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Aggregate and Distributional Effects

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Abstract

We evaluate the aggregate and distributional effects of climate change mitigation policies using a multi-sector equilibrium model with intersectoral input–output linkages and worker heterogeneity calibrated to different countries. The introduction of carbon taxes leads to changes in relative prices and inputs reallocation, including labor. For the United States, reaching its original Paris Agreement pledge would imply at most a 0.8% drop in output. This impact is distributed asymmetrically across sectors and individuals. Workers with a comparative advantage in dirty energy sectors who do not reallocate suffer a welfare loss at least six times larger than workers in other sectors, but constitute less than 2% of the US labor force.

JEL classifications: E13, H23, J24
Keywords: Climate change, Carbon taxes, Worker heterogeneity, Labor reallocation

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1 Introduction

As greenhouse gas emissions reach alarming levels, there is increasing pressure on countries to adopt more aggressive environmental policies. However, concerns regarding their economic and distributional effects hinder the adoption of these policies, as reducing emissions means reallocating resources away from high-carbon sectors towards low-carbon ones. A clear example of such tension can be found in the United States, with the Trump administration dropping out of the climate Paris Agreement Accord, only for the Biden administration to re-join later. This paper investigates the aggregate and distributional effects of climate change mitigation policies by focusing on the reallocation of inputs, and labor in particular, across different sectors of the economy.

We make two contributions towards this goal. First, we develop a general equilibrium model with multiple sectors that are linked to one another via an input-output network and where workers are heterogeneous in their abilities to work in these different sectors. As in a standard Roy (1951) model, individuals choose in which sector to work based on their comparative advantage and on relative wages. There are four energy-producing activities among the various sectors in the model economy. Three of them (oil, coal and natural gas) are "dirty" in the sense that they generate CO_2 emissions, whereas the fourth (green) does not. In our benchmark model, energy is essential for production, but there is substitutability among the different energy types. As such, every intermediate good is produced using a non-energy bundle, consisting of labor and non-energy intermediate goods, and energy, which can be produced from different energy sources.

Our second contribution is to evaluate the economic effects of climate change mitigation policies within this integrated framework. To do this, we introduce a carbon tax to the dirty energy producers, which in turn affects their prices. Given the intersectoral linkages in the economy, these changes in relative prices create substitution possibilities between all inputs of production. This leads to resource reallocation, including labor, across sectors. The overall economic impact depends on the magnitude of the tax and on how the revenue is rebated to the economy. As economies differ in their production structures, energy mix and labor force characteristics, the impact of carbon taxes is likely to vary across countries. We thus calibrate the model parameters for three countries: the United States, China and Brazil.

Using the calibrated model, we estimate the carbon tax needed for the United States to achieve its original Paris Agreement pledge of a 26% reduction in emissions. Targeting this reduction in emissions costs the United States at most a 0.8% drop in output, depending on the revenue recycling scheme. We implement the same climate target for China and Brazil in order to capture cross-country heterogeneity in responses. China witnesses the largest economic loss (up to 3.7%). This higher impact in China is explained by the influence of dirty energy production in the Chinese economy's production network and not on the different levels of development, as Brazil, another emerging economy, suffers a loss comparable to that of the United States (0.5%).

Underneath the aggregate effects of carbon taxation lies sizable heterogeneity at the sectoral and individual levels. Dirty energy sectors directly exposed to the carbon tax witness the largest drop in production, and consequently the largest labor outflow. Zooming into the skill distribution, marginal (relatively less-talented) workers in dirty energy production and energy-intensive sectors choose to reallocate away from their initial activity. However, workers with a strong comparative advantage in the dirty energy sectors remain working there and thus end up bearing the cost of the drop in wages. In the United States, the welfare loss for this group is at least six times higher than for workers in non-dirty sectors, and 1.8 times that of workers who manage to reallocate away from the dirty sectors. Nevertheless, these workers constitute a small fraction of the labor force; less than 2% in the US. Workers in the green energy sector benefit from the carbon tax.

