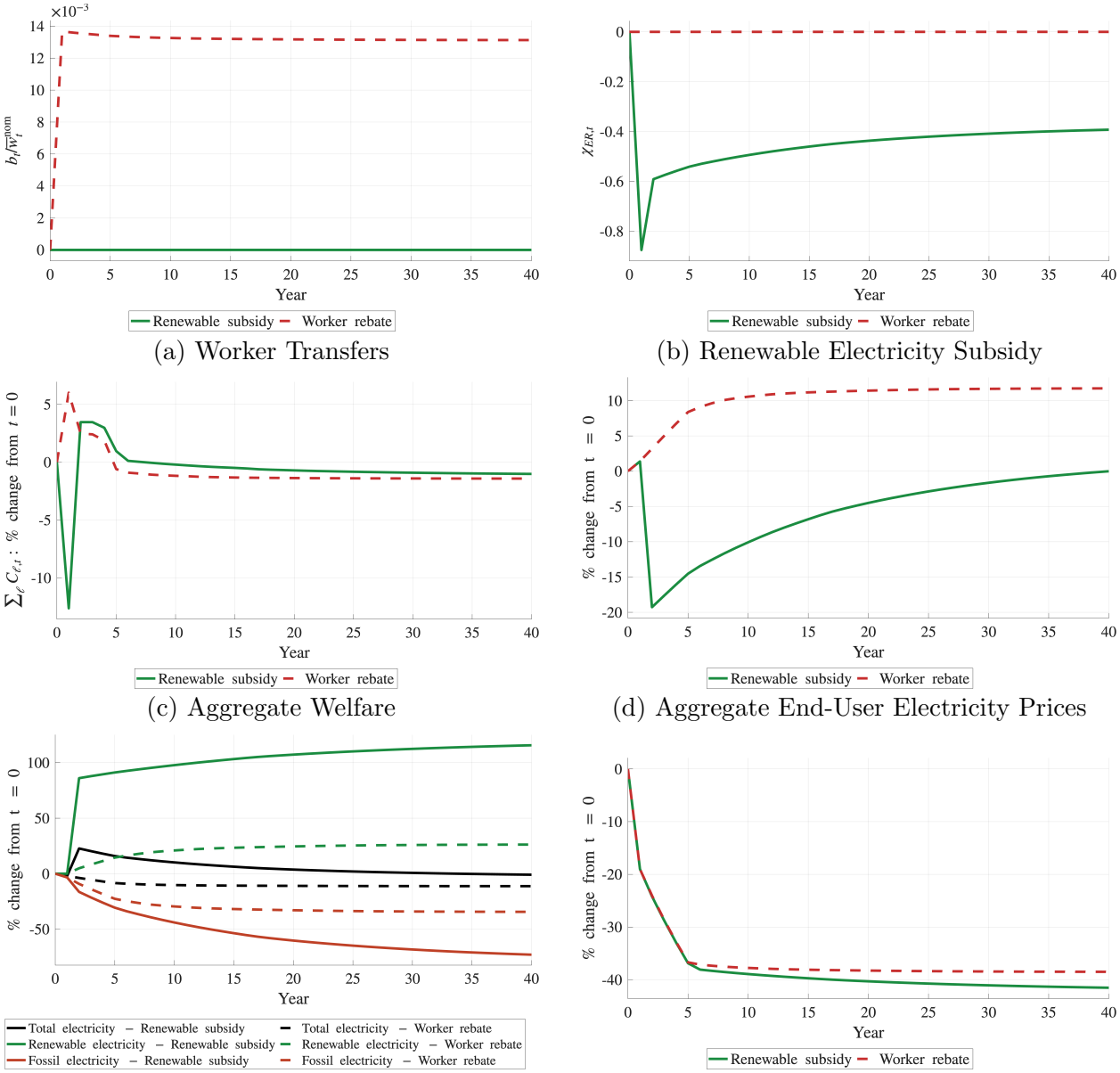
comprehensive cost–benefit analysis of carbon taxation; instead, we take the policy intervention as given and study its incidence and adjustment consequences. Under the assumption that the social cost of carbon is common across individuals, sectors, and locations, incorporating the environmental benefits of lower emissions affects aggregate welfare but not the unequal consequences that are the focus of our analysis.

We illustrate the flexibility of the framework by studying the two policies described in Section 2.6. Both policies impose a 20% carbon tax, implemented as a tax on the production of fossil-fuel goods: $\chi_{F,t}$ rises from zero at $t = 0$ to 20% at $t = 1$ and remains at that level thereafter. The two scenarios differ in how the resulting tax revenues are used. Given the absence of aggregate uncertainty, workers and capital owners have perfect foresight about the evolution of all aggregate variables along the transition.

Under the first policy, which we refer to as the *Uniform Rebate to Workers*, all carbon tax revenues are rebated uniformly to workers according to equation (33), regardless of their employment status, state of residence, or sector of employment. Under the second policy, which we refer to as the *Renewable Subsidy*, the proceeds are instead used to subsidize renewable electricity generation, as specified in equation (35). This policy therefore combines a tax on fossil-fuel production, which discourages fossil-fuel use and reduces carbon emissions, with a subsidy that encourages renewable electricity generation and may accelerate the transition toward a less carbon-intensive economy.

Figure 4a shows the evolution of worker transfers b_t under each policy, while Figure 4b shows the evolution of the renewable electricity subsidy, shown as a negative tax. The *Uniform Rebate to Workers* generates a permanent per-worker rebate of approximately 1.4% of the national average nominal wage. Under the *Renewable Subsidy*, by contrast, the subsidy exceeds 85% in the very short run, when fossil-fuel production—and hence carbon tax revenue—remains relatively high.[6] As fossil-fuel production declines in response to the tax, the associated tax revenue falls, reducing the resources available to subsidize renewable electricity. The subsidy consequently declines over the transition and eventually stabilizes at around 40%.

[6]Given the timing of the model, labor and capital allocations at $t = 1$, when the carbon tax is introduced, remain fixed at their $t = 0$ levels, implying only a small reduction in fossil-fuel production at impact.



(a) Worker Transfers

(b) Renewable Electricity Subsidy

(c) Aggregate Welfare

(d) Aggregate End-User Electricity Prices

(e) National Electricity Production

(f) National Fuel Production

Figure 4: Aggregate Transition Dynamics Across Policies

Notes: In Panel (a), $\overline{w}_t^{nom}$ denotes the average nominal wage at time t. Panel (c) shows aggregate welfare at time t, measured as aggregate consumption across locations, $\sum_{\ell \in \mathcal{L}} Inc_{\ell,t}/P_{\ell,t} - Inv_{\ell,t}$ with $C_{\ell,t} = Inc_{\ell,t}/P_{\ell,t} - Inv_{\ell,t}$. In Panel (d), the aggregate end-user electricity price is computed as $\frac{\sum_{\ell \in \mathcal{L}} X_{\ell,E,t}}{\sum_{\ell \in \mathcal{L}} (X_{\ell,E,t}/P_{\ell,E,t})}$, that is, nationwide end-user expenditures on electricity divided by the nationwide quantity of electricity consumed by end users. Panel (f) shows the evolution of aggregate fossil-fuel production, $\sum_{\ell \in \mathcal{L}} y_{\ell,F,t}$.

5.1 Aggregate Effects

Table 4 compares the long-run aggregate effects of the two policies, measured as changes between the final and initial steady states and therefore abstracting from the transition path. We first consider aggregate welfare, measured by $\sum_{\ell \in \mathcal{L}} C_\ell$, which corresponds to aggregate consumption summed across locations.[7] This measure captures changes in consumption but does not incorporate the benefits from lower carbon emissions, a topic to which we return later. According to this measure, Row 1 shows that both policies reduce long-run welfare, with a larger decline under the *Uniform Rebate to Workers*: 1.43%, compared with 1.16% under the *Renewable Subsidy*.

These long-run differences in welfare impacts mask substantial differences in the *evolution* of aggregate consumption across the two scenarios. Figure 4c plots aggregate consumption along the transition path and highlights important differences in its short-run behavior. Most notable is the sharp initial decline in aggregate consumption under the *Renewable Subsidy*. In this case, the large subsidy to renewable electricity induces renewable capital owners to invest heavily in the short run, postponing consumption to the future. These investments pay off relatively quickly, causing aggregate consumption to rebound sharply and temporarily overshoot its baseline level.

Two forces contribute to this overshooting. First, the rapid accumulation of renewable capital expands the economy's productive capacity. Because capital is irreversible, renewable capacity initially expands faster than fossil-fuel electricity capital depreciates, generating temporary excess electricity capacity and lowering end-user electricity prices. Indeed, Figure 4d shows that end-user electricity prices fall sharply in the short run and remain below baseline for roughly 40 years, benefiting regions specialized in electricity-intensive sectors. Consistent with this mechanism, Figure 4e shows a short-run increase in electricity generation under the *Renewable Subsidy*. Second, the carbon tax induces capital owners in fossil-fuel-intensive activities to sharply reduce investment, freeing resources for current consumption.

The same disinvestment mechanism operates under the *Uniform Rebate to Workers*, but without the offsetting surge in renewable investment. As a result, aggregate consumption jumps up immediately as investment contracts in the fossil-fuel sector and in other sectors that use fossil fuels intensively as intermediate inputs.[8] Over time, however, capital

[7] Aggregate consumption in location ℓ, C_ℓ, is computed as real aggregate income net of investment: $C_\ell = \frac{Inc_\ell}{P_\ell} - Inv_\ell$.

[8] Indeed, as we show later in Figure 8a, the short-run increase in aggregate consumption is driven by Oklahoma, Wyoming, and Louisiana, three states specialized in industries that use fossil fuels very intensively (Figure 2b).

in these fossil-fuel-intensive activities depreciates. In both policy scenarios, this eventually contributes to a long-run decline in aggregate consumption. From around year $t = 6$ onward, the evolution of aggregate consumption is similar across the two policies, although consumption declines somewhat faster under the *Uniform Rebate to Workers*.

Table 4: Long-Run Effects of Carbon Tax Policies

	% change from baseline	
	Uniform rebate to workers	Renewable subsidy
1. Aggregate Welfare	-1.43	-1.16
2. Fuel Output	-38.57	-42.26
3. Electricity Output	-11.29	-3.33
4. Renewable Electricity Output	26.57	121.08
5. Fossil Electricity Output	-34.68	-80.18
6. Real labor income (incl. rebate)	-0.94	-2.06
7. Net Labor Reallocation Across States (000s of Workers)	206.49	274.62
8. Net Labor Reallocation Across Sectors (000s of Workers)	154.34	133.87
9. Agg Welfare, Including SCC = 100 \$/tCO$_2$	-0.106	0.278
10. Agg Welfare, Including SCC = 200 \$/tCO$_2$	1.308	1.817

Notes: The table reports the long-run effects of a 20% carbon tax under the *Uniform Rebate to Workers* and *Renewable Subsidy* policies. We compare the initial and final steady states, abstracting from transitional dynamics. Aggregate Welfare in Row 1 is measured as aggregate consumption summed across locations, $\sum_{\ell \in \mathcal{L}} C_\ell$. Real labor income in Row 6 includes the government rebate, b. In Rows 9 and 10, SCC denotes the "Social Cost of Carbon." Baseline U.S. CO_2 emissions are allocated across states in proportion to their initial use of the fuel composite. State-level emissions are then adjusted according to the proportional change in fuel-composite use. The resulting change in emissions damages is valued using the indicated social cost of carbon and incorporated into aggregate consumption.

The carbon tax is highly effective at reducing fossil-fuel production under either policy, although the long-run decline is somewhat larger under the *Renewable Subsidy*. In that case, $\sum_{\ell \in \mathcal{L}} y_{\ell,F}$ falls by 42%, compared with 38% under the *Uniform Rebate to Workers* (Row 2 of Table 4). Relative to the 20% tax rate, these responses imply a long-run semi-elasticity of aggregate fossil-fuel production of approximately 2.

Two forces in the model help account for this relatively large response. First, input-output linkages magnify the effects of the tax, particularly because fossil-fuel inputs account for 38% of expenditures in the fossil-fuel sector itself. Second, endogenous capital accumulation

further amplifies the long-run response, as the stock of fossil-fuel-specific capital contracts over time. Adjustment is also relatively rapid under both policies: as shown in Figure 4f, national fossil-fuel output falls by approximately 35% within five years in either case. Because the two policies are broadly similar in their effectiveness at reducing fossil-fuel production, their relative desirability depends primarily on their aggregate welfare and distributional consequences.

Both policies also reduce total electricity production in the long run, although the decline is much smaller under the *Renewable Subsidy* (see rows 3–5 of Table 4). Under this policy, renewable electricity output increases by 120%, while fossil-fuel-based electricity production falls by 80%, implying a substantial reallocation of generation toward renewable sources. Despite this shift toward cleaner electricity generation, the aggregate welfare loss to workers is less than half as large under the *Uniform Rebate to Workers*: 0.94%, compared with 2.06% under the *Renewable Subsidy* (Row 6).

Both policies also induce substantial long-run reallocation across states, involving more than 200 thousand workers, as well as substantial reallocation across sectors, involving more than 130 thousand workers. To put these magnitudes into perspective, Dix-Carneiro et al. (2023) estimate that the China shock reduced U.S. manufacturing employment by approximately 500 thousand workers. The magnitudes are therefore comparable, although the extent of reallocation induced by a carbon tax would naturally depend on the size of the tax ultimately adopted.

Finally, Rows 9 and 10 of Table 4 compute long-run aggregate welfare gains after accounting for the benefits from reductions in fossil-fuel use and carbon emissions. To do so, we allocate baseline U.S. carbon emissions across states in proportion to their initial use of the local fossil-fuel composite, imposing a common emissions coefficient per unit of the composite. We scale each state's assigned emissions by the proportional change in its fossil-fuel-composite usage and value the resulting emissions using estimated measures of the social cost of carbon. The associated damages are converted into real model units using state-level consumer prices and subtracted from aggregate consumption.

We consider two values of the social cost of carbon (SCC): $100\$/tCO_2$ and $200\$/tCO_2$. These values bracket recent estimates in the literature.[9] Once the benefits from lower carbon emissions are taken into account, the *Renewable Subsidy* continues to outperform the

[9]Rennert et al. (2022) estimate $185\$/tCO_2$, and Aghion et al. (2025) calibrate their model using $190\$/tCO_2$ based on estimates from the Environmental Protection Agency. These estimates are conservative in comparison with Bilal and Känzig (2026), who estimate a social cost of carbon of $1,200\$/tCO_2$, which would imply much larger aggregate benefits for the U.S.

Uniform Rebate to Workers. At an SCC of 100\$/tCO_2, the aggregate welfare effects of both policies are small, although they are slightly positive under the *Renewable Subsidy*. At an SCC of 200\$/tCO_2, the welfare gains become substantially larger, particularly under the *Renewable Subsidy* (Row 10).

Overall, these results suggest that a 20% carbon tax has quantitatively important effects. Both policies are highly effective in quickly reducing fossil-fuel output and, consequently, carbon emissions, but they entail different trade-offs. The *Renewable Subsidy* achieves a somewhat larger reduction in fossil-fuel output at a lower aggregate welfare cost, whereas the *Uniform Rebate to Workers* imposes a substantially smaller cost on workers.

5.2 Region- and Sector-Specific Impacts

We now turn to more disaggregated impacts of the policies we consider. Figures 5a and 5b show the long-run changes in fossil-fuel output across U.S. states under each policy. Although the magnitude of the response varies across states and policies, the carbon tax leads to substantial reductions in fossil-fuel output throughout the country. These reductions range from 31% in Massachusetts under the *Uniform Rebate to Workers* to 47% in New Mexico under the *Renewable Subsidy*.

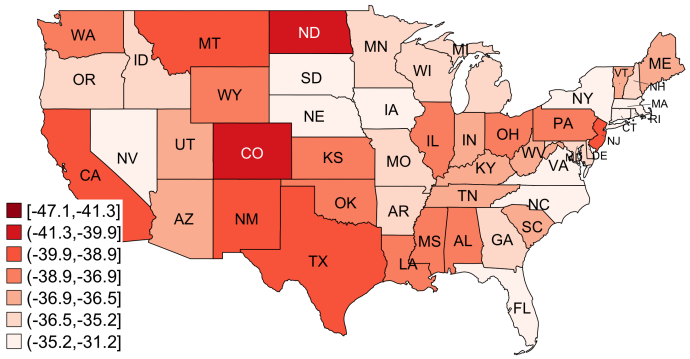
There is substantially more spatial heterogeneity in the response of fossil-fuel-based electricity generation. Under the *Uniform Rebate to Workers*, Figure 5c shows large declines in states such as New York, Washington, and Oregon, but much more modest reductions in Wisconsin, West Virginia, and Missouri. Under the *Renewable Subsidy*, by contrast, fossil-fuel-based electricity generation declines much more sharply and uniformly across states, as shown in Figure 5d. In some states, the long-run decline is so pronounced that long-run fossil-fuel-based electricity generation falls to zero.

These differences do not translate one-for-one into changes in total electricity generation. Figure 6a shows that total electricity generation declines relatively uniformly across states under the *Uniform Rebate to Workers*, whereas many states experience increases under the *Renewable Subsidy*, including Washington, Idaho, and Vermont (Figure 6b). The resulting effects on end-user electricity prices are shown in Figures 6c and 6d. Under the *Uniform Rebate to Workers*, end-user electricity prices, $P_{\ell,E}$, increase by approximately 10% in nearly every state. Under the *Renewable Subsidy*, however, long-run price changes are substantially more heterogeneous, ranging from declines of about 8% in Washington and Oregon to increases of about 10% in Louisiana and Florida.

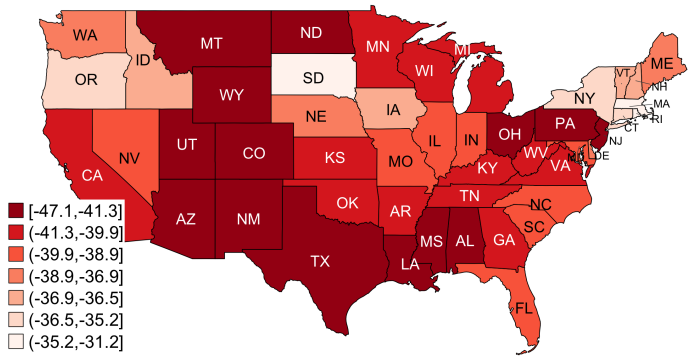
We now turn to the heterogeneous welfare effects across states. Under either policy, state-level consumption declines almost everywhere when the benefits of reduced carbon emissions are excluded. There are, however, a few exceptions under the *Renewable Subsidy*: states such as Idaho, Vermont, Arizona, and South Carolina experience increases in aggregate consumption, driven by capital income and profits from renewable electricity production. For this reason, Figures 7a and 7b report changes in state-level consumption *relative* to the national average change, which more clearly highlights which states are disproportionately affected by the carbon tax.

Under the *Uniform Rebate to Workers*, the largest relative losses are concentrated in Wyoming, Oklahoma, and Louisiana, followed by North Dakota and Texas. Oklahoma experiences the largest loss, while Idaho is the least adversely affected state, with a gap of 5.54 percentage points between the two. Under the *Renewable Subsidy*, Texas joins Louisiana, Oklahoma, and Wyoming among the states experiencing the largest relative losses. In this case, Louisiana experiences the largest loss, while Idaho experiences a modest absolute gain. The difference between Louisiana and Idaho is 8.94 percentage points, indicating substantially greater regional dispersion in the effects of the *Renewable Subsidy* on consumption.

The spatial patterns are broadly similar when we focus on real labor income, inclusive of the worker rebate, rather than aggregate consumption. The main difference is in the aggregate magnitude: as shown in Table 4, the overall decline in real labor income is smaller under the *Uniform Rebate to Workers*.

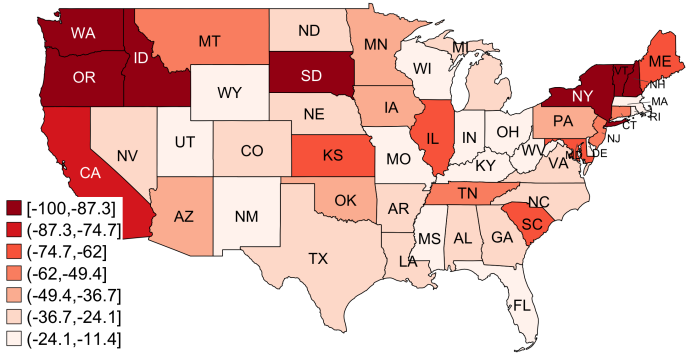


(a) Uniform Rebate to Workers

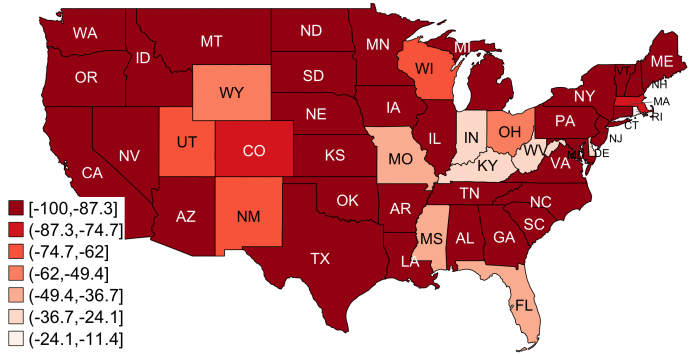


(b) Renewable Subsidy

Fuel output: % change in $y_{\ell,F}$



(c) Uniform Rebate to Workers

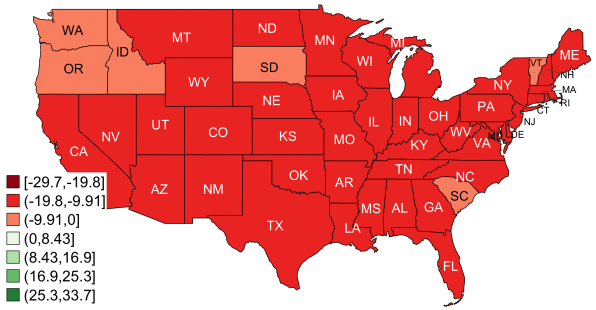


(d) Renewable Subsidy

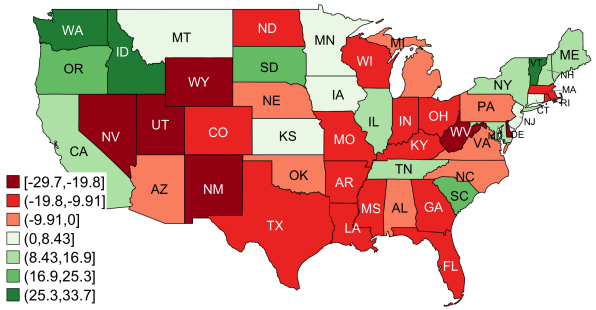
Fossil-fuel electricity output: % change in $y_{\ell,EF}$

Figure 5: Long-Run State-Level Effects on Fuel Production and Fossil-Fuel-Based Electricity Production

Notes: Each figure compares final and initial steady-state values, abstracting from transitional dynamics.

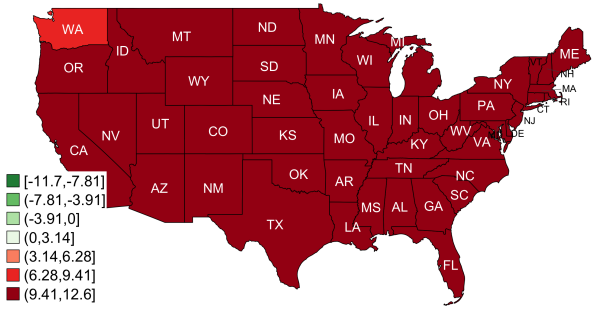


(a) Uniform Rebate to Workers

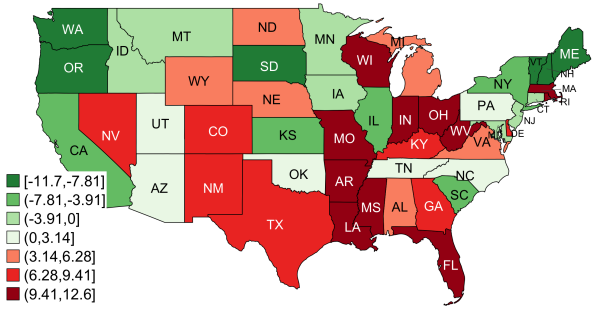


(b) Renewable Subsidy

Total electricity output: % change in $(y_{\ell,ER} + y_{\ell,EF})$



(c) Uniform Rebate to Workers



(d) Renewable Subsidy

End-user electricity price: % change in $P_{\ell,E}$

Figure 6: Long-Run State-Level Effects on Electricity Markets

Notes: Each figure compares final and initial steady-state values, abstracting from transitional dynamics.

This spatial heterogeneity in welfare impacts is also reflected in population changes. Figures 7e and 7f show that states that are more adversely affected by the policies, such as Texas, Louisiana, and New Mexico, lose up to 1% of their population in the long run. By contrast, states that fare relatively better, such as Idaho and Arizona, experience population gains of up to 0.85%. Notably, consistent with the state-level consumption effects, population changes are more dispersed under the *Renewable Subsidy*, with larger population gains and losses across states.

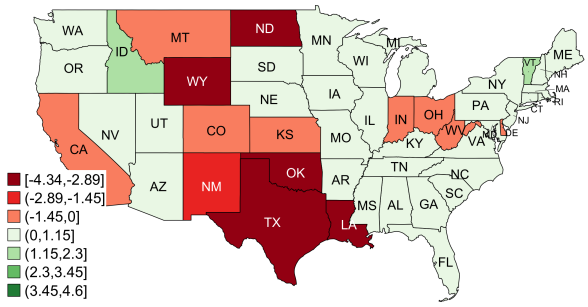
Figures 8a–8d complement the long-run results in Figures 7a, 7b, 7e, and 7f by displaying the full transition paths of state-level aggregate consumption and population under both policy scenarios. As we observe in Figure 4c, short-run adjustments are markedly different from long-run impacts. As discussed earlier, sharp adjustments in the short-run path of consumption are driven by large swings in investment decisions—either sharp increases in investment and declines in consumption by capitalists in the scenario with the subsidy, or large short-run increases in consumption driven by capitalists who cease to invest in fossil fuels in the scenario with the worker rebate.

We complement our region-specific analysis by examining distributional consequences for workers across sectors. Figure 9 shows that real wages fall in all sectors. The largest losses, however, are concentrated among fuel-sector workers, whose real wages decline by approximately 30% under either scenario. Workers in Mining and Chemical Manufacturing also experience substantial losses, although considerably smaller ones.

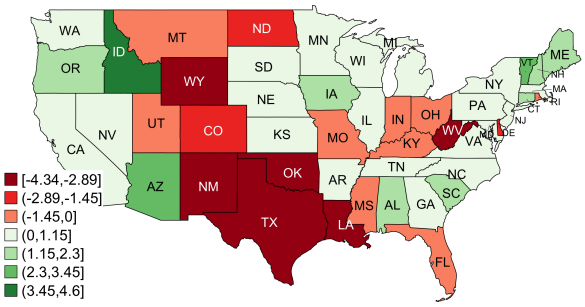
Figures 7c, 7d, and 9 provide snapshots of changes in real labor income between the initial and final steady states. These comparisons, however, do not capture the welfare consequences for workers who are directly exposed to the carbon tax when the policy is introduced. Workers can respond by moving across regions and sectors, but the extent and speed of this adjustment depend on the mobility frictions they face. To capture these dynamics, we evaluate the welfare of workers initially employed in each state-sector pair (ℓ, j) over the full transition path following the introduction of the carbon tax.

Let $\mathcal{V}_{\ell,j,0}$ denote the expected discounted lifetime utility of a worker initially employed in state-sector pair (ℓ, j) in the absence of a carbon tax, so that the economy remains in the initial steady state. Let $\mathcal{V}^{tr}_{\ell,j,1}$ denote the expected discounted lifetime utility of the same worker along the policy-induced transition following the introduction of the carbon tax at $t = 1$. Both value functions account for consumption, location-sector static and idiosyncratic preferences, mobility costs, and expected subsequent moves as described in equation (37).

The baseline expected discounted lifetime consumption of a worker initially employed in

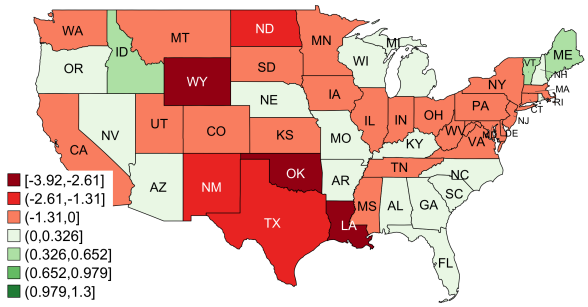


(a) Uniform Rebate to Workers

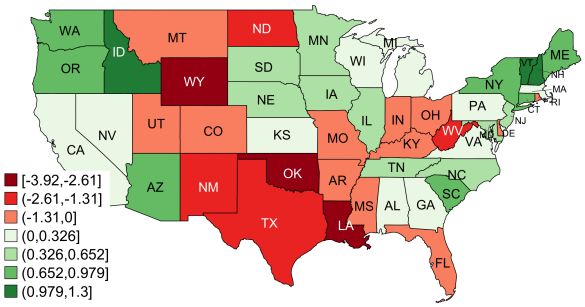


(b) Renewable Subsidy

Aggregate consumption per capita relative to the national change: $\left[\%\text{ change }\frac{C_\ell}{L_\ell}\right] - \left[\%\text{ change }\sum_\ell C_\ell\right]$

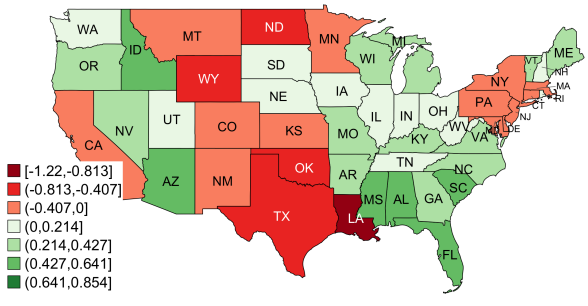


(c) Uniform Rebate to Workers

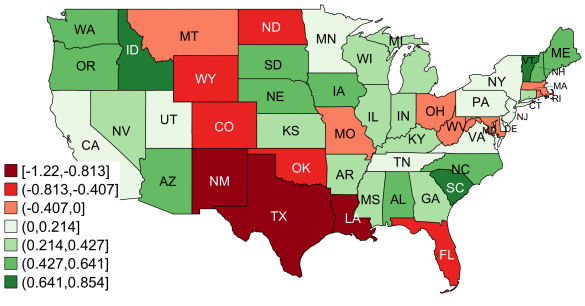


(d) Renewable Subsidy

Real labor income per capita relative to the national change:
$\left[\%\text{ change }\frac{\sum_j (w_{\ell,j}+b) L_{\ell,j}/P_\ell}{L_\ell}\right] - \left[\%\text{ change }\sum_{\ell,j}\left(w_{\ell,j}+b\right) L_{\ell,j}/P_\ell\right]$



(e) Uniform Rebate to Workers

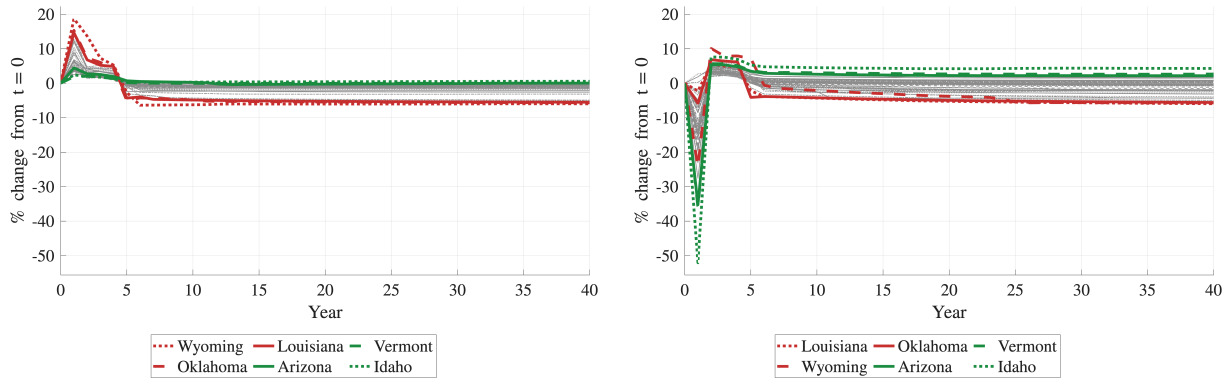


(f) Renewable Subsidy

State population: % change L_ℓ

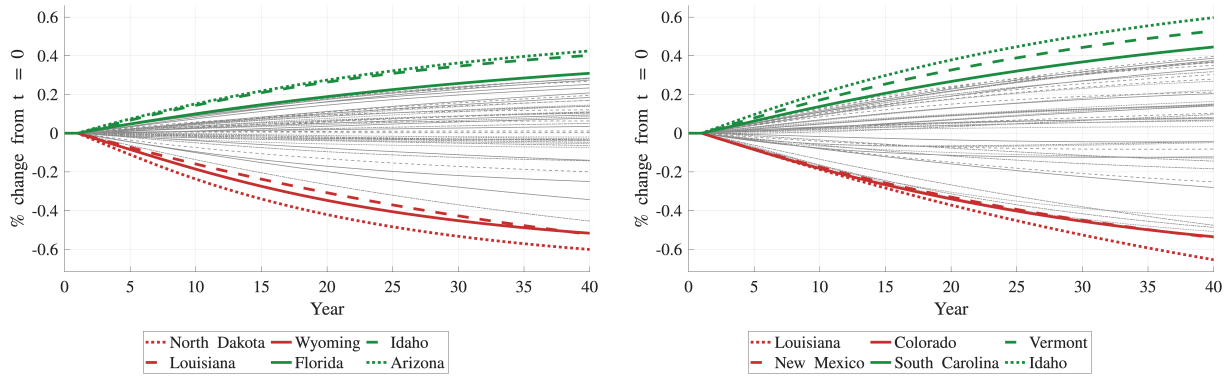
Figure 7: Long-Run Distributional Effects Across States

Notes: Each figure compares final and initial steady-state values, abstracting from transitional dynamics.



(a) Uniform Rebate to Workers (b) Renewable Subsidy

Aggregate consumption by state

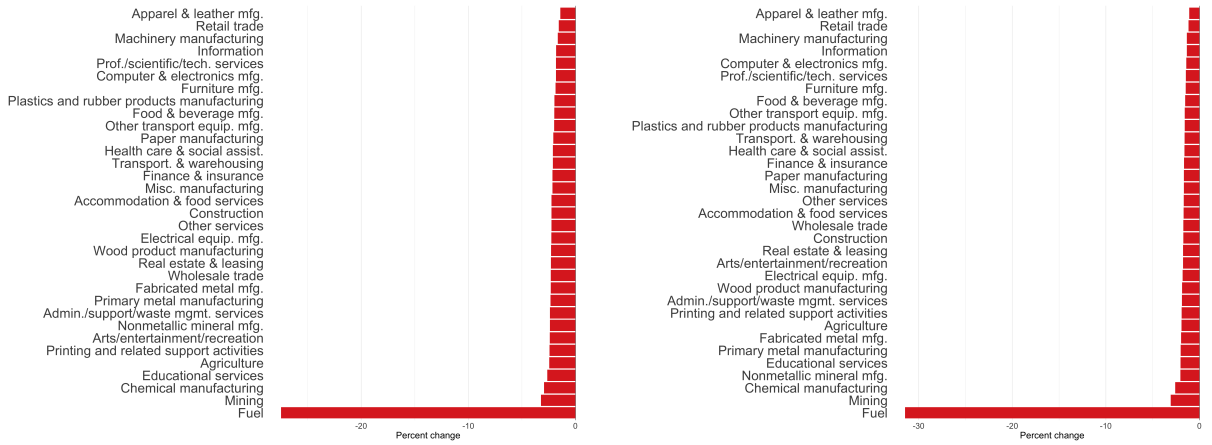


(c) Uniform Rebate to Workers (d) Renewable Subsidy

Population by state

Figure 8: State-Level Transitional Dynamics

Notes: The top panels report the evolution of aggregate consumption by state, and the bottom panels the evolution of state population, both relative to their initial levels.



(a) Uniform Rebate to Workers (b) Renewable Subsidy

Figure 9: Percent change in average real wage by sector.

Notes: Each figure compares final and initial steady-state values, abstracting from transitional dynamics.

state-sector pair (ℓ, j) is given by

$$\bar{c}^W_{\ell,j,0} = \left[(I - \beta \boldsymbol{m})^{-1} c_0^W\right]_{\ell,j}, \qquad c^W_{\ell,j,0} = \frac{w_{\ell,j,0} + b_0}{P_{\ell,0}}, \tag{62}$$

where $\boldsymbol{m}$ is the initial steady-state worker transition matrix given by equation (38), and c_0^W is the vector stacking (ℓ, j)-specific consumption of the final good in the initial steady state.

We report the consumption-equivalent welfare change, in percent, for a worker initially employed in state ℓ and sector j as

$$CE^W_{\ell,j} = 100 \times \frac{\mathcal{V}^{tr}_{\ell,j,1} - \mathcal{V}_{\ell,j,0}}{\bar{c}^W_{\ell,j,0}}. \tag{63}$$

Because consumption enters flow utility linearly, $-CE^W_{\ell,j}$ is the percentage of baseline discounted lifetime consumption that would be needed to compensate a worker initially employed in cell (ℓ, j) for the policy. Thus, negative values of $CE^W_{\ell,j}$ indicate welfare losses, whereas positive values indicate welfare gains.

Table 5 displays the results. Panel A shows that, on average, workers experience smaller welfare losses under the *Uniform Rebate to Workers* than under the *Renewable Subsidy*, with average consumption-equivalent changes of -0.38% and -1.2%, respectively. This ordering is consistent with Row 6 of Table 4, but the consumption-equivalent measures additionally account for welfare over the entire transition path. These average effects, however, mask substantial heterogeneity across state-sector cells.

Panel B shows that, under either policy, the largest losses are experienced by workers initially employed in the fossil-fuel sector in Louisiana, Oklahoma, and Texas. Importantly, however, the magnitude of these losses varies substantially with workers' initial location. Under the *Uniform Rebate to Workers*, fossil-fuel workers in Louisiana lose 10.3%, whereas those in Nebraska lose only 0.8%. Under the *Renewable Subsidy*, the corresponding losses are 11.9% and 1.6%, respectively. This heterogeneity largely reflects differences in workers' outside options, which depend on the initial industrial composition of their region, together with the costs they face in moving across industries and regions.