To better understand the key mechanisms behind our results, we disentangle the roles played by substitutability, input-output linkages, and worker heterogeneity. In our benchmark, there is no production without energy, given that energy is modeled as a perfect complement for the non-energy bundle. To address the role of substitutability, we adjust the model setup with a unitary elasticity of substitution between the energy and non-energy bundles. For the United States, the adverse aggregate effects drop by up to half of those in the benchmark, depending on the revenue recycling scheme. This change is more accentuated for China given its greater reliance on dirty energy. Next, to investigate the role of the input-output network, we model a horizontal economy without such linkages. We find that inter-sectoral linkages amplify the adverse economic effects of a tax as they capture both the direct effects of dirty energy sectors downsizing and their propagation via the production network. Finally, to tackle the role of worker heterogeneity, we solve a version of the model with identical workers. With homogeneous skills, labor reallocation across sectors is less costly. Therefore, smaller carbon taxes are required to achieve similar emission reduction targets. While the aggregate effects are similar to those in the benchmark, dropping worker heterogeneity prevents us from quantifying the distributional effects of carbon taxation and identifying those who gain or lose from such policies.

This paper is related to an important literature that concentrates on finding the optimal level of carbon taxation by integrating the climate and the economy into a single model (e.g., Nordhaus, 1994; Golosov et al., 2014; Dietz and Stern, 2015; Hassler et al., 2018; Tol, 2018; Barrage, 2020). Papers in this literature show the effectiveness of carbon taxes in curbing greenhouse gas emissions. However, these papers abstract from the distributional impacts of climate change mitigation policies, which is a key objective of this paper.

Carbon taxes tend to be regressive if one focuses on the *use-side* incidence of such taxes, as lower-income households devote a larger share of their expenditures to energy (Grainger and Kolstad, 2010). Other papers, however, show that carbon taxes can have progressive impacts once one takes into account the *source-side*, i.e., the relative change in remuneration of factor inputs (e.g., Bosetti and Maffezzoli, 2013; Dissou and Siddiqui, 2014; Chateau et al., 2018; Goulder et al., 2019). We build on the source-side literature and investigate how changes in factor prices induced by carbon taxes cascade to the rest of the economy and lead to sectoral reallocation of inputs. The distributional effects of carbon taxes may depend on how the tax revenue is recycled (Fried et al., 2022). In this paper, we investigate different rebate schemes. Other papers have studied the effect of climate policies on jobs. These studies have typically focused on the unemployment effects of these policies (e.g., Aubert and Chiroleu-Assouline, 2019; Castellanos and Heutel, 2019; Hafstead and Williams III, 2018). The focus of our paper is on occupational choice and mobility costs across sectors. Though parts of the picture have previously been addressed elsewhere, ours is the first paper to provide a unified framework featuring a general equilibrium model with a network of multiple sectors and heterogeneous workers to study the aggregate and distributional effects of climate change mitigation policies.

The rest of this paper is structured as follows. Section 2 describes the model and characterizes its equilibrium. Section 3 discusses the calibration strategy. Section 4 presents the aggregate results and Section 5 reports the sectoral- and individual-level results of the counterfactual analyses. Section 6 inspects the mechanisms behind our results by studying the roles of different modeling assumptions. Finally, Section 7 concludes.

2 The Model

The model economy consists of heterogeneous workers who draw an ability vector that determines their productivity for working in each sector of the economy. Based on this draw and the vector of wages in the economy, individuals make their occupational choice. On the production side, each sector produces a distinct intermediate good, including four types of energy: oil, coal, natural gas and green. These four types of energy are inputs to produce the energy bundle, which is needed in the production of all intermediate goods. There is also a final good sector. We describe the details of the model environment below.

2.1 Households

There is a continuum of measure one of individuals, each working in one of the J intermediate sectors. Individuals supply their labor inelastically to one of the intermediate goods sectors. Each individual derives utility from consumption only, c. The utility function is continuous and increasing in consumption. Without loss of generality for labor allocation and production, we assume a function linear in consumption:

$$U = u(c) = c.$$

The individual's labor income, which is completely spent on consumption, is the product of the wage per efficiency unit in sector j, w_j, and their idiosyncratic ability draw, z_j: $I = w_j z_j$.

Given an occupational choice, wage, and idiosyncratic talent, z_j, the individual's utility maximization implies that:

$$U_j^* = w_j z_j. \tag{1}$$

2.1.1 Occupational Skills

Each worker is endowed with a vector of idiosyncratic abilities $\{z_j\}_{j=1}^{J}$. We assume that the individual's abilities for the J sectors are drawn from a multivariate Fréchet distribution, such that:

$$F(z_1, ..., z_J) = \exp\left(-\sum_{j=1}^{J}(z_j)^{-\lambda}\right), \ \lambda > 1,$$

where the parameter λ measures the dispersion of individual productivity across sectors. A higher value of λ corresponds to smaller dispersion. When λ is small, workers' abilities are more dispersed, and hence a larger change in wages is needed to get workers to reallocate across sectors, and vice versa.