Panel C shows that workers in Educational Services in Arizona, Idaho, and South Carolina gain under the *Uniform Rebate to Workers*. Educational Services are relatively insulated from changes in fuel and electricity prices, while workers in these sectors nevertheless receive the rebate. Under the *Renewable Subsidy*, workers in Retail Trade in Vermont and Health Care in Idaho also experience welfare gains. These sectors are similarly insulated from

Table 5: Consumption-Equivalent Worker Welfare Changes Across States and Sectors

	Uniform rebate		Renewable subsidy
Panel A: Aggregate Distribution			
$L_{\ell,j,0}$-weighted mean (%)	-0.375		-1.215
$L_{\ell,j,0}$-weighted standard deviation (p.p.)	0.822		0.925
Panel B: State-Sector Pairs with Largest Losses			
Louisiana, Sector 1	-10.312	Louisiana, Sector 1	-11.921
Oklahoma, Sector 1	-10.301	Oklahoma, Sector 1	-11.787
Texas, Sector 1	-10.097	Texas, Sector 1	-11.410
Montana, Sector 1	-9.187	New Mexico, Sector 1	-10.655
New Mexico, Sector 1	-8.857	Montana, Sector 1	-10.411
Panel C: State-Sector Pairs with Largest Gains			
Arizona, Sector 29	0.682	Vermont, Sector 22	0.258
Idaho, Sector 29	0.605	Idaho, Sector 30	0.241
South Carolina, Sector 29	0.585	Idaho, Sector 32	0.037
Florida, Sector 29	0.575	Arizona, Sector 22	0.028
Mississippi, Sector 29	0.504	Idaho, Sector 26	0.005
Panel D: States with Lowest State Fixed Effects			
Louisiana	-1.301	Louisiana	-1.775
Oklahoma	-1.139	Oklahoma	-1.550
Texas	-1.059	Texas	-1.314
North Dakota	-0.741	New Mexico	-0.952
Wyoming	-0.635	Wyoming	-0.869
Panel E: States with Highest State Fixed Effects			
Arizona	0.569	Idaho	0.695
Idaho	0.528	Arizona	0.683
Florida	0.475	Vermont	0.657
South Carolina	0.475	Oregon	0.625
Maine	0.457	New York	0.578
Panel F: Sectors with Lowest Sector Fixed Effects			
Sector 1	-7.661	Sector 1	-7.862
Sector 3	-1.109	Sector 3	-0.794
Sector 15	-0.398	Sector 10	-0.128
Sector 11	-0.380	Sector 29	-0.097
Sector 10	-0.371	Sector 4	-0.068
Panel G: Sectors with Highest Sector Fixed Effects			
Sector 29	0.372	Sector 6	0.350
Sector 2	0.218	Sector 16	0.311
Sector 32	0.181	Sector 22	0.295
Sector 21	0.177	Sector 15	0.257
Sector 31	0.171	Sector 19	0.220

Notes: The table reports consumption-equivalent welfare changes following a 20% carbon tax under our two alternative redistributive policies. Changes at the (ℓ, j) level are given by $100 \times (\mathcal{V}^{\text{tr}}_{\ell,j,1} - \mathcal{V}_{\ell,j,0})/\bar{c}^W_{\ell,j,0}$, where $\bar{c}^W_0 = (I - \beta \boldsymbol{m})^{-1} c^W_0$, as explained in the main text. Negative values denote losses and positive values denote gains. Panel A uses initial employment weights $L_{\ell,j,0}$; the standard deviation is measured in percentage points. Panels B–C report cell-level changes in percent. Panels D–G report employment-weighted two-way fixed effects in percentage points, with each set centered to have employment-weighted mean zero. Larger fixed effects indicate greater gains relative to the mean. See Table A.1 for sector definitions.

fuel prices, while Vermont and Idaho additionally benefit from lower electricity prices and stronger demand associated with the increased income from renewable-electricity capitalists.

To separate regional from sectoral components of these welfare effects, we regress worker consumption-equivalent changes on separate sets of region and sector indicators. Panel D shows that Louisiana, Oklahoma, and Texas experience the largest negative regional effects of the carbon tax, controlling for sector, whereas Arizona and Idaho are among the states with the largest positive regional effects. Finally, Panel F shows that workers in fuels and mining experience some of the largest negative sectoral effects, controlling for location. By contrast, the sectors experiencing the largest positive effects are substantially more sensitive to the policy scenario under consideration.

For a capital owner associated with cell (ℓ, j), let $\mathcal{V}^K_{\ell,j,0}$ denote discounted lifetime utility in the initial steady state and $\mathcal{V}^{K,tr}_{\ell,j,1}$ discounted lifetime utility along the transition. Baseline discounted lifetime consumption and the corresponding percentage welfare effects are

$$\bar{c}^K_{\ell,j,0} = \frac{1}{1-\beta}\left(\frac{r_{\ell,j,0}K_{\ell,j,0}}{P_{\ell,0}} - Inv_{\ell,j,0}\right), \qquad CE^K_{\ell,j} = 100 \times \frac{\mathcal{V}^{K,tr}_{\ell,j,1} - \mathcal{V}^K_{\ell,j,0}}{\bar{c}^K_{\ell,j,0}}. \tag{64}$$

Table 6 displays the corresponding results for capital owners. Capital owners lose on average under both policy scenarios, but the renewable subsidy generates substantially greater dispersion in welfare effects. This is perhaps not surprising: the policy harms capital owners in the fossil-fuel sector and in fossil-fuel-based electricity generation, while benefiting capital owners in renewable electricity generation, thereby producing larger differences across sectors.

Under the uniform rebate, fossil-fuel capital owners experience the largest losses in Colorado, North Dakota, and Wyoming. Under the renewable subsidy, by contrast, capital owners in fossil-fuel-based electricity generation experience the largest losses, particularly in states that almost completely substitute away from fossil-fuel-based electricity, such as Washington, Oregon, and Idaho—see Panel B. Panel C, in turn, shows substantial gains among capital owners in renewable electricity generation.

The remainder of the table reveals meaningful regional variation in capital owners' welfare effects, with the ranking of regions depending on the policy considered, as well as substantial dispersion across sectors. Capital owners in fossil-fuel-based electricity generation are among the losers under both policies, but their losses are particularly pronounced under the renewable subsidy.

Overall, Tables 5 and 6 point to substantial heterogeneity in the welfare effects of the

Table 6: Consumption-Equivalent Capital-Owner Welfare Changes Across States and Sectors

	Uniform rebate		Renewable subsidy
Panel A: Aggregate Distribution			
$c^K_{\ell,j,0}$-weighted mean (%)	-0.361		-0.736
$c^K_{\ell,j,0}$-weighted standard deviation (p.p.)	1.576		4.151
Panel B: State-Sector Pairs with Largest Losses			
Colorado, Sector 1	-9.222	Washington, EF	-34.379
North Dakota, Sector 1	-9.153	Oregon, EF	-33.234
Wyoming, Sector 1	-9.120	Idaho, EF	-32.952
Ohio, Sector 1	-8.992	South Dakota, EF	-32.908
Montana, Sector 1	-8.952	Vermont, EF	-32.315
Panel C: State-Sector Pairs with Largest Gains			
Oklahoma, Sector 16	0.483	Rhode Island, ER	8.678
Oklahoma, Sector 18	0.448	Wyoming, ER	8.652
Louisiana, Sector 16	0.395	Delaware, ER	8.601
Oklahoma, Sector 8	0.373	West Virginia, ER	8.583
Oklahoma, Sector 11	0.361	Kentucky, ER	8.575
Panel D: States with Lowest State Fixed Effects			
Idaho	-0.114	Arizona	-0.410
North Dakota	-0.089	North Dakota	-0.260
Montana	-0.082	Idaho	-0.252
Vermont	-0.071	Pennsylvania	-0.241
South Dakota	-0.066	Montana	-0.239
Panel E: States with Highest State Fixed Effects			
West Virginia	0.199	Rhode Island	1.832
Rhode Island	0.194	West Virginia	1.652
Wyoming	0.178	Kentucky	1.283
Kentucky	0.164	Wyoming	1.059
Mississippi	0.081	Indiana	0.812
Panel F: Sectors with Lowest Sector Fixed Effects			
Sector 1	-8.349	EF	-19.555
EF	-1.343	Sector 1	-8.642
Sector 3	0.038	Sector 3	0.357
Sector 10	0.156	Sector 13	0.490
Sector 13	0.219	Sector 10	0.529
Panel G: Sectors with Highest Sector Fixed Effects			
ER	0.485	ER	9.219
Sector 22	0.358	Sector 29	0.731
Sector 30	0.348	Sector 24	0.730
Sector 32	0.347	Sector 22	0.726
Sector 33	0.346	Sector 16	0.726

Notes: The table reports consumption-equivalent welfare changes following a 20% carbon tax. For each state-sector cell (ℓ, j), the change is given by $100 \times (\mathcal{V}^{K,\mathrm{tr}}_{\ell,j,1} - \mathcal{V}^{K}_{\ell,j,0})/\bar{c}^{K}_{\ell,j,0}$, as explained in the main text. Negative values denote losses and positive values gains. Panel A and the two-way fixed-effects decompositions use initial consumption, $c^K_{\ell,j,0}$, as weights. The weighted mean equals the aggregate present-value change divided by aggregate baseline lifetime consumption. Panels B–C report cell-level changes in percent, while Panels D–G report fixed effects in percentage points, with each set of fixed effects centered to have a weighted mean of zero. The sample includes cells with positive baseline capital in sectors 1–33, renewable electricity (ER), and fossil electricity (EF). See Table A.1 for sector definitions.

carbon tax across both workers and capital owners, depending on their region and sector of employment or residence. These results identify where the distributional costs of the carbon tax are concentrated and illustrate how the allocation of carbon-tax revenues can substantially reshape those costs across regions, sectors, workers, and capital owners.

6 Conclusion

This paper develops a dynamic spatial general-equilibrium model of the U.S. designed to study the distributional and transitional consequences of decarbonization policies. By combining trade and input-output linkages, costly worker mobility, capital accumulation, and interstate electricity transmission, the framework allows us to trace how climate policies affect workers, capital owners, sectors, and regions over time.

We use the model to study a 20% tax on fossil-fuel production under two alternative uses of the resulting revenues: a uniform rebate to workers and subsidies to renewable electricity production. Our results point to three main conclusions. First, both policies generate large and relatively rapid reductions in fossil-fuel production, with output falling by approximately 35% within five years and by 38–42% in the long run. Second, the use of carbon-tax revenues generates an important trade-off. Renewable subsidies produce a much larger shift toward clean electricity and a smaller decline in long-run aggregate consumption, whereas the uniform rebate substantially reduces workers' welfare losses. The transition paths also differ sharply. Renewable subsidies induce rapid investment in clean electricity, initially depressing consumption but expanding generating capacity and temporarily lowering electricity prices. Under the uniform rebate, by contrast, aggregate consumption initially rises as investment contracts sharply in fossil-fuel-intensive activities.

Third, these aggregate effects mask substantial heterogeneity in incidence and adjustment across regions, sectors, workers, and capital owners. Losses are concentrated in fossil-fuel-producing states and carbon-intensive industries, and the *Renewable Subsidy* generates substantially greater cross-state dispersion in both consumption and population changes. Workers initially employed in fossil fuels experience some of the largest lifetime welfare losses under either policy, but the magnitude of these losses varies substantially across locations. This variation reflects differences in workers' outside employment opportunities and in the costs they face when moving across sectors and regions. Worker mobility mitigates some of these losses over time and generates substantial reallocation across both regions and sectors, but does not eliminate the concentration of welfare losses among workers initially

most exposed to the policy. Welfare effects are also highly heterogeneous across capital owners: the renewable subsidy generates particularly large losses for owners of fossil-fuel and fossil-fuel-based electricity capital while producing substantial gains for owners of renewable electricity capital.

Several extensions are important for the next stage of the analysis. First, we plan to introduce worker demographics, particularly age and education, which are likely to shape mobility frictions across regions and sectors. This extension will allow us to identify more precisely which groups bear the costs of decarbonization and to study the resulting political-economy implications. Second, we plan to replace the tax on fuel sales with a tax directly linked to carbon emissions. This distinction matters because industries differ in the amount of carbon emissions associated with a given quantity of fuel use. Third, we plan to assess the robustness of our results to alternative functional forms and patterns of substitution in production. Finally, we plan to introduce greater heterogeneity within renewable electricity generation, distinguishing technologies that are more closely tied to fixed geographic factors, such as hydroelectric power, from technologies such as solar and wind.

References

Aghion, Philippe, Timo Boppart, Michael Peters, Matthew Schwartzman, and Fabrizio Zilibotti. 2025. "A Theory of Endogenous Degrowth and Environmental Sustainability." National Bureau of Economic Research NBER Working Paper 33634.

Allen, Treb, and Costas Arkolakis. 2022. "The Welfare Effects of Transportation Infrastructure Improvements." *The Review of Economic Studies*, 89(6): 2911–2957.

Arkolakis, Costas, and Conor Walsh. 2023. "Clean Growth." Working Paper.

Artuç, Erhan, and John McLaren. 2015. "Trade policy and wage inequality: A structural analysis with occupational and sectoral mobility." *Journal of International Economics*, 97(2): 278–294.

Artuç, Erhan, Shubham Chaudhuri, and John McLaren. 2010. "Trade Shocks and Labor Adjustment: A Structural Empirical Approach." *American Economic Review*, 100(3): 1008–1045.

Bigio, Saki, Diego R. Känzig, Pablo Sánchez, and Conor Walsh. 2026. "Carbon Pricing and Inequality: A Normative Perspective." *The Economic Journal*, 136(677): 1659–1682.

Bijnens, Gert, John Hutchinson, and Arthur Saint Guilhem. 2026. "Navigating the Carbon Price Shock: Electricity Costs and Employment Reallocation in Europe." *Utilities Policy*, 99: 102144.

Bilal, Adrien, and Diego R. Känzig. 2026. "The Macroeconomic Impact of Climate Change: Global Versus Local Temperature." *The Quarterly Journal of Economics*, 141(2): 889–944.

Bilal, Adrien, and James H. Stock. 2026. "A Guide to Macroeconomics and Climate Change." Manuscript.

Broda, Christian, and David E. Weinstein. 2006. "Globalization and the Gains from Variety." *Quarterly Journal of Economics*, 121(2): 541–585.

Caliendo, Lorenzo, and Fernando Parro. 2015. "Estimates of the Trade and Welfare Effects of NAFTA." *The Review of Economic Studies*, 82(1): 1–44.

Caliendo, Lorenzo, Maximiliano Dvorkin, and Fernando Parro. 2019. "Trade and Labor Market Dynamics: General Equilibrium Analysis of the China Trade Shock." *Econometrica*, 87(3): 741–835.

Dix-Carneiro, Rafael. 2014. "Trade Liberalization and Labor Market Dynamics." *Econometrica*, 82(3): 825–885.

Dix-Carneiro, Rafael, João Paulo Pessoa, Ricardo Reyes-Heroles, and Sharon Traiberman. 2023. "Globalization, Trade Imbalances, and Labor Market Adjustment." *The Quarterly Journal of Economics*, 138(2): 1109–1171.

Eckert, Fabian. 2019. "Growing Apart: Tradable Services and the Fragmentation of the U.S. Economy." Working Paper.

Head, Keith, and John Ries. 2001. "Increasing Returns versus National Product Differentiation as an Explanation for the Pattern of U.S.-Canada Trade." *American Economic Review*, 91(4): 858–876.

Johnson, Erik Paul. 2014. "The cost of carbon dioxide abatement from state renewable portfolio standards." *Resource and Energy Economics*, 36(2): 332–350.

Kleinman, Benny, Ernest Liu, and Stephen J. Redding. 2023. "Dynamic Spatial General Equilibrium." *Econometrica*, 91(2): 385–424.

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James H. Stock, Tammy Tan, Mark Watson, Tony E. Wong, and David Anthoff. 2022. "Comprehensive Evidence Implies a Higher Social Cost of CO_2." *Nature*, 610: 687–692.

Traiberman, Sharon. 2019. "Occupations and Import Competition: Evidence from Denmark." *American Economic Review*, 109(12): 4260–4301.

Walker, W. Reed. 2013. "The Transitional Costs of Sectoral Reallocation: Evidence From the Clean Air Act and the Workforce." *The Quarterly Journal of Economics*, 128(4): 1787–1835.

A Data Appendix

A.1 Sector Definitions

Table A.1 provides a complete list of our sector aggregation, following the NAICS 2022 labels. In the text, we refer to sectors with(out) available trade flows data as (non) CFS sectors.

Sector	NAICS 2022	NAICS Description	Trade flows data
1	211, 324	*Fuel*: Oil and gas extraction, Petroleum and Coal Products Manufacturing	Available
2	11	Crop Production, Animal Production, Aquaculture, Forestry, Fishing	Not available
3	212–213	Mining	Available
4	23	Construction	Not available
5	311–312	Food, Beverage, and Tobacco Product Manufacturing	Available
6	313–316	Textile mills, apparel, leather, allied products	Available
7	321	Wood product manufacturing	Available
8	322	Paper manufacturing	Available
9	323	Printing and related support activities	Available
10	325	Chemical manufacturing	Available
11	326	Plastics and rubber products manufacturing	Available
12	327	Nonmetallic mineral product manufacturing	Available
13	331	Primary metal manufacturing	Available
14	332	Fabricated metal product manufacturing	Available
15	333	Machinery manufacturing	Available
16	334	Computer and electronic product manufacturing	Available
17	335	Electrical equipment, appliance, and component manufacturing	Available
18	336	Motor vehicles, bodies and trailers, and parts manufacturing	Available
19	337	Furniture and related product manufacturing	Available
20	339	Miscellaneous manufacturing	Available
21	42	Wholesale trade	Available
22	44–45	Retail trade	Not available
23	48–49	Transportation and warehousing	Not available
24	51	Information	Not available
25	52	Finance and insurance	Not available
26	53	Real estate and rental and leasing	Not available
27	54–55	Professional, Scientific, and Technical Services, Management of companies	Not available
28	56	Administrative and support and waste management and remediation services	Not available
29	61	Educational services	Not available
30	62	Health care and social assistance	Not available
31	71	Arts, entertainment, and recreation	Not available
32	72	Accommodation and food services	Not available
33	81	Other services (except government and government enterprises)	Not available

Table A.1: Sector definitions according to the 2022 North American Industry Classification System (NAICS)

A.2 Electricity Production Data

A.2.1 Energy Information Administration (EIA)

Installed Capacity, Generation, and Prices Data on energy nameplate capacities are collected from the Energy Information Administration's (EIA) mandatory annual census

(Form EIA-860) for the year 2017. Specifically:

- We measure renewable electricity capital, $K_{\ell,ER}$, as the sum of the nameplate capacities of power plants in state ℓ using the following energy sources: solar, wind, geothermal, hydroelectric, and nuclear. Nameplate capacities are expressed in MWh per year.[10]

- We measure fossil-fuel-based electricity capital, $K_{\ell,EF}$, as the sum of the nameplate capacities of power plants in state ℓ using the following energy sources: coal, natural gas, petroleum, other biomass, other gases, and wood and wood-derived fuels. Nameplate capacities are expressed in MWh per year.

Data on electricity generation and the prices received by generators are obtained from the "Power Plant Operations Report" (Form EIA-923). Specifically:

- We measure renewable electricity generation, $y_{\ell,ER}$, as the sum of net generation in state ℓ from the following energy sources: solar, wind, geothermal, hydroelectric, and nuclear.[11] Net generation is expressed in MWh.

- We measure fossil-fuel-based electricity generation, $y_{\ell,EF}$, as the sum of net generation in state ℓ from the following energy sources: coal, natural gas, petroleum, other biomass, other gases, and wood and wood-derived fuels. Net generation is expressed in MWh.

- We measure electricity prices received by generators, $p_{\ell,E}$, as the ratio of revenues from wholesale electricity sales (Schedule 7A) to the quantity of wholesale electricity sales in MWh (Schedule 6) in state ℓ, expressed in \$/MWh.

For both nameplate capacity and net generation, we aggregate quantities from "Electric Generators, Independent Power Producers" and "Electric Generators, Electric Utilities."[12]

Data on end-user electricity prices, $P_{\ell,E}$, and expenditures, $X_{\ell,E}$, inclusive of delivery fees, are obtained from the EIA's mandatory annual census (Form EIA-861) for 2017.

[10] At the point of generation, nuclear does not emit CO_2. Over the complete lifecycle, including construction and manufacturing, nuclear has a similar carbon footprint to the other renewable resources included in our label.

[11] The EIA definition of net generation is: "The amount of gross generation less the electrical energy consumed at the generating station(s) for station service or auxiliaries." Data on gross generation is not available.

[12] The other producer types are "Combined Heat and Power, Industrial Power," "Combined Heat and Power, Commercial Power," and "Combined Heat and Power, Electric Power." We exclude these categories because they primarily capture electricity generated in-house by firms rather than electricity purchased from generators.

Electricity flows We use EIA Form 930 to measure directional electricity interchange between Balancing Authorities (BAs). Because BA territories do not generally coincide with state borders, the form does not directly provide every state-to-state flow $f_{i,j,E}$. BA borders and state borders imply different partitions of the contiguous United States. The only exception is New York, where there is a unique BA operating in all the state's counties. If BA territories were consistently subsets of states, we would just need to aggregate the flows within each state. This is the case for Florida (approximately) and California. If states were consistently subsets of BA territories, we would be able to identify the sum of flows between groups of states. This is the case for New England and several states in the Midwest. In all other cases, BA territories and states intersect and overlap without a clear correspondence. We recover more observations by identifying groups of states, each of them being a superset for the union set of some BA territories, and the flows between these groups. We therefore construct a limited set of state and regional-group flow moments as follows:

1. Using EIA Form 860, we associate each power plant with its county and BA. The *dominant BA* of a county is the BA accounting for the largest share of the county's installed nameplate capacity.

2. We identify state pairs and regional-group pairs for which the relevant state-to-state flow can be approximated by the sum of directional interchange flows among the BAs operating in the relevant locations. Following this procedure, we identify 26 directed flows.

3. We classify two border-sharing states as neighbors when either they have a non-zero imputed flow or a sizeable number of counties in both states have the same dominant BA.[13]

A.3 Labor Market Data

A.3.1 American Community Survey (ACS)

We collect state-sector-specific labor allocations and flows from the American Community Survey (ACS). We pool annual ACS samples from 2015 to 2019 to increase the sample size and construct five-year averages that represent 2017 values. We restrict the sample to individuals plausibly attached to the labor force, according to the following criteria:

[13] Under this definition, Texas is not a neighbor of New Mexico or Louisiana, and Montana is not a neighbor of North Dakota. All other border-sharing state pairs are classified as neighbors.

- only individuals aged 20 to 60 are included;
- individuals attending school who are younger than 25 are excluded;
- recipients of Social Security or Supplemental Security income are excluded.

We also exclude:

- individuals in the armed forces;
- individuals whose place of residence in the previous year was not one of our 48 locations.[14]

Individuals are considered non-employed whenever they are classified as "unemployed" or "out of the labor force" by the variable `empstat`.

From these data, we construct the following variables, meant to represent 2017 values:

- $L_{\ell,j}^{ACS}$ – labor allocations in state ℓ and sector j. We calculate these as the sum of person weights (`perwt`) for workers in each (ℓ, j) cell and then average them between 2015 and 2019.
- $f_{o,\ell n}^{\text{ACS}}$ – annual labor flows from origin o to location ℓ and sector n. We use the ACS variable `migplac1`, which reports the respondent's previous-year place of residence, and average the flows across the five years.

A.3.2 Current Population Survey (CPS)

We compute annual sector-to-sector flows from sector p to sector n, denoted by $f_{p,n}^{\text{CPS}}$, using data from the Current Population Survey (CPS) for each year from 2015 to 2019. We then average these flows across years. The same sample restrictions used for the ACS apply here:

- only individuals aged 20 to 60 are included;
- individuals attending school who are younger than 25 are excluded;
- recipients of Social Security or Supplemental Security income are excluded;
- individuals in the armed forces are excluded.

[14] We exclude people residing abroad during the previous year so as to have a square transition matrix, since the ACS includes only individuals residing in the U.S. in the survey year.

Individuals are considered non-employed whenever they are classified as "unemployed" or "out of the labor force" by the variable `empstat`.

To compute flows, we track respondents across sectors over time using `ind90ly`, which reports the industry in which the respondent worked during the previous year.

A.4 Trade Flows

A.4.1 Commodity Flow Survey (CFS) data

We collect data on trade flows $X_{\ell,\ell',j}$ from the Commodity Flow Survey (CFS) for 2012 and 2017. We use the two most recent CFS datasets to increase the sample size and minimize the number of ℓ, ℓ', j cells with no recorded trade. The CFS data contain shipment-level information for approximately 6 million "domestic freight shipments" between 60,000 U.S. establishments.

For each shipment record i, we use the state-level origin $\ell(i)$, state-level destination $\ell'(i)$, shipper industry $j(i)$, and shipment value $\widetilde{X}_i$. The CFS covers traded goods but not services. Thus, information on trade flows is available only for a subset $J^{CFS} \subset J \cup F$ of the sectors we consider. The availability of trade-flow data by sector is indicated in Table A.1.

To construct the model's ℓ, ℓ', j trade flows, we use the survey weights ω_i^X provided by the dataset.[15] For each period t, we compute

$$X_{\ell,\ell',j,t} = \sum_{i \,|\, \ell(i)=\ell,\, \ell'(i)=\ell',\, j(i)=j} \omega_{i,t}^X \widetilde{X}_{i,t} \quad \forall \ell,\, \forall \ell',\, \forall j \in J^{CFS}$$

We then take the simple average across 2012 and 2017 for each ℓ, ℓ', j cell to obtain $X_{\ell,\ell',j}$.

For 8.3% of ℓ, ℓ', j cells among CFS sectors, neither the 2012 nor the 2017 CFS contains an entry. We treat these cells as follows:

1. There are 5 cases (out of 43,776 cells) in which $X_{\ell,\ell',j} > 0$ and $X_{\ell,\ell,j} = 0$, for $\ell \neq \ell'$. In these situations, we set $X_{\ell,\ell',j} = 0$.

2. There are 13 cases in which $X_{\text{Texas},\ell',j} = 0$ and $X_{\ell',\ell',j} > 0$. Because we use these flows to compute location-sector-specific productivities in the Parameter Extraction algorithm, we impute those 13 entries using a gravity equation;

3. In all other cases, we leave $X_{\ell,\ell',j} = 0$.

[15] The "shipment tabulation weighting factor" expands numeric shipment data, such as dollar values, to represent the total population of U.S. shipments in the survey year.

A.5 Production, Investment, and Energy Expenditure Data

A.5.1 Bureau of Economic Analysis – Fixed Assets Accounts Table

We collect the historical-cost net stock of private fixed assets and relative annual depreciation at the sector level for 2015 to 2019. We compute the annual ratio of depreciation to net stock and store sector-level depreciation rates δ_j as five-year averages representing 2017 values.

A.5.2 Bureau of Economic Analysis – Use and Supply Tables

We leverage the 2017 BEA Use and Supply Tables to obtain data on sector j's expenditures on inputs from sector k, X_j^k, as well as the wage bill and gross sales of each sector j, $WageBill_j$ and GO_j, respectively.

Raw data We collect the following variables from the 2017 BEA Use and Supply Tables:

- S_j^c is the supply of commodity c by sector j, $c \in C$ and $j \in J^*$, where J^* is the set of sectors in the economy, and C is the set of commodities in the economy.
- U_j^c is the use of commodity c by sector j, $c \in C$ and $j \in J^*$.
- GO_j, VA_j, $WageBill_j$ are respectively the gross sales, value added, and wage bill of sector j, $j \in J^*$.
- NX^c denotes net exports of commodity c ($NX^c = Exports^c - Imports^c$), with exports taken from the Use Table and imports from the Supply Table.
- T^c denotes net taxes on commodity c (taxes minus subsidies, from the Supply Table).
- D^c denotes trade margins involved in the sale of commodity c.
- R^c denotes transportation costs involved in the sale of commodity c.
- X_{HH}^c, I^c, and G^c are, respectively, household expenditure, private investment expenditure (including inventory changes), and government expenditure on commodity c.

BEA accounting identities Using the raw-data notation defined above, the BEA Use and Supply Tables satisfy

$$GO_j = \sum_{c \in C} U_j^c + VA_j, \qquad \forall j \in J^*, \tag{65}$$

$$GO_j = \sum_{c \in C} S_j^c, \qquad \forall j \in J^*, \tag{66}$$

$$\sum_{j \in J^*} U_j^c + X_{HH}^c + I^c + G^c + NX^c = \sum_{j \in J^*} S_j^c + D^c + R^c + T^c, \qquad \forall c \in C. \tag{67}$$

The first two identities equate industry gross output to intermediate purchases plus value added and to total commodity production, respectively. The third identity equates commodity supply and use, accounting for net exports, trade and transportation margins, and net taxes.

Model accounting identities

$$GO_j = \sum_{k \in J \cup F \cup E} X_j^k + VA_j \qquad \forall j \in J \cup F \tag{68}$$

$$GO_j = \sum_{k \in J \cup F} X_k^j + X_{HH}^j \qquad \forall j \in J \tag{69}$$

$$GO_F = \sum_{k \in J \cup F \cup E} X_k^F + X_{HH}^F \tag{70}$$

$$VA_j = WageBill_j + CapExp_j \qquad \forall j \in J \cup F \tag{71}$$

Here, $CapExp_j$ denotes payments to capital in sector j.

Without the procedure described in this section, the model accounting relationships above would not be guaranteed to hold; indeed, the following discrepancies arise between the model and the raw BEA tables:

1. Sectors are not multiproduct in our model, whereas in the data the output of each sector may be split across several commodities.[16] The Use Table records sectors' expenditures on commodities (equation 65), while the Supply Table records sectors' production of commodities (equation 66). Because there is no one-to-one mapping between commodities and sectors, we need a procedure to reconcile the two classifications;

[16] For example, the Farms sector (Sector 2) sells a non-negligible amount of the Amusement and Recreation commodity, even though that commodity is primarily supplied by Sector 31.

2. There are no model counterparts to net exports (NX^c), trade margins (D^c), transportation margins (R^c), taxes (T^c), government expenditure (G^c), and private investment (I^c) by commodity. Thus, a mapping between commodities and sectors would not suffice, as mapping equation 67 to its sector-to-sector counterpart would still include those margins;

3. Our sector definition excludes some sectors that are present in the BEA tables and supply commodities to sectors included in our model;[17]

4. In our model, Electricity is an input into all sectors but uses only Fuel as an intermediate input. Both sectors therefore require special treatment, since:

    - we need to account for Fuel sales to Electricity;
    - although we model the generation of Electricity differently from production in other sectors and do not use BEA data to inform its calibration, we still need to store household expenditure on Electricity for the cost shares of the final good.

Imputation Description The objective of the procedure is to impute the matrix $\{X_j^k\}$ from the raw matrices $\{U_j^c\}$ and $\{S_j^c\}$.

We first rescale expenditures and sales so as to account for net exports, taxes, and the other margins not accounted for by the model. We then use a proportionality assumption to convert commodity expenditures into sector expenditures. Finally, we use the imputed sector-to-sector expenditures to define gross sales, value added, and wage bill consistent with equations 68, 69, and 70.

Comparing the BEA accounting identity in equation 67 with the corresponding model identities in equations 69 and 70 makes the discrepancy clear: our model abstracts from international trade and other margins; the sales of a sector are matched by the sum of the household and sector expenditures. We address the issue by rescaling $\{S_j^c\}$, $\{U_j^c\}$, and $\{X_{HH}^c\}$ so as to absorb the margins we don't model and the sales and expenditures of sectors we exclude. Notice that the apportionment of specific margins to any of the three variables is somewhat

[17] In particular, as is customary, we exclude Federal government enterprises and State and local government enterprises, since they may not follow profit-maximizing objectives. This, however, creates discrepancies between the data and the model since, for example, the service "Education" could be provided both by the corresponding (private) sector and by state and federal government enterprises.

arbitrary – we could rescale commodity sales by sector, commodity expenditure by sector, or household expenditure to account for transportation margins. However, some rules might deliver negative entries.[18]

We rescale commodity sales so that their total includes net exports and taxes; we rescale sector expenditures so that their total includes a portion of transportation and trade margins.[19] We also rescale the commodity sales and expenditures of commodity c so that their total includes respectively the sales and expenditures of sectors not included in the model.

After the rescaling, we need a mapping between commodities and sectors. We assume that sector j's share of aggregate sales of commodity c is constant across all sector-to-sector transactions; for example, if sector k's sales of the commodity "Rubber" amount to 10% of total rubber sales, sector j is going to allocate 10% of its rubber expenditure to sector k. This delivers our imputed matrix $\{\widehat{X}_j^k\}$.

To reconcile the BEA identities in equations 65 and 66 with the model equations 68, 69, and 70, we need to make sure that gross sales, value added, and the wage bill are rescaled consistently with $\{\widehat{X}_j^k\}$. We thus define gross sales of sector j as the sum of all (rescaled) commodity sales by that sector, and value added as the difference between gross sales and (rescaled) input expenditures by that sector. Finally, we rescale the wage bill of each sector so as to preserve the original ratio of wage payments to value added from the raw data.

Imputation Procedure Define the special commodities $c^E = \arg\max_c S_E^c$ and $c^F = \arg\max_c S_F^c$; we are going to treat these commodities differently for the reasons outlined above.

For each commodity c, define the relative weight of sales to sectors and households as:

$$\theta^c = \frac{X_{HH}^c + G^c + I^c}{X_{HH}^c + G^c + I^c + \sum_{j \in J^*} U_j^c} \tag{72}$$

This is the share of household consumption, government expenditure, and private investment

[18]For example, if we were to rescale only household expenditure, i.e., treat it as the residual difference between commodity sales and expenditures between sectors, we would obtain several negative entries. One possible reason is that net imports are larger than domestic household expenditures.

[19]As explained below, we attribute a share of transportation and trade margins to sector expenditures, and the complementary share to household expenditure.

in total expenditure on commodity c, including intermediate purchases by sectors. We will split trade margins between sector-to-sector and sector-to-household transactions in the scaling procedure using this weight. We scale the U and S matrices as follows: we rescale commodity sales so as to take into account net exports and taxes; transportation costs and trade margins are split proportionally between sector expenditures and household expenditures. We also rescale the sales and expenditures of commodity c to account for sectors not included in the model.

$$\xi^c = \frac{\sum_{j\in J\cup F} S_j^c}{\sum_{j\in J^*} S_j^c - NX^c + T^c} \qquad \forall c \in C \setminus \{c^E\}$$

$$\zeta^c = \frac{\sum_{j\in J\cup F} U_j^c}{\sum_{j\in J^*} U_j^c - (1-\theta^c)(R^c + D^c)} \qquad \forall c \in C \setminus \{c^E, c^F\}$$

$$\zeta^{c^F} = \frac{\sum_{j\in J\cup F} U_j^{c^F}}{\sum_{j\in J^*\setminus\{E\}} U_j^{c^F} - (1-\theta^{c^F})(R^{c^F} + D^{c^F})}$$

The adjusted use matrix is defined for buyers $j \in J \cup \{F\}$, while the adjusted supply matrix is defined for sellers $j \in J \cup \{F, E\}$:

$$\begin{aligned}
\widehat{U}_j^c &= U_j^c/\zeta^c, && c \in C \setminus \{c^E\}, \quad j \in J \cup \{F\},\\
\widehat{S}_j^c &= S_j^c/\xi^c, && c \in C \setminus \{c^E\}, \quad j \in J \cup \{F, E\},\\
\widehat{S}_j^{c^E} &= \mathbf{1}(j = E) S_j^{c^E}, && j \in J \cup \{F, E\},\\
\widehat{U}_j^{c^E} &= U_j^{c^E}, && j \in J \cup \{F\}.
\end{aligned}$$

ξ^c is the rescaling factor for commodity sales, meant to take into account net exports, sectors not included in our sector list, and net taxes. ζ^c is the rescaling factor for commodity expenditures, meant to take into account expenditures by sectors not included in our sector list, and (the appropriate portion of) trade margins and transportation costs. After this rescaling, we have a simplified expression for each $c \in C \setminus \{c^E\}$:

$$\sum_{j\in J\cup F} \widehat{U}_j^c + \mathbf{1}(c = c^F)\, U_E^c + X_{HH}^c + G^c + I^c - \theta^c(D^c + R^c) = \sum_{j\in J\cup F} \widehat{S_j^c} \tag{73}$$

Notice that now the left-hand side – the overall expenditures at the commodity level – can be divided into sector expenditure and a composite expenditure that includes household consumption, investment, and government expenditure, less the allocated trade and transportation margins.

We construct model-consistent sector-to-sector expenditures. To do that, we use a proportionality assumption: if sector j's sales of the commodity "Rubber" amount to 10% of total rubber sales, each sector that purchases rubber is going to allocate 10% of its rubber expenditure to sector j. First, define the share of commodity c sold by sector j as:

$$\pi_j^c = \frac{\widehat{S_j^c}}{\sum_{k \in J \cup \{F,E\}} \widehat{S_k^c}}, \qquad j \in J \cup \{F, E\}, \quad c \in C, \tag{74}$$

which is the ratio of adjusted sales of commodity c by sector j to total adjusted sales of that commodity across all retained model sectors, including Fuel and Electricity. Sectors excluded from the model do not enter the denominator. Then build

$$\widehat{X_j^k} = \sum_{c \in C} \pi_k^c \, \widehat{U_j^c} \qquad j \in J \cup F \quad k \in J \cup F \cup E \tag{75}$$

For the electricity sector, we set $\widehat{X_E^k} = 0 \; \forall k \in J$, and $\widehat{X_E^F} = U_E^{c^F}$.[20] This is aligned with the model, where the generation of electricity requires only fuel as intermediate input.

We have now derived sector-to-sector expenditures, first rescaling sector-to-commodity variables and then mapping commodity expenditures to sector expenditures under a proportionality assumption. Finally, we ensure that the model accounting equations 68, 69, and 70 hold. For each sector, we subtract sales to sectors from adjusted gross sales. We assign the remaining sales to household expenditure. Adjusted household expenditure is a model-consistent final-demand residual; it does not correspond to observed household consumption alone. For the fuel sector, intermediate sales also include fuel purchased by electricity pro-

[20] In the model we have that the sector Fuel provides the input for electricity generation. In the raw data, 99% of sales of the Fuel commodity come from the Fuel sector. We thus decide not to apply the proportionality rule. Moreover, as we do not apply any rescaling to electricity sales (we source them from EIA), we deem appropriate to use the un-scaled fuel input.

ducers. Therefore, we define

$$\widehat{GO_j} = \sum_c \widehat{S_j^c} \qquad \forall j \in J \cup F \tag{76}$$

$$\widehat{X}_{HH}^j = \widehat{GO_j} - \sum_{k \in J \cup F \cup E} \widehat{X_k^j} \qquad \forall j \in J \cup F \tag{77}$$

$$\widehat{X}_{HH}^E = X_{HH}^{c^E} \tag{78}$$

$$\widehat{VA_j} = \widehat{GO_j} - \sum_{k \in J \cup F \cup E} \widehat{X_j^k} \qquad \forall j \in J \cup F \tag{79}$$

$$\widehat{WageBill}_j = \widehat{VA}_j \frac{WageBill_j}{VA_j} \qquad \forall j \in J \cup F \tag{80}$$

The procedure ensures that the following model-consistent accounting relationships hold:[21]

$$\widehat{GO_j} = \sum_{k \in J \cup F \cup E} \widehat{X}_j^k + \widehat{VA_j} \qquad \forall j \in J \cup F \tag{81}$$

$$\widehat{GO_j} = \sum_{k \in J \cup F} \widehat{X}_k^j + \widehat{X}_{HH}^j \qquad \forall j \in J \tag{82}$$

$$\widehat{GO_F} = \sum_{k \in J \cup F \cup E} \widehat{X}_k^F + \widehat{X}_{HH}^F \tag{83}$$

$$\widehat{VA_j} > \widehat{WageBill}_j \qquad \forall j \in J \cup F \tag{84}$$

Model-consistent measures of electricity expenditure $\widehat{X}_j^E$, total wage bill $\widehat{WageBill}_j$, household expenditure on electricity $\widehat{X}_{HH}^E$, material expenditures $\widehat{X_j^k}$ for $k \in J \cup \{F\}$, and gross sales $\widehat{GO_j}$ are recorded in millions of dollars.

A.5.3 Bureau of Economic Analysis – Regional Accounts

We collect value added $\widetilde{VA}_{\ell,j}$ at the state-sector level from the Regional Economic Accounts of the BEA for 2015 to 2019; we pool the data and compute five-year averages to reflect 2017 variables.

These value-added data *include* taxes on products and imports and subsidies. Consequently, the sum of state-sector value added within a sector does not equal the model-consistent $\widehat{VA_j}$ estimated in the previous subsection. We rescale state-sector value added under the assumption that taxes and subsidies are proportionally uniform across states.

[21] As explained above, the procedure delivers positive entries given the raw data at hand.

We therefore record the following values in millions of dollars:

$$VA_{\ell,j}^{BEA} = \widehat{VA}_j \, \frac{\widetilde{VA}_{\ell,j}}{\sum_\ell \widetilde{VA}_{\ell,j}} \tag{85}$$

B Electricity Transmission: Derivations

This appendix derives the reduced-form bilateral transmission costs $\tau_{k,\ell,E}$, bilateral electricity shipments $q_{k,\ell,E}$, and link-level electricity flows $f_{i,j,E}$ used in the main text. We take the electricity procurement problem described in Section 2.5 as given. For expositional simplicity, we suppress time subscripts throughout the derivation.