2.1.2 Occupational Choice

Self-selection is driven by how heterogeneous abilities interact with sectoral wages. Workers supply their labor to the sector which offers them the highest *relative* returns given their vector of ability, $w_j z_j$, instead of *absolute* returns w_j. That is, workers choose to work in the sector that yields them the highest utility: $\max_j\{U_j\}$.

With the decision rule behind workers' occupational choice and the tractability afforded by the Fréchet distribution, we can calculate the share of workers in each sector in the economy.

Proposition 1 *The share of workers in sector j, denoted by q_j, is given by:*

$$q_j = \frac{w_j^{\lambda}}{\sum_{j=1}^{J} w_j^{\lambda}} \text{ for } j \in \{1, ..., J\}. \tag{2}$$

Proof: See Appendix A.1. ■

Having calculated the labor share in each sector, we can now compute the efficiency units of labor supplied (i.e., effective labor supply) in each sector.

Proposition 2 *The effective labor supply for sector j is given by:*

$$L_j^s = q_j^{1-\frac{1}{\lambda}} \Gamma\left(1 - \frac{1}{\lambda}\right) \text{ for } j \in \{1, ..., J\}, \tag{3}$$

where $\Gamma\left(1 - \frac{1}{\lambda}\right)$ is the Gamma function evaluated at the constant $\frac{1}{\lambda}$.

Proof: See Appendix A.2. ■

Using equations (2) and (3), we can calculate average worker quality in a sector by taking the ratio of efficiency units of labor supplied over the units of labor supplied, L_j^s/q_j. Average quality is therefore inversely related to the labor share in each sector, which captures the selection effect.

2.2 Production

We will now describe each of the J intermediate good sectors and the final good sector in turn. All firms operate under perfect competition in both input and output markets.

2.2.1 Intermediate Goods

Our production setup is motivated by the literature on production networks (e.g., Acemoglu et al., 2012; Atalay, 2017; Baqaee and Farhi, 2020; Jones, 2011) and trade models (e.g., Eaton and Kortum, 2002). There are J sectors, each producing a differentiated intermediate good. Among these, there are four energy sectors: oil, coal, natural gas, and green. The first three energy sectors are responsible for CO_2 emissions, so we will refer to them as the "dirty" energy sectors. Let $j \in \{1, 2, ..., J-4\}$ denote the non-energy sectors and $j \in \{J-3, J-2, J-1, J\}$ represent the energy sectors. The last energy sector corresponds to the green sector.

Each intermediate sector j requires a minimum amount of an energy bundle, E_j, and a non-energy bundle, M_j, to produce Y_j, according to the following Leontief production function:

$$Y_j = \min\left\{\frac{M_j}{\eta_j}, \frac{E_j}{1-\eta_j}\right\},\ \eta_j \in (0,1), \tag{4}$$

where M_j is given by:

$$M_j = L_j^{\alpha_j} \prod_{k=1}^{J-4} x_{jk}^{\nu_{jk}},\ \alpha_j, \nu_{jk} \in [0,1]. \tag{5}$$

L_j corresponds to effective labor input and α_j is the labor share in sector j. The variable x_{jk} denotes the quantity of non-energy good k used in the production of good j. Parameter ν_{jk} determines the relative importance of good k in the production of sector j. M_j displays constant returns to scale in its inputs, such that $\alpha_j^L + \sum_{k=1}^{J-4} \nu_{jk} = 1$.

The energy bundle E_j aggregates the four types of energy according to the following technology:

$$E_j = \prod_{k=J-3}^{J} x_{jk}^{\theta_{jk}},\ \theta_{jk} \in [0,1], \tag{6}$$

where $\sum_{k=J-3}^{J} \theta_{jk} = 1$. Energy production of each type also requires a particular energy bundle for production. Therefore, as in Fried and Lagakos (2020) and Hassler et al. (2012), energy is essential for production, but there is some degree of substitutability across energy types within the energy bundle.[1] Production without energy is not possible, but we allow for transition to clean energy since E_j can be produced with different combinations of energy types.