Define

$$\widetilde{P}_{\ell,E} \equiv P_{\ell,E}^{-\theta}, \qquad \widetilde{p}_{\ell,E} \equiv p_{\ell,E}^{-\theta},$$

and denote $\widetilde{\boldsymbol{\kappa}}$ the matrix with elements

$$\widetilde{\kappa}_{k,\ell} = \begin{cases} \kappa_{k,\ell}^{-\theta}, & k \in \mathcal{N}_\ell \cup \{\ell\}, \\ 0, & k \notin \mathcal{N}_\ell \cup \{\ell\}, \end{cases}$$

We restate equation (29)—without time subscripts—as

$$\widetilde{P}_{\ell,E} = \widetilde{\kappa}_{\ell,\ell}\widetilde{p}_{\ell,E} + \sum_{k \in \mathcal{N}_\ell} \widetilde{\kappa}_{k,\ell}\widetilde{P}_{k,E}.$$

Stacking this expression across locations gives

$$\widetilde{\boldsymbol{P}}_E = Diag\left(\widetilde{\boldsymbol{\kappa}}\right)\widetilde{\boldsymbol{p}}_E + \left(\widetilde{\boldsymbol{\kappa}} - Diag\left(\widetilde{\boldsymbol{\kappa}}\right)\right)'\widetilde{\boldsymbol{P}}_E. \tag{86}$$

Where $Diag\left(\widetilde{\boldsymbol{\kappa}}\right)$ is a matrix whose diagonal coincides with the diagonal of $\widetilde{\boldsymbol{\kappa}}$ but the off-diagonal elements are zero. On the other hand, let $\widehat{\boldsymbol{\kappa}}$ denote the matrix whose off-diagonal elements coincide with those of $\widetilde{\boldsymbol{\kappa}}$, but the diagonal elements are set to zero. Formally:

$$\widehat{\boldsymbol{\kappa}} = \widetilde{\boldsymbol{\kappa}} - Diag\left(\widetilde{\boldsymbol{\kappa}}\right).$$

Now define the matrix $\widetilde{\boldsymbol{\tau}}_E$ such that

$$\widetilde{\boldsymbol{\tau}}_E' = \left(I - \widehat{\boldsymbol{\kappa}}'\right)^{-1} Diag\left(\widetilde{\boldsymbol{\kappa}}\right)$$

Then we can invert equation (86) to obtain

$$\widetilde{\boldsymbol{P}}_E = \widetilde{\boldsymbol{\tau}}'_E \widetilde{\boldsymbol{p}}_E,$$

so that

$$\widetilde{P}_{\ell,E} = \sum_{k \in \mathcal{L}} \widetilde{\tau}_{k,\ell,E} \widetilde{p}_{k,E}, \tag{87}$$

or equivalently,

$$P_{\ell,E}^{-\theta} = \sum_{k \in \mathcal{L}} \left(\tau_{k,\ell,E} p_{k,E}\right)^{-\theta}, \tag{88}$$

which is equation (30) in the main text.

We now derive equation (31). Return to the problem of the trader in location ℓ. Its cost of sourcing electricity in a given second s is given by:

$$C_{\ell,E}(s) = \min\left\{ \frac{p_{\ell,E}\kappa_{\ell,\ell}}{\zeta_{\ell,\ell}(s)}, \min_{k \in \mathcal{N}_\ell}\left\{ \frac{P_{k,E}\kappa_{k,\ell}}{\zeta_{k,\ell}(s)} \right\} \right\}.$$

Assume that each of the $\zeta_{k,\ell}(s)$, for $s \in [0,1]$, is i.i.d. Fréchet with shape θ and scale $\Gamma\left(1+\frac{1}{\theta}\right)^\theta$. For a given s, let $\pi_{k,\ell}(s)$ denote the probability that node ℓ sources *directly* from trader k, where $k \in \mathcal{N}_\ell$. Then, using standard results in Eaton and Kortum (2002):

$$\pi_{k,\ell}(s) = \frac{\left(P_{k,E}\kappa_{k,\ell}\right)^{-\theta}}{\left(p_{\ell,E}\kappa_{\ell,\ell}\right)^{-\theta} + \sum_{n \in \mathcal{N}_\ell}\left(P_{n,E}\kappa_{n,\ell}\right)^{-\theta}} \qquad \text{for } k \in \mathcal{N}_\ell.$$

Similarly, the probability that node ℓ sources locally is given by:

$$\pi_{\ell,\ell}(s) = \frac{\left(p_{\ell,E}\kappa_{\ell,\ell}\right)^{-\theta}}{\left(p_{\ell,E}\kappa_{\ell,\ell}\right)^{-\theta} + \sum_{n \in \mathcal{N}_\ell}\left(P_{n,E}\kappa_{n,\ell}\right)^{-\theta}}.$$

Using

$$P_{\ell,E}^{-\theta} = \left(p_{\ell,E}\kappa_{\ell,\ell}\right)^{-\theta} + \sum_{n \in \mathcal{N}_\ell}\left(P_{n,E}\kappa_{n,\ell}\right)^{-\theta},$$

we can write these direct sourcing probabilities as

$$\pi_{k,\ell} = \frac{\left(P_{k,E}\kappa_{k,\ell}\right)^{-\theta}}{P_{\ell,E}^{-\theta}} \qquad \text{for } k \in \mathcal{N}_\ell,$$

$$\pi_{\ell,\ell} = \frac{\left(p_{\ell,E}\kappa_{\ell,\ell}\right)^{-\theta}}{P_{\ell,E}^{-\theta}}.$$

We have dropped the argument s because these probabilities are constant over time, by means of the independence of draws.

When ℓ sources from some $k \in \mathcal{N}_\ell$, it receives electricity that the trader at k may have purchased elsewhere. That trader in turn sourced from the cheapest option available to *them*. Therefore, a Joule that arrives at ℓ may have been generated somewhere further upstream.

Let $\phi_{k,\ell}$ denote the probability that a given Joule arriving at node ℓ was originally generated at node k.

Recursively,

$$\phi_{k,\ell} = \mathbf{1}[k = \ell]\pi_{\ell,\ell} + \sum_{m \in \mathcal{N}_\ell} \phi_{k,m}\pi_{m,\ell}, \qquad \text{for all } k, \ell \in \mathcal{L}. \tag{89}$$

The interpretation is: a Joule arriving at ℓ originates at k either because (i) $k = \ell$ and ℓ sourced locally, or (ii) ℓ sourced from some direct neighbor m, and the Joule arriving from m was itself generated at k. If (ii), we need to sum across all neighbor's connections to k.

Define matrices $\mathbf{\Phi}$, $\mathbf{\Pi}^{loc}$, and $\mathbf{\Pi}^{net}$ by setting

$$\mathbf{\Phi}_{k,\ell} \equiv \phi_{k,\ell},$$

$$\mathbf{\Pi}^{loc}_{\ell,\ell} \equiv \pi_{\ell,\ell} \qquad \text{and} \qquad \mathbf{\Pi}^{loc}_{k,\ell} \equiv 0 \text{ for } k \neq \ell,$$

and

$$\mathbf{\Pi}^{net}_{k,\ell} = \begin{cases} \pi_{k,\ell}, & \text{if } k \in \mathcal{N}_\ell, \\ 0, & \text{otherwise.} \end{cases}$$

Then the recursive equation (89) becomes

$$\mathbf{\Phi} = \mathbf{\Pi}^{loc} + \mathbf{\Phi}\mathbf{\Pi}^{net},$$

so that

$$\mathbf{\Phi}(I - \mathbf{\Pi}^{net}) = \mathbf{\Pi}^{loc}.$$

Next we rewrite $\mathbf{\Pi}^{net}$ using that, for $k \in \mathcal{N}_\ell$:

$$\pi_{k,\ell} = \frac{\widetilde{\kappa}_{k,\ell}\widetilde{P}_{k,E}}{\widetilde{P}_{\ell,E}}.$$

Let $\boldsymbol{D}$ be a diagonal matrix with

$$D_{\ell,\ell} = \widetilde{P}_{\ell,E} = P_{\ell,E}^{-\theta}.$$

Then

$$\mathbf{\Pi}^{net} = \boldsymbol{D}\widehat{\boldsymbol{\kappa}}\boldsymbol{D}^{-1}.$$

Hence

$$\mathbf{\Phi}(I - \mathbf{\Pi}^{net}) = \mathbf{\Pi}^{loc}$$

can be written as

$$\mathbf{\Phi}\boldsymbol{D}(I - \widehat{\boldsymbol{\kappa}})\boldsymbol{D}^{-1} = \mathbf{\Pi}^{loc}.$$

Transposing,

$$\boldsymbol{D}^{-1}(I - \widehat{\boldsymbol{\kappa}}')\boldsymbol{D}\mathbf{\Phi}' = \mathbf{\Pi}^{loc}.$$

Therefore,

$$\begin{aligned}\boldsymbol{D}\mathbf{\Phi}' &= (I - \widehat{\boldsymbol{\kappa}}')^{-1}\boldsymbol{D}\mathbf{\Pi}^{loc} \\ &= \widetilde{\boldsymbol{\tau}}'_E Diag\left(\widetilde{\boldsymbol{\kappa}}\right)^{-1}\boldsymbol{D}\mathbf{\Pi}^{loc}\end{aligned}$$

Now read off element (ℓ, k) from

$$\boldsymbol{D}\mathbf{\Phi}' = \widetilde{\boldsymbol{\tau}}'_E Diag\left(\widetilde{\boldsymbol{\kappa}}\right)^{-1}\boldsymbol{D}\mathbf{\Pi}^{loc}.$$

The (ℓ, k) element of $\boldsymbol{D}\mathbf{\Phi}'$ is:

$$D_{\ell,\ell}\left(\mathbf{\Phi}'\right)_{\ell,k} = \widetilde{P}_{\ell,E}\phi_{k,\ell}.$$

The (ℓ, k) element of $\widetilde{\boldsymbol{\tau}}'_E Diag\left(\widetilde{\boldsymbol{\kappa}}\right)^{-1} \boldsymbol{D}\boldsymbol{\Pi}^{loc}$ is

$$\sum_{j\in\mathcal{L}} \left(\widetilde{\boldsymbol{\tau}}'_E\right)_{\ell,j} \left(Diag\left(\widetilde{\boldsymbol{\kappa}}\right)^{-1} \boldsymbol{D}\boldsymbol{\Pi}^{loc}\right)_{j,k} = \widetilde{\tau}_{k,\ell,E} \frac{\widetilde{P}_{k,E}\pi_{k,k}}{\widetilde{\kappa}_{k,k}},$$

because $Diag\left(\widetilde{\boldsymbol{\kappa}}\right)^{-1} \boldsymbol{D}\boldsymbol{\Pi}^{loc}$ is diagonal and

$$\left(Diag\left(\widetilde{\boldsymbol{\kappa}}\right)^{-1} \boldsymbol{D}\boldsymbol{\Pi}^{loc}\right)_{k,k} = \frac{\widetilde{P}_{k,E}\pi_{k,k}}{\widetilde{\kappa}_{k,k}} = \widetilde{p}_{k,E}.$$

Therefore,

$$\widetilde{P}_{\ell,E}\phi_{k,\ell} = \widetilde{\tau}_{k,\ell,E}\widetilde{p}_{k,E}.$$

Hence

$$\phi_{k,\ell} = \frac{\widetilde{\tau}_{k,\ell,E}\widetilde{p}_{k,E}}{\widetilde{P}_{\ell,E}} = \frac{\tau_{k,\ell,E}^{-\theta} p_{k,E}^{-\theta}}{P_{\ell,E}^{-\theta}}.$$

This has a clean economic interpretation: the probability that an Joule arriving at ℓ originated at k equals k's contribution to ℓ's effective price index. This is the Eaton–Kortum sourcing share analogue, but now for indirect multi-node supply chains rather than only direct bilateral trade.

Accordingly, if $X_{\ell,E}$ is total expenditure on electricity in location ℓ and $X_{k,\ell,E}$ is the component of that expenditure going to electricity generated at location k, then

$$\frac{X_{k,\ell,E}}{X_{\ell,E}} = \phi_{k,\ell} = \frac{\tau_{k,\ell,E}^{-\theta} p_{k,E}^{-\theta}}{P_{\ell,E}^{-\theta}}.$$

We can then move from expenditures to physical quantities using:

$$X_{k,\ell,E} = \tau_{k,\ell,E} p_{k,E} q_{k,\ell,E},$$

and so:

$$q_{k,\ell,E} = \frac{\tau_{k,\ell,E}^{-(\theta+1)} p_{k,E}^{-(\theta+1)}}{P_{\ell,E}^{-\theta}} X_{\ell,E}.$$

Where $q_{k,\ell,E}$ is the quantity that is shipped from k and that actually arrives in ℓ.

Now, given the quantity $\tau_{k,\ell,E} q_{k,\ell,E}$ shipped from origin k to destination ℓ (before transmission

costs), how can we decompose that quantity into flows across individual links $(i \to j)$ in the network?

Link-level decomposition of bilateral flows.

Recall that

$$\widetilde{\boldsymbol{\tau}}'_E = \left(I - \widehat{\boldsymbol{\kappa}}'\right)^{-1} Diag\left(\widetilde{\boldsymbol{\kappa}}\right) = \left(I + \widehat{\boldsymbol{\kappa}}' + \left(\widehat{\boldsymbol{\kappa}}'\right)^2 + \left(\widehat{\boldsymbol{\kappa}}'\right)^3 + \cdots\right) Diag\left(\widetilde{\boldsymbol{\kappa}}\right),$$

so that

$$\widetilde{\tau}_{k,\ell,E} = \widetilde{\kappa}_{k,k} \sum_{r \in \mathcal{R}(k,\ell)} w(r),$$

where $\mathcal{R}(k,\ell)$ is the set of all directed paths from origin k to destination ℓ, and

$$w(r) \equiv \prod_{(a \to b) \in r} \widetilde{\kappa}_{a,b}$$

denotes the weight of path r, that is, the product of the link weights $\widetilde{\kappa}_{a,b}$ along all edges $(a \to b)$ that compose the path. Note that for a Joule generated in k to go to ℓ it first must incur the transmission cost $\kappa_{k,k}$.

Path probabilities. A unit of electricity arriving at ℓ is obtained through a sequence of sourcing decisions across nodes. Consider a path

$$r = (r_0, r_1, \ldots, r_n)$$

with initial node $r_0 = k$ and final node $r_n = \ell$.

The probability that node r_q sources directly from node r_{q-1} is

$$\pi_{r_{q-1},r_q} = \frac{\widetilde{\kappa}_{r_{q-1},r_q} \widetilde{P}_{r_{q-1},E}}{\widetilde{P}_{r_q,E}}.$$

Multiplying along the path, price indices telescope:

$$\prod_{q=1}^{n} \pi_{r_{q-1},r_q} = \left(\prod_{q=1}^{n} \widetilde{\kappa}_{r_{q-1},r_q}\right) \frac{\widetilde{P}_{k,E}}{\widetilde{P}_{\ell,E}} = w(r) \frac{\widetilde{P}_{k,E}}{\widetilde{P}_{\ell,E}}.$$

Conditional on the event that the electricity arriving at ℓ was originally generated at k, the common factor $\widetilde{P}_{k,E}/\widetilde{P}_{\ell,E}$ cancels out across paths, so the conditional probability of path r is

$$\Pr[r \mid (k,\ell)] = \frac{\widetilde{\kappa}_{k,k} w(r)}{\widetilde{\kappa}_{k,k} \sum_{r' \in \mathcal{R}(k,\ell)} w(r')} = \frac{w(r)}{\widetilde{\tau}_{k,\ell,E}/\widetilde{\kappa}_{k,k}}.$$

Therefore, the share of the $k \to \ell$ flow that traverses edge $(i \to j)$ is

$$s_{i,j}^{k,\ell} = \frac{1}{\widetilde{\tau}_{k,\ell,E}/\widetilde{\kappa}_{k,k}} \sum_{r:(i\to j)\in r} w(r).$$

Using Allen and Arkolakis (2022), the sum over all paths from k to ℓ that use edge $(i \to j)$ factorizes as

$$\widetilde{\kappa}_{k,k} \sum_{r:(i\to j)\in\mathcal{R}(k,\ell)} w(r) = \widetilde{\kappa}_{k,k} \frac{\widetilde{\tau}_{k,i,E}}{\widetilde{\kappa}_{k,k}} \widetilde{\kappa}_{i,j} \frac{\widetilde{\tau}_{j,\ell,E}}{\widetilde{\kappa}_{j,j}}.$$

The left hand side is the sum of the weights of all paths r leading generation from k to ℓ going through edge $(i \to j)$. Notice that $\widetilde{\tau}_{k,i,E}$ already include $\widetilde{\kappa}_{k,k}$ and so it must be divided by $\widetilde{\kappa}_{k,k}$. Similarly, $\widetilde{\tau}_{j,\ell,E}$ includes $\widetilde{\kappa}_{j,j}$ and so it must be divided by $\widetilde{\kappa}_{j,j}$ as well.

Hence

$$\begin{aligned} s_{i,j}^{k,\ell} &= \frac{\widetilde{\tau}_{k,i,E}\,\widetilde{\kappa}_{i,j}\,\widetilde{\tau}_{j,\ell,E}}{\widetilde{\tau}_{k,\ell,E}\widetilde{\kappa}_{j,j}} \\ &= \left(\frac{\kappa_{j,j}\tau_{k,\ell,E}}{\tau_{k,i,E}\kappa_{i,j}\tau_{j,\ell,E}}\right)^{\theta} \end{aligned}$$

$q_{k,\ell,E}$ is the quantity shipped from k that actually arrives in ℓ (after transimission costs). The quantity actually shipped from k is given by $\tau_{k,\ell,E} q_{k,\ell,E}$ (before transmission costs). The quantity flowing on edge $(i \to j)$ that is associated with those shipments is therefore:

$$s_{i,j}^{k,\ell}\, \tau_{k,\ell,E} q_{k,\ell,E}.$$

Total electricity flowing through edge $(i \to j)$ is given by summing the expression above

across all origins k and destinations $\ell \in \mathcal{L}$.

$$
\begin{aligned}
f_{i,j,E} &= \sum_{k\in\mathcal{L}}\sum_{\ell\in\mathcal{L}} s_{i,j}^{k,\ell}\,\tau_{k,\ell,E} q_{k,\ell,E} \\
&= \sum_{k\in\mathcal{L}}\sum_{\ell\in\mathcal{L}} \left(\frac{\kappa_{j,j}\tau_{k,\ell,E}}{\tau_{k,i,E}\kappa_{i,j}\tau_{j,\ell,E}}\right)^{\theta} \frac{\tau_{k,\ell,E}^{-\theta} p_{k,E}^{-(\theta+1)}}{P_{\ell,E}^{-\theta}} X_{\ell,E} \\
&= \sum_{k\in\mathcal{L}}\sum_{\ell\in\mathcal{L}} \left(\frac{\kappa_{j,j}\tau_{k,\ell,E}}{\tau_{k,i,E}\kappa_{i,j}\tau_{j,\ell,E}}\right)^{\theta} \frac{\tau_{k,\ell,E}^{-\theta} p_{k,E}^{-(\theta+1)}}{\sum_{m\in\mathcal{L}} \left(\tau_{m,\ell,E}\, p_{m,E}\right)^{-\theta}} X_{\ell,E}
\end{aligned}
$$