Let P_j denote the price of intermediate good j. We split the profit maximization problem of

[1] Golosov et al. (2014) estimated the elasticity of substitution between dirty and clean energy sources to be 0.95 based on a metastudy of 47 studies of interfuel substitution (Stern, 2012). Therefore, the unitary elasticity of substitution assumed in equation (6) is a reasonable approximation.

the intermediate firm in sector j into two parts. First, the representative firm combines the non-energy bundle, M_j, and the energy bundle, E_j to produce its output Y_j. Let P_j^M be the price of the non-energy bundle j, and P_j^E be the price of the energy bundle j. This problem can be represented by

$$\pi_j = \max_{M_j, E_j} \left\{ P_j Y_j - P_j^M M_j - P_j^E E_j \right\}, \tag{7}$$

subject to (4). The solution of this problem requires

$$P_j = \eta_j P_j^M + (1 - \eta_j) P_j^E.$$

The representative firm then allocates labor, L_j, and intermediate inputs, $\{x_{jk}\}_{k=1}^J$ to minimize the cost of the non-energy bundle, M_j, and the energy bundle, E_j, subject to (5) and (6), respectively. The optimal conditions are:

$$\alpha_j \left(P_j - (1 - \eta_j) P_j^E \right) Y_j = w_j L_j,$$

$$\nu_{jk} \left(P_j - (1 - \eta_j) P_j^E \right) Y_j = P_k x_{jk}, \;\; k \in \{1, 2, ..., J-4\},$$

$$\theta_{jk} \left(P_j - \eta_j P_j^M \right) Y_j = P_k x_{jk}, \;\; k \in \{J-3, ..., J\}.$$

In addition, it can be shown that P_j^M and P_j^E are:

$$P_j^M = \left(\frac{w_j}{\alpha_j^L} \right)^{\alpha_j^L} \prod_{k=1}^{k=J-4} \left(\frac{P_k}{\nu_{jk}} \right)^{\nu_{jk}},$$

$$P_j^E = \prod_{k=J-3}^{k=J} \left(\frac{P_k}{\theta_{jk}} \right)^{\theta_{jk}}.$$

2.2.2 Final Good

The technology for the final good, Y_f, is given by a production function that uses differentiated intermediate goods $\{Y_j^F\}_{j=1}^J$ according to the following aggregator:

$$Y_f = \prod_{j=1} \left(Y_j^F \right)^{\sigma_j}, \;\; \sigma_j \in [0,1] \text{ and } \sum_{j=1}^{J} \sigma_j = 1. \tag{8}$$

The final good is the numéraire, such that its price P_f is normalized to 1. The optimization problem of the representative firm in the final good sector is to choose each input $\{Y_j^F\}_{j=1}^J$

to maximize:

$$\pi_f = \max_{Y_j} \left\{ \prod_{j=1} \left(Y_j^F\right)^{\sigma_j} - \sum_j P_j Y_j^F \right\}, \tag{9}$$

and the optimal demand for each input satisfies:

$$Y_j^F = \sigma_j \frac{Y_f}{P_j}, \ \forall j \in \{1, 2, ..., J\}.$$

2.3 Equilibrium

The stationary competitive equilibrium for this economy consists of individual choices $\{c\}$, individual occupational choices, efficiency units of labor input in each sector $\{L_j\}_{j=1}^J$, intermediate goods $\{Y_j\}_{j=1}^J$, final output Y_f, wages $\{w_j\}_{j=1}^J$ and prices of intermediate goods $\{P_j\}_{j=1}^J$, such that:

- Individuals supply their labor to the sector that provides them with the highest income according to their abilities.
- Firms producing intermediate goods maximize profits, according to problem (7).
- The representative firm of the final good maximizes profits, according to problem (9).
- All markets clear.

2.4 Carbon Taxation

A carbon tax affects the prices of energy inputs, particularly those emitting CO_2 gases. Therefore, the burden of the tax on the price of each energy type should depend on the carbon content of that particular energy type. Following Golosov et al. (2014) and Hassler et al. (2018), we differentiate among four energy inputs (oil, coal, natural gas and green) according to their carbon content (intensity of carbon emissions to the atmosphere). Denote this content by g_j, such that $g_j \in [0, 1]$. Green energy types (such as wind and solar) are not associated with any climate externality, so $g_{green} = 0$. The carbon tax rate on each energy type is given by $\tau_j = \tau g_j \ \forall j$ (note that $\tau_{green} = 0$ since $g_{green} = 0$).