C Calibration Procedure

C.1 Transmission Costs

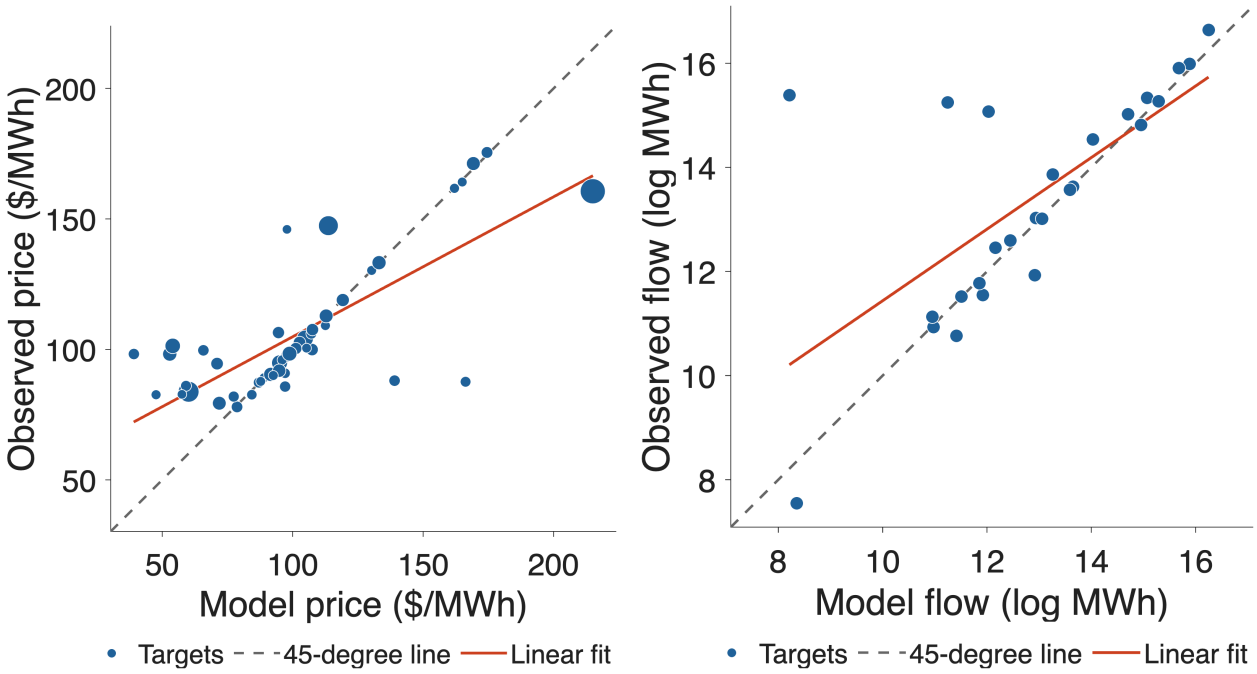
As explained in Section 4.2, the estimates $(\widehat{\gamma}, \widehat{\theta})$ solve

$$
\begin{aligned}
(\widehat{\gamma}, \widehat{\theta}) = \arg\min_{\gamma,\theta} \quad & \sum_{\ell\in\mathcal{L}} \omega_{\ell} \left(\frac{P_{\ell,E}^{Model} - P_{\ell,E}^{Data}}{P_{\ell,E}^{Model} + P_{\ell,E}^{Data}}\right)^2 \\
& + \frac{1}{2}\sum_{g\in\mathcal{G}}\sum_{g'\in\mathcal{G}} \left(\frac{F_{g,g',E}^{Model} - F_{g,g',E}^{Data}}{F_{g,g',E}^{Model} + F_{g,g',E}^{Data}}\right)^2 \\
& + \left(\frac{\sum_{g\in\mathcal{G}}\sum_{g'\in\mathcal{G}} F_{g,g',E}^{Model} - \sum_{g\in\mathcal{G}}\sum_{g'\in\mathcal{G}} F_{g,g',E}^{Data}}{\sum_{g\in\mathcal{G}}\sum_{g'\in\mathcal{G}} F_{g,g',E}^{Model} + \sum_{g\in\mathcal{G}}\sum_{g'\in\mathcal{G}} F_{g,g',E}^{Data}}\right)^2 .
\end{aligned}
$$

The loss therefore combines value-added-weighted price discrepancies, group-flow discrepancies, and the discrepancy in their sum. The groups $\mathcal{G}$ are defined in Section 4.2; the flow sums include only pairs with usable observations. The broad East–West moment overlaps the Oklahoma–New Mexico moment, so this sum is not total unique physical interchange. The loss contains 48 price discrepancies, 26 directed-flow discrepancies, and their aggregate discrepancy, for 49 parameters. We minimize the loss function with a two-stage search. The first stage consists of 250 independent genetic-algorithm runs. The second stage independently refines the ten lowest-loss genetic-algorithm candidates using bounded Nelder–Mead searches. We retain the refined candidate with the lowest loss. Figure C.1 reports the fit to prices and directional flows.

Once the vector γ is estimated, we construct the transmission costs as follows:

$$\kappa_{\ell,k} = \begin{cases} \exp(\gamma_\ell), & \text{if } \ell = k, \\ \exp(\gamma_\ell + \gamma_k), & \text{if } k \in \mathcal{N}_\ell, \\ \infty, & \text{if } k \notin \mathcal{N}_\ell \cup \{\ell\} \end{cases} \tag{90}$$



(a) End-user electricity prices

(b) Directional electricity flows

Figure C.1: Transmission Calibration: Model Fit

Notes: Model predictions use the saved transmission estimates and observed producer prices and electricity expenditures. Panel (a) compares 48 state prices in dollars per MWh; marker size increases with state value added. Panel (b) compares the 26 selected directional flow moments in natural logs of MWh.

C.2 Imputation of the Full Worker Flows Matrix

We employ the following data:

- $f^{ACS}_{o,\ell n}$: 1-year flows from region o to region ℓ sector n from the ACS (simple averages between 2015 and 2019).
- $f^{CPS}_{p,n}$: 1-year flows from industry p to industry n from the CPS (simple averages between 2015 and 2019).

Let $t = -1$ denote the initial period and $t = 0$ denote the final period.

The ACS distribution of employment at $t = 0$ is obtained as

$$L^{ACS,0}_{\ell n} = \sum_{o} f^{ACS}_{o,\ell n}.$$

We take it as the "true" observed distribution of employment across regions and industries in 2017.

We wish to obtain a full *imputed* matrix of 1-year flows $\widehat{f}_{op,\ell n}$ with the following properties:

- Imputed flows imply the "true" observed distribution of employment at $t = 0$: $\sum_o \sum_p \widehat{f}_{op,\ell n} = L^{ACS,0}_{\ell n}$
- Imputed flows from region o to region ℓ and industry n, $\sum_p \widehat{f}_{op,\ell n}$, are "close" to $f^{ACS}_{o,\ell n}$ (which is data)
- Imputed flows from industry p to industry n, $\sum_o \sum_\ell \widehat{f}_{op,\ell n}$, are "close" to $f^{CPS}_{p,n}$ (which is data)
- Imputed flows imply steady state: the implied distribution of employment at $t = -1$ replicates the observed distribution of employment at $t = 0$. That is, $\sum_\ell \sum_n \widehat{f}_{op,\ell n} = \widehat{L}^{ACS,-1}_{op}$ where $\widehat{L}^{ACS,-1}_{op} = L^{ACS,0}_{op}$

Note that there is a tension between $f^{ACS}_{o,\ell n}$ and $f^{CPS}_{p,n}$. Given that these flows come from different datasets, they will tend to generate different distributions of employment at the sector level at $t = 0$. Consider the heuristic method below, which addresses this tension.

Step 1: Let $\widehat{f}^i_{p,n} = \alpha_n \beta_p f^{CPS}_{p,n}$ where α_n and β_p are determined such that $\widehat{f}^i_{p,n}$ is consistent with industry-specific employment levels $L^{ACS,-1}_p$ and $L^{ACS,0}_n$. That is:

$\beta_p \sum_n \alpha_n f^{CPS}_{p,n} = L^{ACS,-1}_p$

$\alpha_n \sum_p \beta_p f^{CPS}_{p,n} = L^{ACS,0}_n$

Note: This step ensures that flows $\widehat{f}^i_{p,n}$ are consistent with the distributions of employment we impose at $t = -1$ and $t = 0$.

Step 2: Let $\widehat{f}_{o,\ell n} = \xi_o \zeta_{\ell n} f^{ACS}_{o,\ell n}$ where ξ_o and $\zeta_{\ell n}$ are determined such that $\widehat{f}_{o,\ell n}$ is consistent with both $L^{ACS,-1}_o$ and $L^{ACS,0}_{\ell n}$. That is:

$\sum_\ell \sum_n \widehat{f}_{o,\ell n} = \xi_o \sum_\ell \sum_n \zeta_{\ell n} f^{ACS}_{o,\ell n} = L^{-1}_o$

$\sum_o \widehat{f}_{o,\ell n} = \zeta_{\ell n} \sum_o \xi_o f^{ACS}_{o,\ell n} = L^0_{\ell n}$

Note: Similarly, this step ensures that flows $\widehat{f}_{o,\ell n}$ are consistent with the distributions of employment we impose at $t = -1$ and $t = 0$.

Step 3: Solve for flows $\widehat{f}_{op,\ell n} = w_{o,\ell n} x_{op} y_{pn}$ satisfying all the following conditions:

1. $\sum_\ell \sum_n \widehat{f}_{op,\ell n} = x_{op} \sum_\ell \sum_n w_{o,\ell n} y_{pn} = L^{ACS,-1}_{o,p}$
2. $\sum_o \sum_\ell \widehat{f}_{op,\ell n} = y_{pn} \sum_o \sum_\ell w_{o,\ell n} x_{op} = \widehat{f}^i_{p,n}$
3. $\sum_p \widehat{f}_{op,\ell n} = w_{o,\ell n} \sum_p x_{op} y_{pn} = \widehat{f}_{o,\ell n}$

Once we impute the full matrix of flows $\widehat{f}_{op,\ell n}$, we compute transition rates

$$m_{op,\ell n} = \frac{\widehat{f}_{op,\ell n}}{\sum_{\ell,n} \widehat{f}_{op,\ell n}}$$

C.3 Parameter Extraction Procedure

This algorithm jointly extracts the following parameters: $\{\beta^E_j\}_{j \in J \cup F}$, $\{\beta^L_j\}_{j \in J \cup F}$, $\{\beta^M_j\}_{j \in J \cup F}$, $\{\gamma_{j,n}\}_{j,n \in J \cup F}$, $\{\mu_j\}_{j \in J \cup F \cup E}$, $\{z_{\ell,ER}\}_{\ell \in \mathcal{L}}$, $\{z_{\ell,EF}\}_{\ell \in \mathcal{L}}$, $\{z_{\ell,j}\}_{\ell \in \mathcal{L}, j \in J \cup F}$, $\{K_{\ell,j}\}_{\ell \in \mathcal{L}, j \in J \cup F \cup ER \cup EF}$, $\{\tau_{i,j,E}\}_{i,j \in \mathcal{L}}$,$\{C_{\ell,j,k,n}\}_{\ell,k \in \mathcal{L}, j,n \in J \cup F \cup u}$ and $\{\eta_{\ell,j}\}_{\ell \in \mathcal{L}, j \in J \cup F \cup u}$ conditional on the following data.

- $L^{ACS}_{\ell,j}$ – ACS labor allocations (state and sector specific)

- $VA_{\ell,j}^{BEA}$ – Value added from the BEA (state and sector specific), which **subtracts** expenditures on electricity and materials.
- GO_j^{BEA} – Gross output from the BEA (sector specific), which **includes** value added, expenditures on electricity, and expenditures on intermediate inputs.
- $X_j^{k,BEA}$ – Sector j's expenditures on inputs from sector k from the BEA
- $X_j^{E,BEA}$ – Electricity expenditures from the BEA (sector specific) from the production side
- $X_{HH}^{E,BEA}$ – Electricity expenditures from the BEA from households
- $WageBill_j^{BEA}$ – The wage bill at the industry level can be constructed using BEA data directly or using "inflated" ACS data.
- $y_{\ell,ER}$, $y_{\ell,EF}$ – Electricity production (based on renewables and fossil fuels) by location from the EIA
- $K_{\ell,ER}$, $K_{\ell,EF}$ – Renewable electricity capital and fossil-fuel-based capital by location from the EIA
- $m_{\ell,j,k,n}$ – imputed yearly transition rates from the ACS and CPS
- $\tau_{\ell,k,j}$ – Head and Ries indices (state to state and sector specific)
- $\kappa_{\ell,k}$ – electricity transmission costs
- $\mathcal{N}_\ell$ – electricity network
- θ – the elasticity of substitution across electricity origins
- δ_j – sector-specific depreciation rates $j \in J \cup F \cup ER \cup EF$
- ρ_j – Armington elasticity (sector specific)
- χ_j – output taxes are all set to 0
- α_F – capital share in fossil-fuel electricity production
- α_R – capital returns to scale in renewable electricity
- β – intertemporal discount factor

- ν – the migration elasticity

Consider Cobb-Douglas production functions:

$$y_{\ell,j} = \frac{z_{\ell,j}}{\left(\beta_j^E\right)^{\beta_j^E}\left(1-\beta_j^E\right)^{\left(1-\beta_j^E\right)}} E_{\ell,j}^{\beta_j^E}\left(L_{\ell,j}^{\beta_j^L} M_{\ell,j}^{\beta_j^M} K_{\ell,j}^{\beta_j^K}\right)^{1-\beta_j^E}.$$

Step 1: Given θ, transmission costs $\{\kappa_{\ell,k}\}$ and the network $\{\mathcal{N}_\ell\}$ obtain $\{\tau_{m,\ell,E}\}$.

Construct matrix $\widetilde{\kappa}$ with elements

$$\widetilde{\kappa}_{k,\ell} \equiv \begin{cases} \kappa_{k,\ell}^{-\theta}, & \text{if } k \in \mathcal{N}_\ell \cup \{\ell\}, \\ 0, & \text{if } k \notin \mathcal{N}_\ell \cup \{\ell\}. \end{cases}$$

Compute

$$\widehat{\kappa} = \widetilde{\kappa} - Diag\left(\widetilde{\kappa}\right)$$

Obtain matrix $\widetilde{\tau}_E$ whose transpose is given by:

$$\widetilde{\tau}_E' = \left(I - \widehat{\kappa}\right)^{-1} Diag\left(\widetilde{\kappa}\right).$$

Compute

$$\tau_{m,\ell,E} = \widetilde{\tau}_{m,\ell,E}^{-1/\theta}$$

Step 2: Obtain β_j^L for all $j \in J \cup F$:

$$\beta_j^L = \frac{WageBill_j^{BEA}}{GO_j^{BEA} - X_j^{E,BEA}}.$$

Step 3: Obtain β_j^M for all $j \in J \cup F$:

$$\beta_j^M = \frac{GO_j^{BEA} - X_j^{E,BEA} - \sum_{\ell \in \mathcal{L}} VA_{\ell,j}^{BEA}}{GO_j^{BEA} - X_j^{E,BEA}}.$$

and compute:

$$\beta_j^K = 1 - \beta_j^L - \beta_j^M \text{ for all } j \in J \cup F.$$

Step 4: Compute β_j^E using:

$$\beta_j^E = \frac{X_j^{E,BEA}}{GO_j^{BEA}}.$$

Step 5: Obtain $\gamma_{j,n}$ for all $j, n \in J \cup F$:

$$\gamma_{j,n} = \frac{X_j^{n,BEA}}{\sum\limits_{p \in J \cup F} X_j^{p,BEA}}.$$

Step 6: Compute wages $w_{\ell,j}$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$.

$$w_{\ell,j} = \frac{\beta_j^L VA_{\ell,j}^{BEA}}{\left(1 - \beta_j^M\right) L_{\ell,j}^{ACS}}.$$

Step 7: Compute expenditures on electricity $X_{\ell,j}^E$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$X_{\ell,j}^E = \frac{\beta_j^E}{\left(1 - \beta_j^E\right)\left(1 - \beta_j^M\right)} VA_{\ell,j}^{BEA}$$

Step 8: Compute capital payments for $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$r_{\ell,j} K_{\ell,j} = \frac{\beta_j^K}{1 - \beta_j^M} VA_{\ell,j}^{BEA}.$$

Step 9: Obtain expenditures on material for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$X_{\ell,j}^M \equiv P_{\ell,j}^M M_{\ell,j} = \frac{\beta_j^M}{1 - \beta_j^M} VA_{\ell,j}^{BEA}.$$

Step 10: Guess prices $\{p_{\ell,E}\}_{\ell \in \mathcal{L}}$ and $\{p_{\ell,j}\}_{\ell \in \mathcal{L}, j \in J \cup F}$

Step 11: Compute

$$r_{\ell,ER}K_{\ell,ER} = \alpha_R p_{\ell,E} y_{\ell,ER}$$
$$r_{\ell,EF}K_{\ell,EF} = \alpha_F p_{\ell,E} y_{\ell,EF}$$
$$\Pi_{\ell,ER} = (1-\alpha_R)\, p_{\ell,E} y_{\ell,ER}$$

Step 12: Compute income across all locations $\ell \in \mathcal{L}$:

$$Inc_\ell = \sum_{j \in J \cup F} w_{\ell,j} L_{\ell,j}^{ACS} + \sum_{j \in J \cup F \cup ER \cup EF} r_{\ell,j} K_{\ell,j} + \Pi_{\ell,ER}.$$

Step 13: Obtain expenditure shares

$$\mu_j = \frac{GO_j^{BEA} - \sum\limits_{n \in J \cup F} \gamma_{n,j} \beta_n^M \left(GO_n^{BEA} - X_n^{E,BEA} \right)}{\sum_{\ell \in \mathcal{L}} Inc_\ell}, \; j \in J$$

$$\mu_F = \frac{GO_F^{BEA} - \sum\limits_{n \in J \cup F} \gamma_{n,F} \beta_n^M \left(GO_n^{BEA} - X_n^{E,BEA} \right) - \sum_{\ell \in \mathcal{L}} (1-\alpha_F)\, p_{\ell,E} y_{\ell,EF}}{\sum_{\ell \in \mathcal{L}} Inc_\ell}$$

$$\mu_E = \frac{X_{HH}^{E,BEA}}{\sum_{\ell \in \mathcal{L}} Inc_\ell}$$

Step 14: Given prices $\{p_{\ell,j}\}$ obtain price indices for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$P_{\ell,j} \equiv \left(\sum_{k=1}^{L} \left(p_{k,j} \tau_{k,\ell,j} \right)^{1-\rho_j} \right)^{\frac{1}{1-\rho_j}}.$$

Given prices $\{p_{\ell,E}\}$ obtain $P_{\ell,E}$ prices for all $\ell \in \mathcal{L}$:

$$P_{\ell,E} = \left(\sum_{m \in \mathcal{L}} \left(p_{m,E} \tau_{m,\ell,E} \right)^{-\theta} \right)^{-\frac{1}{\theta}}.$$

Step 15: Compute price updates using:

$$p_{\ell,j}^{new} = \left(\frac{\frac{VA_{\ell,j}^{BEA}}{\left(1-\beta_j^E\right)\left(1-\beta_j^M\right)}}{\sum_{k\in\mathcal{L}} \left(\mu_j Inc_k + \sum_{n\in J\cup F} \gamma_{n,j} X_{k,n}^M\right) \frac{\left(\tau_{\ell,k,j}\right)^{1-\rho_j}}{P_{k,j}^{1-\rho_j}}} \right)^{\frac{1}{1-\rho_j}} \quad \text{for } j \in J,$$

$$p_{\ell,F}^{new} = \left(\frac{\frac{VA_{\ell,F}^{BEA}}{\left(1-\beta_F^E\right)\left(1-\beta_F^M\right)}}{\sum_{k\in\mathcal{L}} \left(\mu_F Inc_k + \sum_{n\in J\cup F} \gamma_{n,F} X_{k,n}^M + (1-\alpha_F)\, p_{k,E} y_{k,EF}\right) \frac{\left(\tau_{\ell,k,F}\right)^{1-\rho_F}}{P_{k,F}^{1-\rho_F}}} \right)^{\frac{1}{1-\rho_F}} \quad \text{for } j = F.$$

$$p_{\ell,E}^{new} = \left(\frac{y_{\ell,E}}{\sum_{k\in\mathcal{L}} \left(\mu_E Inc_k + \sum_{n\in J\cup F} X_{k,n}^E\right) \frac{\tau_{\ell,k,E}^{-\theta}}{P_{k,E}^{-\theta}}} \right)^{-\frac{1}{(\theta+1)}}$$

Go back to Step 10 until the convergence of $\{p_{\ell,j}\}$ and $\{p_{\ell,E}\}$.

Note: We need normalizations. Impose $p_{Texas,j} = 1$ for all $j \in J \cup F$.

For the electricity sector, we need to impose

$$\sum_{\ell\in\mathcal{L}} p_{\ell,E} \left(y_{\ell,EF} + y_{\ell,ER}\right) = \sum_{j\in J\cup F} X_j^{E,BEA} + X_{HH}^{E,BEA}$$

to ensure that $\sum_{j\in J\cup F\cup E} \mu_j = 1$. That is, the level of electricity prices must be consistent with measured expenditures on electricity in the data. More details after the end of the algorithm.