We introduce the carbon tax as a sales tax to each dirty energy type, such that profits in energy type j, in the presence of such a tax, are given by:

$$\pi_j = (1 - \tau_j) P_j Y_j - P_j^M M_j - P_j^E E_j.$$

In our simulations, we consider different ways to allocate revenues raised with carbon taxes and adjust the equilibrium conditions accordingly. For instance, in one counterfactual experiment, we consider the use of tax revenues in dirty energy sectors to subsidize the green energy sector. In that experiment, the green subsidy is designed such that the carbon tax is revenue neutral (i.e., $\sum_{j=1}^{J} \tau_j P_j Y_j = 0$), which implies that $\tau_{green} < 0$.

3 Calibration

This section discusses how we discipline the model parameters in order to investigate the aggregate and distributional effects of climate change mitigation policies. Since these effects are likely to vary across countries due to country-specific characteristics (e.g., production structure and labor force composition), the calibration of the model is conducted by disciplining the parameters with micro-level data for a sample of three countries spanning a set of emerging and advanced economies with varying degrees of energy intensity, namely: the United States, China and Brazil.

We have prior information about some model parameters, such as the importance of each input in the production of intermediate goods. Other parameters are specific to the analysis, however, and we do not have much information about their magnitude. They will be internally estimated such that the model matches key moments of the data. Table B1 in the Appendix lists all the model parameters and divides them into externally and internally calibrated moments.

External Calibration. To set values for J, α_j^L, and ν_{jk}, we use data from the World Input Output Database (WIOD), which contains national input-output tables, as well as data on sectoral labor shares, and environmental accounts for the countries in our sample. We aggregate the 56 sectors in the WIOD into 15 sectors including one aggregate energy sector. We then split the aggregate energy sector into oil, coal, natural gas and green energy production based on the energy input mix of each of the intermediate sectors, according to the WIOD environmental accounts on energy use by sector and energy type. We thus end up with $J = 18$ sectors. The first 14 sectors are non-energy, and the last four sectors are energy (oil, coal, gas and green, respectively). For more details, see Table B2 in the Appendix.

Turn now to the production parameters α_j and ν_{jk}. We first use data on inter-sectoral sales to calculate a matrix β such that $\beta_{jk} = \frac{P_k x_{jk}}{P_j Y_j}$. We next calculate $\beta_j^L = 1 - \sum_{k=1}^{J} \beta_{jk}$. β_j^L thus represents labor compensation, i.e., sector j's value added in the model. We then scale β_j^L with η to fit this into the Leontief model economy such that $\alpha_j = \frac{\beta_j^L}{\eta_j}$, whereby η_j will be internally calibrated to match the non-energy expenditure shares in the data (more on this below). The matrix ν with all the values for ν_{jk} takes the values of the first 14 columns of matrix β and replaces the last four columns (denoting consumption of energy) with zeros since every intermediate good j uses only the 14 non-energy intermediate goods in its non-energy bundle. We then rescale the entries in ν to add up to 1 in each row and scale it again with $(1-\alpha_j)$ such that: $\alpha_j + \sum_{k=1}^{14} \nu_{jk} = 1 \ \forall j$. As for the energy use matrix θ, its first 14 columns are zero, but the last four columns are the same as in the original data matrix β, such that each intermediate good only consumes energy in its energy bundle. We re-scale the entries of θ such that $\sum_{k=15}^{18} \theta_{jk} = 1$.

We use the WIOD environmental accounts data on CO_2 emissions by sector and energy type to calculate the effect of taxes on emissions.[2] More details on these parameters are presented in Appendix B. Finally, the sectoral carbon content, g_j, is based on Golosov et al. (2014). Their numbers for oil and coal are $g_{oil} = 0.846$ and $g_{coal} = 0.716$. We replicate their methodology and calculate $g_{gas} = 0.734$ using estimates from Garg et al. (2006).

Internal Calibration. The remaining parameters σ_j, η_j and λ are disciplined by solving the model and targeting certain data moments. In particular, we calibrate the expenditure shares σ_j such that the sectoral value added shares in the model match those in the data. We calibrate η_j such that the non-energy expenditure in the model matches that in the data, i.e., $\frac{P_j^M M_j}{P_j Y_j} = \sum_{k=1}^{k=14} \beta_{jk}$. This means that the expenditure on the energy bundle will be targeted as well, i.e., $\frac{P_j^E E_j}{P_j Y_j} = \sum_{k=15}^{k=18} \beta_{jk}$.