Step 16: Obtain material prices for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$P_{\ell,j}^M = \prod_{n\in J\cup F} \left(\frac{P_{\ell,n}}{\gamma_{j,n}}\right)^{\gamma_{j,n}}.$$

Step 17: Obtain P_ℓ for all $\ell \in \mathcal{L}$:

$$P_\ell = \prod_{j\in J\cup F\cup E} \left(\frac{P_{\ell,j}}{\mu_j}\right)^{\mu_j}.$$

Step 18: Compute capital rental prices for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$r_{\ell,j} = \left(\frac{1-\beta(1-\delta_j)}{\beta}\right) P_\ell.$$

[**Comment**: we set $\xi_{\ell,j} = 1$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$. This is because we do not observe the capital stocks, so there is a degree of freedom here that we do not have when we compute the capital rental prices in renewable and fossil-fuel based electricity generation.]

Step 19: Compute for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$c_{\ell,j}^{LMK} = \left(\frac{w_{\ell,j}}{\beta_j^L}\right)^{\beta_j^L} \left(\frac{P_{\ell,j}^M}{\beta_j^M}\right)^{\beta_j^M} \left(\frac{r_{\ell,j}}{\beta_j^K}\right)^{\beta_j^K},$$

$$\overline{c}_{\ell,j} = P_{\ell,E}^{\beta_j^E} \left(c_{\ell,j}^{LMK}\right)^{1-\beta_j^E}.$$

Step 20: Back out productivities $z_{\ell,j}$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$ using:

$$z_{\ell,j} = \frac{\overline{c}_{\ell,j}}{p_{\ell,j}}.$$

Step 21: Obtain $z_{\ell,ER}$ and $z_{\ell,EF}$ that rationalize data on $y_{\ell,ER}$ and $y_{\ell,EF}$:

$$z_{\ell,ER} = \frac{y_{\ell,ER}}{K_{\ell,ER}^{\alpha_R}}$$

$$z_{\ell,EF} = \frac{\left(y_{\ell,EF}\right)^{\alpha_F}}{K_{\ell,EF}^{\alpha_F} \left((1-\alpha_F)\frac{p_{\ell,E}}{P_{\ell,F}}\right)^{1-\alpha_F}}$$

Step 22: Obtain capital stocks for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$K_{\ell,j} = \frac{\beta_j^K}{\left(1-\beta_j^M\right) r_{\ell,j}} VA_{\ell,j}^{BEA}.$$

Step 23: Consider the equations driving payments to capital in the electricity generation sector:

$$\alpha_R p_{\ell,E} y_{\ell,ER} = r_{\ell,ER} K_{\ell,ER},$$

$$\alpha_F p_{\ell,E} y_{\ell,EF} = r_{\ell,EF} K_{\ell,EF}.$$

In these two equations, the left hand side is observed in the data as are $K_{\ell,ER}$ and $K_{\ell,EF}$. We then back out:

$$r_{\ell,ER} = \frac{\alpha_R p_{\ell,E} y_{\ell,ER}}{K_{\ell,ER}},$$

$$r_{\ell,EF} = \frac{\alpha_F p_{\ell,E} y_{\ell,EF}}{K_{\ell,EF}}.$$

However, in steady state for $j \in \{ER, EF\}$, the Euler equation dictates:

$$\frac{r_{\ell,j}}{P_\ell} = \left(\frac{1}{\beta} - (1-\delta_j)\right)\frac{1}{\xi_{\ell,j}}.$$

Given $r_{\ell,ER}$, $r_{\ell,EF}$, δ_{ER}, δ_{EF}, β and P_ℓ, obtain $\xi_{\ell,ER}$ and $\xi_{\ell,EF}$ using:

$$\xi_{\ell,j} = \left(\frac{1}{\beta} - (1-\delta_j)\right)\frac{1}{\frac{r_{\ell,j}}{P_\ell}}.$$

In other words, we need to resort to the conversion parameters $\xi_{\ell,ER}$ and $\xi_{\ell,EF}$ in order to perfectly match the steady state capital rental rates implied by our observed data.

Step 24: Impose $C_{\ell,j,\ell,j} = 0$ (no cost of not moving) for all $\ell \in \mathcal{L}$ and $j \in J \cup F$, $C_{\ell,j,\ell,u} = 0$ (no cost of moving locally to unemployment) and $\eta_{\ell,u} = 0$ (unemployment gives zero utility) for all regions ℓ:

we obtain for all ℓ, j:

If $m_{\ell,j,\ell,j} > 0$ and $L_{\ell,j}^{ACS} > 0$:

$$\eta_{\ell,j} = -\frac{\nu}{\beta}\log\left(\frac{m_{\ell,j,\ell,u}}{m_{\ell,j,\ell,j}}\right) - \nu\log\left(\frac{m_{\ell,u,\ell,u}}{m_{\ell,j,\ell,u}}\right) - \left(\frac{w_{\ell,j}+b}{P_\ell}\right)$$

If $m_{\ell,j,\ell,j} = 0$ or $L_{\ell,j}^{ACS} = 0$:

$$\eta_{\ell,j} = -\infty$$

We can then recover mobility costs using:

If $m_{\ell,j,\ell,j} > 0$, $L_{\ell,j}^{ACS} > 0$ and $m_{\ell,j,k,n} > 0$:

$$\begin{aligned} C_{\ell,j,k,n} = &-\frac{\nu}{1-\beta}\log\left(\frac{m_{\ell,j,k,n}}{m_{\ell,j,\ell,j}}\right) - \frac{\nu\beta}{(1-\beta)}\log\left(\frac{m_{k,n,k,n}}{m_{\ell,j,k,n}}\right) \\ &+ \frac{\beta}{1-\beta}\left(\frac{w_{k,n}+b}{P_k} - \frac{w_{\ell,j}+b}{P_\ell}\right) + \frac{\beta}{1-\beta}\left(\eta_{k,n} - \eta_{\ell,j}\right) \end{aligned}$$

Else

$$C_{\ell,j,k,n} = +\infty$$

Step 25: Normalize all nominal variables to guarantee that $\sum_{\ell \in \mathcal{L}} Inc_\ell = 1$. This step is not necessary, but will be helpful to get good starting guesses of nominal variables in the counterfactual steady state algorithm.

Normalization of the electricity prices

Note that local disposable income is given by:

$$Inc_\ell = \sum_{j \in J \cup F} w_{\ell,j} L_{\ell,j}^{ACS} + \sum_{j \in J \cup F \cup ER \cup EF} r_{\ell,j} K_{\ell,j} + \Pi_{\ell,ER}$$

And note that the expenditure shares are given by:

$$\mu_j = \frac{GO_j^{BEA} - \sum_{n \in J \cup F} \gamma_{n,j} \beta_n^M \left(GO_n^{BEA} - X_n^{E,BEA} \right)}{\sum_{\ell \in \mathcal{L}} Inc_\ell}, \; j \in J$$

$$\mu_F = \frac{GO_F^{BEA} - \sum_{n \in J \cup F} \gamma_{n,F} \beta_n^M \left(GO_n^{BEA} - X_n^{E,BEA} \right) - \sum_{\ell \in \mathcal{L}} (1 - \alpha_F) \, p_{\ell,E} y_{\ell,EF}}{\sum_{\ell \in \mathcal{L}} Inc_\ell}$$

$$\mu_E = \frac{X_{HH}^{E,BEA}}{\sum_{\ell \in \mathcal{L}} Inc_\ell}$$

To ensure that $\sum_{j \in J \cup F \cup E} \mu_j = 1$ we need:

$$\begin{aligned} \sum_{\ell \in \mathcal{L}} Inc_\ell = & \sum_{j \in J \cup F} GO_j^{BEA} - \sum_{j \in J \cup F} \sum_{n \in J \cup F} \gamma_{n,j} \beta_n^M \left(GO_n^{BEA} - X_n^{E,BEA} \right) \\ & - \sum_{\ell \in \mathcal{L}} (1 - \alpha_F) \, p_{\ell,E} y_{\ell,EF} + X_{HH}^{E,BEA} \end{aligned}$$

Let us first inspect the left hand side:

$$\begin{aligned}
\sum_{\ell\in\mathcal{L}} Inc_\ell &= \sum_{\ell\in\mathcal{L}}\sum_{j\in J\cup F} w_{\ell,j}L^{ACS}_{\ell,j} + \sum_{\ell\in\mathcal{L}}\sum_{j\in J\cup F} r_{\ell,j}K_{\ell,j} \\
&\quad + \sum_{\ell\in\mathcal{L}} \left(r_{\ell,EF}K_{\ell,EF} + r_{\ell,ER}K_{\ell,ER}\right) + \sum_{\ell\in\mathcal{L}} \Pi_{\ell,ER} \\
&= \sum_{\ell\in\mathcal{L}}\sum_{j\in J\cup F} \frac{\beta^L_j VA^{BEA}_{\ell,j}}{\left(1-\beta^M_j\right)} + \sum_{\ell\in\mathcal{L}}\sum_{j\in J\cup F} \frac{\beta^K_j VA^{BEA}_{\ell,j}}{1-\beta^M_j} \\
&\quad + \sum_{\ell\in\mathcal{L}} \left(\alpha_F p_{\ell,E}y_{\ell,EF} + p_{\ell,E}y_{\ell,ER}\right) \\
&= \sum_{j\in J\cup F} VA^{BEA}_j + \sum_{\ell\in\mathcal{L}} p_{\ell,E}\left(y_{\ell,EF} + y_{\ell,ER}\right) - \left(1-\alpha_F\right)\sum_{\ell\in\mathcal{L}} p_{\ell,E}y_{\ell,EF} \\
&= \sum_{j\in J\cup F} \left(1-\beta^E_j\right)\left(1-\beta^M_j\right) GO^{BEA}_j + \sum_{\ell\in\mathcal{L}} p_{\ell,E}\left(y_{\ell,EF} + y_{\ell,ER}\right) - \left(1-\alpha_F\right)\sum_{\ell\in\mathcal{L}} p_{\ell,E}y_{\ell,EF}
\end{aligned}$$

The right hand side is given by:

$$\begin{aligned}
RHS &= \sum_{j\in J\cup F} GO^{BEA}_j - \sum_{j\in J\cup F} \beta^M_j \left(GO^{BEA}_j - X^{E,BEA}_j\right) \\
&\quad - \left(1-\alpha_F\right)\sum_{\ell\in\mathcal{L}} p_{\ell,E}y_{\ell,EF} + X^{E,BEA}_{HH} \\
&= \sum_{j\in J\cup F} \left(1-\beta^M_j\right) GO^{BEA}_j + \sum_{j\in J\cup F} \beta^M_j X^{E,BEA}_j \\
&\quad - \left(1-\alpha_F\right)\sum_{\ell\in\mathcal{L}} p_{\ell,E}y_{\ell,EF} + X^{E,BEA}_{HH} \\
&= \sum_{j\in J\cup F} \left(1-\beta^M_j+\beta^M_j\beta^E_j\right) GO^{BEA}_j \\
&\quad - \left(1-\alpha_F\right)\sum_{\ell\in\mathcal{L}} p_{\ell,E}y_{\ell,EF} + X^{E,BEA}_{HH}
\end{aligned}$$

$$\begin{aligned}
&\sum_{\ell\in\mathcal{L}} Inc_\ell = RHS \\
&\iff \sum_{\ell\in\mathcal{L}} p_{\ell,E}\left(y_{\ell,EF} + y_{\ell,ER}\right) = \sum_{j\in J\cup F} \beta^E_j GO^{BEA}_j + X^{E,BEA}_{HH} \\
&\iff \sum_{\ell\in\mathcal{L}} p_{\ell,E}\left(y_{\ell,EF} + y_{\ell,ER}\right) = \sum_{j\in J\cup F} X^{E,BEA}_j + X^{E,BEA}_{HH}
\end{aligned}$$

D Algorithm for Steady State Counterfactuals

Consider Cobb-Douglas production functions.

$$y_{\ell,j} = \frac{z_{\ell,j}}{\left(\beta_j^E\right)^{\beta_j^E}\left(1-\beta_j^E\right)^{\left(1-\beta_j^E\right)}} E_{\ell,j}^{\beta_j^E}\left(L_{\ell,j}^{\beta_j^L} M_{\ell,j}^{\beta_j^M} K_{\ell,j}^{1-\beta_j^L-\beta_j^M}\right)^{1-\beta_j^E}$$

US GDP is the numeraire: $\sum_{\ell\in\mathcal{L}} Inc_\ell = 1$.

Step 1: Guess $\{Inc_\ell\}_{\ell\in\mathcal{L}}$.

Step 2: Guess the price of the labor-materials-capital bundle, $\{c_{\ell,j}^{LMK}\}$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$.

Step 3: Guess fuel-based capital $\{K_{\ell,EF}\}$ for all $\ell \in \mathcal{L}$.

Step 4: Guess generator-level electricity prices $\{p_{\ell,E}\}$ for all $\ell \in \mathcal{L}$.

Step 5: Compute electricity prices that households and variety producers face for all $\ell \in \mathcal{L}$:

$$P_{\ell,E} = \left(\sum_{k\in\mathcal{L}} \left(p_{k,E}\tau_{k,\ell,E}\right)^{-\theta}\right)^{-\frac{1}{\theta}}.$$

Step 6: Compute prices for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$p_{\ell,j} = \frac{P_{\ell,E}^{\beta_j^E}\left(c_{\ell,j}^{LMK}\right)^{1-\beta_j^E}}{(1-\chi_j)z_{\ell,j}}.$$

Step 7: Compute price indices for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$P_{\ell,j} \equiv \left(\sum_{k\in\mathcal{L}} \left(p_{k,j}\tau_{k,\ell,j}\right)^{1-\rho_j}\right)^{\frac{1}{1-\rho_j}}.$$

Step 8: Compute local price indices for all $\ell \in \mathcal{L}$:

$$P_\ell = \prod_{j\in J\cup F\cup E}\left(\frac{P_{\ell,j}}{\mu_j}\right)^{\mu_j}.$$

Step 9: Compute $\{r_{\ell,ER}\}$ and $\{K_{\ell,ER}\}$ for all $\ell \in \mathcal{L}$:

$$r_{\ell,ER} = \left(\frac{1}{\beta} - (1 - \delta_{ER})\right) \frac{P_\ell}{\xi_{\ell,ER}},$$

$$K_{\ell,ER} = \left(\frac{r_{\ell,ER}}{\alpha_R \left(1 - \chi_{ER}\right) p_{\ell,E} z_{\ell,ER}}\right)^{\frac{1}{\alpha_R - 1}}.$$

Step 10: Obtain the supply of electricity $y_{\ell,E}$ for all $\ell \in \mathcal{L}$:

$$y_{\ell,ER} = z_{\ell,ER} K_{\ell,ER}^{\alpha_R}$$

$$y_{\ell,EF} = \left(\frac{\left(1 - \alpha_F\right)\left(1 - \chi_{EF}\right) p_{\ell,E}}{P_{\ell,F}}\right)^{\frac{1-\alpha_F}{\alpha_F}} z_{\ell,EF}^{\frac{1}{\alpha_F}} K_{\ell,EF}$$

$$y_{\ell,E} = y_{\ell,ER} + y_{\ell,EF}$$

Step 11: Compute the price of materials for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$P_{\ell,j}^M = \prod_{n \in J \cup F} \left(\frac{P_{\ell,n}}{\gamma_{j,n}}\right)^{\gamma_{j,n}}.$$

Step 12: Guess material usage $\{M_{\ell,j}\}$ for all $\ell \in \mathcal{L}$ and $j \in J \cup F$.

Step 13: Compute quantities for all $j \in J$ and all location pairs k and $\ell \in \mathcal{L}$:

$$q_{k,\ell,j} = \left(\mu_j Inc_\ell + \sum_{n \in J \cup F} \gamma_{n,j} P_{\ell,n}^M M_{\ell,n}\right) \frac{\left(p_{k,j} \tau_{k,\ell,j}\right)^{-\rho_j}}{P_{\ell,j}^{1-\rho_j}}$$

For fuels, use:

$$q_{k,\ell,F} = \left(\mu_F Inc_\ell + \sum_{n \in J \cup F} \gamma_{n,F} P_{\ell,n}^M M_{\ell,n} + \left(1 - \alpha_F\right)\left(1 - \chi_{EF}\right) p_{\ell,E} y_{\ell,EF}\right) \frac{\left(p_{k,F} \tau_{k,\ell,F}\right)^{-\rho_F}}{P_{\ell,F}^{1-\rho_F}}$$

Step 14: Obtain the level of production for all $\ell \in \mathcal{L}$ and $j \in J \cup F$ that clears their respective markets:

$$y_{\ell,j} = \sum_{k \in \mathcal{L}} \tau_{\ell,k,j} q_{\ell,k,j}.$$

Step 15: Update usage of materials ($\ell \in \mathcal{L}$, $j \in J \cup F$):

$$M'_{\ell,j} = \frac{\beta_j^M \left(1-\beta_j^E\right)(1-\chi_j)\, p_{\ell,j} y_{\ell,j}}{P_{\ell,j}^M},$$

$$M_{\ell,j}^{new} = (1-\lambda_M)\, M_{\ell,j} + \lambda_M M'_{\ell,j}.$$

Go back to Step 12 until the convergence of $\{M_{\ell,j}\}$.

Step 16: Compute the demand for electricity for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$E_{\ell,j}^D = \frac{\beta_j^E (1-\chi_j)\, p_{\ell,j} y_{\ell,j}}{P_{\ell,E}}.$$

Step 17: Compute for all $k, \ell \in \mathcal{L}$:

$$q_{k,\ell,E} = \left(\mu_E Inc_\ell + P_{\ell,E} \sum_{n \in J \cup F} E_{\ell,n}^D\right) \frac{\left(p_{k,E}\tau_{k,\ell,E}\right)^{-(\theta+1)}}{P_{\ell,E}^{-\theta}}$$

Step 18: Update prices $\{p_{\ell,E}\}$ to get demand for local electricity generation and local generation supply closer to each other:

$$p_{\ell,E}^{new} = (1-\lambda_E)\, p_{\ell,E} + \lambda_E p_{\ell,E} \frac{\sum_{k \in \mathcal{L}} \tau_{\ell,k,E} q_{\ell,k,E}}{y_{\ell,E}}$$

Go back to step 4 until convergence of $\{p_{\ell,E}\}$.

Step 19: Update $\{K_{\ell,EF}\}$ for all $\ell \in \mathcal{L}$.

First compute the user cost of EF-capital:

$$uc_{\ell,EF} = \left(\frac{1}{\beta} - (1-\delta_{EF})\right) \frac{P_\ell}{\xi_{\ell,EF}}.$$

Next, compute the rental rate of EF-capital:

$$r_{\ell,EF} = \alpha_F \left(\frac{(1-\chi_{EF})\, p_{\ell,E} z_{\ell,EF}}{\left(\frac{P_{\ell,F}}{1-\alpha_F}\right)^{1-\alpha_F}}\right)^{\frac{1}{\alpha_F}}$$

Update $K_{\ell,EF}$:

$$K_{\ell,EF}^{new} = \max\left\{0, \left(1 + \frac{r_{\ell,EF} - uc_{\ell,EF}}{uc_{\ell,EF}}\lambda_K\right) K_{\ell,EF}\right\}$$

Back to Step 3 and repeat until $\max_\ell \left\{\frac{K_{\ell,EF}}{\overline{K}_{EF}+K_{\ell,EF}} \left|\log\left(\frac{r_{\ell,EF}}{uc_{\ell,EF}}\right)\right|\right\} < \varepsilon$ for some small ε and where $\overline{K}_{EF}$ is the maximum capital stock across locations given by the initial guess.

Step 20: Compute capital rental rates for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$r_{\ell,j} = \left(\frac{1}{\beta} - (1-\delta_j)\right)\frac{P_\ell}{\xi_{\ell,j}}.$$

Step 21: Recover wages for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$w_{\ell,j} = \beta_j^L \left[\frac{c_{\ell,j}^{LMK}}{\left(\frac{P_{\ell,j}^M}{\beta_j^M}\right)^{\beta_j^M}\left(\frac{r_{\ell,j}}{\beta_j^K}\right)^{\beta_j^K}}\right]^{\frac{1}{\beta_j^L}}.$$

Step 22: Compute capital stocks for all $\ell \in \mathcal{L}$ and $j \in J \cup F$ that are consistent with $y_{\ell,j}$, $E_{\ell,j}$, $M_{\ell,j}$, $w_{\ell,j}$ and $r_{\ell,j}$:

$$K_{\ell,j} = \left(\left(\frac{\beta_j^K}{\beta_j^L}\right)^{\beta_j^L\left(1-\beta_j^E\right)} \times \left(\frac{w_{\ell,j}}{r_{\ell,j}}\right)^{\beta_j^L\left(1-\beta_j^E\right)} \times \frac{\left(\beta_j^E\right)^{\beta_j^E}\left(1-\beta_j^E\right)^{\left(1-\beta_j^E\right)}}{E_{\ell,j}^{\beta_j^E} M_{\ell,j}^{\beta_j^M\left(1-\beta_j^E\right)}}\frac{y_{\ell,j}}{z_{\ell,j}}\right)^{\frac{1}{\left(1-\beta_j^M\right)\left(1-\beta_j^E\right)}}$$

Step 23: Compute labor demand for all $\ell \in \mathcal{L}$ and $j \in J \cup F$

$$L_{\ell,j}^D = K_{\ell,j} \times \frac{\beta_j^L}{\beta_j^K} \times \frac{r_{\ell,j}}{w_{\ell,j}}.$$

Step 24: Compute tax revenues for all $\ell \in \mathcal{L}$ and rebates:

$$T_\ell = \sum_{j \in J \cup F} \chi_j p_{\ell,j} y_{\ell,j},$$

If we implement worker rebates:

$$b = \frac{\sum_{\ell \in \mathcal{L}} T_\ell}{\overline{L}}$$
$$\chi_{ER} = 0$$

If we subsidize renewable energy production:

$$b = 0$$
$$\chi_{ER} = -\frac{\sum_{\ell \in \mathcal{L}} T_\ell}{\sum_{\ell \in \mathcal{L}} p_{\ell,E} y_{\ell,ER}}$$

Step 25: Solve the Bellman equation for workers for all $\ell \in \mathcal{L}$ and $j \in J \cup F \cup u$:

$$\mathcal{V}_{\ell,j} = \frac{w_{\ell,j} + b}{P_\ell} + \eta_{\ell,j} + \nu \log \left(\sum_{k \in \mathcal{L}, n \in J \cup F \cup u} \exp \left(\frac{-C_{\ell j,kn} + \beta \mathcal{V}_{k,n}}{\nu} \right) \right),$$

and recover the policy functions:

$$m_{\ell,j,k,n} = \frac{\exp\left(\frac{-C_{\ell,j,k,n} + \beta \mathcal{V}_{k,n}}{\nu}\right)}{\sum_{k' \in \mathcal{L}, n' \in J \cup F \cup u} \exp\left(\frac{-C_{\ell,j,k',n'} + \beta \mathcal{V}_{k',n'}}{\nu}\right)}.$$

Step 26: Labor supply solves the system below:

$$(I - m')\, L = 0$$
$$L'e = \overline{L}$$

where e is a column vector of 1's.

Step 27: Update the price of the labor-materials-capital bundle for all $\ell \in \mathcal{L}$ and all $j \in J \cup F$:

$$\left(c_{\ell,j}^{LMK}\right)^{new} = (1 - \lambda_c)\, c_{\ell,j}^{LMK} + \lambda_c c_{\ell,j}^{LMK} \frac{L_{\ell,j}^D}{L_{\ell,j}^S}.$$

Go back to step 2 until convergence of $\left\{c_{\ell,j}^{LMK}\right\}$.

Step 28: Compute profits of renewable electricity generators for all $\ell \in \mathcal{L}$:

$$\Pi_{\ell,ER} = (1 - \chi_{ER})(1 - \alpha_R) p_{\ell,E} y_{\ell,ER}.$$

Step 29: Update income for all $\ell \in \mathcal{L}$:

$$\begin{aligned} Inc'_\ell = & \sum_{j \in J \cup F} (w_{\ell j} + b) L_{\ell,j} + b L_{\ell,u} \\ & + \sum_{j \in J \cup F \cup ER \cup EF} r_{\ell,j} K_{\ell,j} + \Pi_{\ell,ER}, \end{aligned}$$

$$Inc_\ell^{new} = \frac{(1 - \lambda_I) Inc_\ell + \lambda_I Inc'_\ell}{\sum_{k \in \mathcal{L}} (1 - \lambda_I) Inc_k + \lambda_I Inc'_k}.$$

Go back to Step 1 until convergence of $\{Inc_\ell\}$.

Step 30: Save the Lagrange Multipliers:

$$\begin{aligned} \widetilde{\mu}_{\ell,j} &= \frac{r_{\ell,j}}{P_\ell} \frac{\beta}{1 - \beta(1 - \delta_j)} \\ \widetilde{\mu}_{\ell,ER} &= \frac{r_{\ell,ER}}{P_\ell} \frac{\beta}{1 - \beta(1 - \delta_{ER})} \\ \widetilde{\mu}_{\ell,EF} &= \frac{r_{\ell,EF}}{P_\ell} \frac{\beta}{1 - \beta(1 - \delta_{EF})} \end{aligned}$$

E Algorithm for Transitional Dynamics

Pick a large value of the end period T.

Consider a path of taxes $\{\chi_{j,t}\}_{j\in J\cup F\cup\{ER\}\cup\{EF\}}$ for $t=0,...,T$

US GDP is the numeraire: $\sum_{\ell\in\mathcal{L}} Inc_{\ell,t}=1$.

Compute the initial steady state and compute the final steady state. Initial guesses at T are given by the final steady state. Final steady states will give initial guesses for t=T variables (such as capital stocks, investments, value functions).

Step 1: Guess path $\{Inc_{\ell,t}\}_{\ell\in\mathcal{L}}$ for $t=1,...,T$. $Inc_{\ell,T}$ comes from the final steady state.

Step 2: Guess path for the price of the labor-materials-capital bundle, $\{c^{LMK}_{\ell,j,t}\}$ for all $\ell\in\mathcal{L}$, $j\in J\cup F$ and $t=1,...,T$. $c^{LMK}_{\ell,j,T}$ comes from the final steady state.

Step 3: Guess paths for investments $\{Inv_{\ell,EF,t}\}_{\ell\in\mathcal{L}}$, $\{Inv_{\ell,ER,t}\}_{\ell\in\mathcal{L}}$, $\{Inv_{\ell,j,t}\}_{\ell\in\mathcal{L},j\in J\cup F}$ for $t=1,...,T$. Given timing assumptions: $K_{\ell,j,1}=K_{\ell,j,0}$. Time T values for investment come from the final steady state.

Compute paths of capital stocks across locations and sectors $\{K_{\ell,EF,t}\}_{\ell\in\mathcal{L}}$, $\{K_{\ell,ER,t}\}_{\ell\in\mathcal{L}}$, $\{K_{\ell,j,t}\}_{\ell\in\mathcal{L},j\in J\cup F}$ for $t=1,...,T$ using

$$K_{\ell,j,t+1}=(1-\delta_j)\,K_{\ell,j,t}+\xi_{\ell,j}Inv_{\ell,j,t}.$$

Step 4: Guess path for generator-level electricity prices $\{p_{\ell,E,t}\}$ for all $\ell\in\mathcal{L}$ and $t=1,...,T$.

Static Block: Embed Steps 5 to 19 in a loop in $t=1,...,T$.

Step 5: Compute electricity prices that households and variety producers face for all $\ell\in\mathcal{L}$.

$$P_{\ell,E,t}=\left(\sum_{k\in\mathcal{L}}\left(p_{k,E,t}\tau_{k,\ell,E}\right)^{-\theta}\right)^{-\frac{1}{\theta}}.$$

Step 6: Compute prices for all $\ell\in\mathcal{L}$ and $j\in J\cup F$:

$$p_{\ell,j,t}=\frac{P^{\beta^E_j}_{\ell,E,t}\left(c^{LMK}_{\ell,j,t}\right)^{1-\beta^E_j}}{(1-\chi_{j,t})z_{\ell,j}}.$$

Step 7: Compute price indices for all $\ell \in \mathcal{L}$, $j \in J \cup F$:

$$P_{\ell,j,t} \equiv \left(\sum_{k \in \mathcal{L}} \left(p_{k,j,t} \tau_{k,\ell,j} \right)^{1-\rho_j} \right)^{\frac{1}{1-\rho_j}}.$$

Step 8: Compute local price indices for all $\ell \in \mathcal{L}$:

$$P_{\ell,t} = \prod_{j \in J \cup F \cup E} \left(\frac{P_{\ell,j,t}}{\mu_j} \right)^{\mu_j}.$$

Step 9: Obtain the supply of electricity $y_{\ell,E,t}$ for all $\ell \in \mathcal{L}$:

$$y_{\ell,ER,t} = z_{\ell,ER} K_{\ell,ER,t}^{\alpha_R}$$

$$y_{\ell,EF,t} = \left(\frac{(1-\alpha_F)(1-\chi_{EF,t}) p_{\ell,E,t}}{P_{\ell,F,t}} \right)^{\frac{1-\alpha_F}{\alpha_F}} z_{\ell,EF}^{\frac{1}{\alpha_F}} K_{\ell,EF,t}$$

$$y_{\ell,E,t} = y_{\ell,ER,t} + y_{\ell,EF,t}$$

Step 10: Compute the price of materials for all $\ell \in \mathcal{L}$, $j \in J \cup F$:

$$P_{\ell,j,t}^M = \prod_{n \in J \cup F} \left(\frac{P_{\ell,n,t}}{\gamma_{j,n}} \right)^{\gamma_{j,n}}.$$

Step 11: Guess material usage $\{M_{\ell,j,t}\}$ for all $\ell \in \mathcal{L}$, $j \in J \cup F$.

Step 12: Compute quantities for all $j \in J$ and all location pairs k and $\ell \in \mathcal{L}$:

$$q_{k,\ell,j,t} = \left(\mu_j Inc_{\ell,t} + \sum_{n \in J \cup F} \gamma_{n,j} P_{\ell,n,t}^M M_{\ell,n,t} \right) \frac{\left(p_{k,j,t} \tau_{k,\ell,j} \right)^{-\rho_j}}{P_{\ell,j,t}^{1-\rho_j}}$$

For fuels, use:

$$q_{k,\ell,F,t} = \left(\mu_F Inc_{\ell,t} + \sum_{n \in J \cup F} \gamma_{n,F} P_{\ell,n,t}^M M_{\ell,n,t} + (1-\alpha_F)(1-\chi_{EF,t}) p_{\ell,E,t} y_{\ell,EF,t} \right) \frac{\left(p_{k,F,t} \tau_{k,\ell,F} \right)^{-\rho_F}}{P_{\ell,F,t}^{1-\rho_F}}$$

Step 13: Obtain the level of production for all $\ell \in \mathcal{L}$ and $j \in J \cup F$ that clears their

respective markets:

$$y_{\ell,j,t} = \sum_{k \in \mathcal{L}} \tau_{\ell,k,j} q_{\ell,k,j,t}.$$

Step 14: Update usage of materials ($\ell \in \mathcal{L}$, $j \in J \cup F$):

$$M'_{\ell,j,t} = \frac{\beta_j^M \left(1 - \beta_j^E\right) \left(1 - \chi_{j,t}\right) p_{\ell,j,t} y_{\ell,j,t}}{P^M_{\ell,j,t}},$$

$$M^{new}_{\ell,j,t} = \left(1 - \lambda_M\right) M_{\ell,j,t} + \lambda_M M'_{\ell,j,t}.$$

Go back to Step 12 until the convergence of $\{M_{\ell,j,t}\}$.

Step 15: Compute the demand for electricity for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$E^D_{\ell,j,t} = \frac{\beta_j^E \left(1 - \chi_{j,t}\right) p_{\ell,j,t} y_{\ell,j,t}}{P_{\ell,E,t}}.$$

Step 16: Compute for all $k, \ell \in \mathcal{L}$:

$$q_{k,\ell,E,t} = \left(\mu_E Inc_{\ell,t} + P_{\ell,E,t} \sum_{n \in J \cup F} E^D_{\ell,n,t} \right) \frac{\left(p_{k,E,t} \tau_{k,\ell,E}\right)^{-(\theta+1)}}{P^{-\theta}_{\ell,E,t}}$$

Step 17: Update prices $\{p_{\ell,E,t}\}$ to get demand for local electricity generation and local generation supply closer to each other:

$$p^{new}_{\ell,E,t} = \left(1 - \lambda_E\right) p_{\ell,E,t} + \lambda_E p_{\ell,E,t} \frac{\sum_{k \in \mathcal{L}} \tau_{\ell,k,E} q_{\ell,k,E,t}}{y_{\ell,E,t}}$$

Go back to step 5 until convergence of $\{p_{\ell,E,t}\}$.

Step 18: Obtain $\{r_{\ell,j,t}\}$ for all $\ell \in \mathcal{L}$, $j \in J \cup F \cup \{ER, EF\}$ and $t = 1, ..., T-1$.

$$r_{\ell,j,t} = \begin{cases} \frac{\beta_j^K \left(1-\beta_j^E\right)(1-\chi_{j,t}) p_{\ell,j,t} y_{\ell,j,t}}{K_{\ell,j,t}} & \text{for } j \in J \cup F \\ \frac{\left(1-\chi_{ER,t}\right)\alpha_R p_{\ell,E,t} y_{\ell,ER,t}}{K_{\ell,ER,t}} & \text{for } j = ER \\ \frac{\left(1-\chi_{EF,t}\right)\alpha_F p_{\ell,E,t} y_{\ell,EF,t}}{K_{\ell,EF,t}} & \text{for } j = EF \end{cases}$$

Step 19: Recover wages for all $\ell \in \mathcal{L}$ and $j \in J \cup F$:

$$w_{\ell,j,t} = \beta_j^L \left[\frac{c_{\ell,j,t}^{LMK}}{\left(\frac{P_{\ell,j,t}^M}{\beta_j^M}\right)^{\beta_j^M} \left(\frac{r_{\ell,j,t}}{\beta_j^K}\right)^{\beta_j^K}} \right]^{\frac{1}{\beta_j^L}}.$$

End of Static Block / big loop in t.

Step 20: For all $\ell \in \mathcal{L}$, $j \in J \cup F \cup \{ER, EF\}$ recover Lagrange Multipliers starting from time $t = T$ values from the final steady state and going backwards until $t = 2$:

$$\widetilde{\mu}_{\ell,j,t-1} = \beta \left(\frac{r_{\ell,j,t}}{P_{\ell,t}} + (1 - \delta_j)\widetilde{\mu}_{\ell,j,t} \right)$$

And calculate residuals for $t = 1, ..., T-1$

$$res_{\ell,j,t} = \xi_{\ell,j}\widetilde{\mu}_{\ell,j,t} - 1$$

Step 21: Update paths for investments for each $j \in J \cup \{F, ER, EF\}$ and $t = 1, ..., T-1$

$$Inv'_{\ell,j,t} = Inv_{\ell,j,t} + \lambda_I Inv_{\ell,j,t} \log\left(\xi_{\ell,j}\widetilde{\mu}_{\ell,j,t}\right)$$

That is, if $\xi_{\ell,j}\widetilde{\mu}_{\ell,j,t} > 1$ increase investment and if $\xi_{\ell,j}\widetilde{\mu}_{\ell,j,t} < 1$ decrease investment. Form new guess:

$$I_{\ell,j,t}^{new} = \max\left\{0, I'_{\ell,j,t}\right\}$$

And go back to Step 3 until

$$dist_I = \max_{\ell,j,0<t<T} \left| \frac{I_{\ell,j,t}}{\overline{I}_j + I_{\ell,j,t}} \log\left(\xi_{\ell,j}\widetilde{\mu}_{\ell,j,t}\right) \right| < \varepsilon$$

for some small ε and where $\overline{I}_j$ is the maximum investment level across all locations ℓ in the previous steady state.

Step 22: Compute labor demand for all $\ell \in \mathcal{L}$ and $j \in J \cup F$

$$L_{\ell,j,t}^D = K_{\ell,j,t} \times \frac{\beta_j^L}{\beta_j^K} \times \frac{r_{\ell,j,t}}{w_{\ell,j,t}}.$$

Step 23: Compute tax revenues for all $\ell \in \mathcal{L}$ and rebate b:

$$T_{\ell,t} = \sum_{j \in J \cup F \cup ER \cup EF} \chi_{j,t} p_{\ell,j,t} y_{\ell,j,t},$$

$$b_t = \frac{\sum_{\ell \in \mathcal{L}} T_{\ell,t}}{\overline{L}}.$$

Step 24: Solve the Bellman equation for workers for all $\ell \in \mathcal{L}$ and $j \in J \cup F \cup u$ (remember that $w_{\ell,u,t} = 0$).

Solve for the Steady State Bellman at $t = T$.

$$\mathcal{V}_{\ell,j,T} = \frac{w_{\ell,j,T} + b_T}{P_{\ell,T}} + \eta_{\ell,j} + \nu \log \left(\sum_{k \in \mathcal{L}, n \in J \cup F \cup u} \exp \left(\frac{-C_{\ell,j,k,n} + \beta \mathcal{V}_{k,n,T}}{\nu} \right) \right),$$

Then, start at $t = T - 1$ and go backwards until $t = 1$.

$$\mathcal{V}_{\ell,j,t} = \frac{w_{\ell,j,t} + b_t}{P_{\ell,t}} + \eta_{\ell,j} + \nu \log \left(\sum_{k \in \mathcal{L}, n \in J \cup F \cup u} \exp \left(\frac{-C_{\ell,j,k,n} + \beta \mathcal{V}_{k,n,t+1}}{\nu} \right) \right),$$

and recover the policy functions:

$$m_{\ell,j,k,n,t,t+1} = \frac{\exp \left(\frac{-C_{\ell,j,k,n} + \beta \mathcal{V}_{k,n,t+1}}{\nu} \right)}{\sum_{k' \in \mathcal{L}, n' \in J \cup F \cup u} \exp \left(\frac{-C_{\ell,j,k',n'} + \beta \mathcal{V}_{k',n',t+1}}{\nu} \right)}.$$

Step 25: Compute labor supply from $t = 1$ to $t = T - 1$ according to:

$$L^S_{k,n,t+1} = \sum_{\ell \in \mathcal{L}} \sum_{j \in J \cup F \cup u} m_{\ell,j,k,n,t,t+1} \, L^S_{\ell,j,t}.$$

Note: given assumptions on timing, labor supply at $t = 1$ is fixed at $t = 0$ levels (we assume that the shock is announced at the end of $t = 0$, after workers made their decisions of where to work at $t = 1$).

Step 26: Update the price of the labor-materials-capital bundle for all $\ell \in \mathcal{L}$, $j \in J \cup F$

and $t = 1, ..., T$:

$$\left(c_{\ell,j,t}^{LMK}\right)^{new} = (1 - \lambda_c)\, c_{\ell,j,t}^{LMK} + \lambda_c c_{\ell,j,t}^{LMK} \frac{L_{\ell,j,t}^{D}}{L_{\ell,j,t}^{S}}.$$

Go back to step 2 until convergence of $\left\{c_{\ell,j,t}^{LMK}\right\}$.

Step 27: Compute profits of renewable electricity generators for all $\ell \in \mathcal{L}$:

$$\Pi_{\ell,ER,t} = (1 - \chi_{ER,t})\,(1 - \alpha_R)\, p_{\ell,E,t} y_{\ell,ER,t}.$$

Step 28: Update income for all $\ell \in \mathcal{L}$ and $t = 1, ..., T$:

$$\begin{aligned} Inc'_{\ell,t} = & \sum_{j \in J \cup F} (w_{\ell,j,t} + b_t)\, L_{\ell,j,t} + b_t L_{\ell,u,t} \\ & + \sum_{j \in J \cup F \cup ER \cup EF} r_{\ell,j,t} K_{\ell,j,t} + \Pi_{\ell,ER,t}, \end{aligned}$$

$$Inc_{\ell,t}^{new} = \frac{(1 - \lambda_I)\, Inc_{\ell,t} + \lambda_I Inc'_{\ell,t}}{\sum_{k \in \mathcal{L}} (1 - \lambda_I)\, Inc_{k,t} + \lambda_I Inc'_{k,t}}.$$

Go back to Step 1 until convergence of $\{Inc_{\ell,t}\}$.