In order to estimate λ, we follow the methodology in Hsieh et al. (2019). We use micro-data from the Integrated Public Use Micro-data Series (IPUMS) for the United States and Brazil. For China, we use micro-data from the Chinese Household Income Project, 2013. We use micro-data on individual wages to fit the distribution of residuals from a cross-sectional regression of log income earned on age-industry dummies in a given year for each country. We then match the coefficient of variation of sectoral residual wages. The values of estimated Fréchet parameters, alongside data and the model's estimates of the coefficient of variation of wages for each country are presented in Table B10 in the Appendix. Appendix C.1 provides sensitivity analysis for the parameter λ.

Model Fit. Following the calibration strategy above, we target sectoral value added shares, expenditure shares on non-energy and energy, as well as the coefficient of variation of wages. Although sectoral labor shares are not targeted, the model's estimates of these shares are

[2] Note that our framework does not model the feedback effects of emissions on the economy. We compute the change in emissions in order to discipline the size of the carbon tax.

highly correlated to their data counterparts (84.8% in the United States, 71.7% in China, and 69.7% in Brazil); see Table B11 in Appendix B.

4 The Aggregate Effects of Climate Change Mitigation Policies

To investigate how the economy reacts to climate change mitigation policies, we introduce a carbon tax on the three dirty-energy sectors: oil, coal and gas. We consider four different counterfactual policies in which tax revenue is either: i) wastefully spent, i.e., not rebated back ("Wasteful Spending"); ii) used to subsidize green energy ("Green Subsidy"); iii) used to subsidize all non-dirty sectors in the economy ("Useful Spending"); or iv) rebated back to households uniformly as lump-sum transfers ("Household Transfers"). In policies ii)-iv), subsidies/lump-sum transfers are designed such that the government budget is balanced.[3]

More specifically, our experiments first calculate the tax rate needed for the United States to achieve its original Paris Agreement pledge of reducing total emissions by 26% (Ramstein et al., 2019). Then, we quantify the aftermath of the tax at the aggregate, sectoral and individual levels. Finally, we replicate the same exercises for China and Brazil. Investigating countries with different levels of development and production structures allows us to capture heterogeneous responses across countries when trying to achieve the same climate change mitigation target.

Table 1 displays the main aggregate results for the benchmark model. Panel A reports that the United States requires a 63.9% tax on dirty-energy production to achieve its original Paris pledge in the wasteful spending scenario. Since the dirty energy sectors pollute more than the non-dirty sectors, the drop in fossil emissions is larger (26.6%). As energy becomes more expensive, the economy contracts and GDP falls by 0.4%. With the tax, reallocation of resources and fall in output, consumption/welfare decreases by 3.5%.[4] The difference between GDP and household consumption is explained by the carbon tax revenue, which amounts to 3.1% of GDP in this case.

The effects on consumption can be largely offset by implementing tax rebates. If the govern-

[3]Similar to King et al. (2019), our model does not feature a carbon externality since emissions do not affect production or consumption. Hence, there is no negative externality to be corrected by policy in the model. Therefore, our exercises are positive rather than normative.

[4]Consumption and welfare are the same in this economy since utility is just a linear function of consumption.

Table 1: Macroeconomic Effects of Targeting a 26% Reduction in Emissions

Panel A: United States	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Consumption (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	63.9	-	3.1	-0.4	-3.5	-26.6	-26.0
Green Subsidy	51.7	99.5	2.0	-0.8	-0.8	-26.8	-26.0
Useful Spending	65.4	1.9	3.3	-0.5	-0.5	-26.6	-26.0
Household Transfers	63.9	-	3.1	-0.4	-0.4	-26.6	-26.0
Panel B: China	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Consumption (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	49.6	-	10.8	-1.6	-12.2	-26.6	-26.0
Green Subsidy	46.4	109.2	8.8	-3.7	-3.7	-27.2	-26.0
Useful Spending	62.0	6.6	19.4	-2.2	-2.2	-26.9	-26.0
Household Transfers	49.6	-	10.8	-1.6	-1.6	-26.6	-26.0
Panel C: Brazil	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Cons. (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	52.1	-	2.4	-0.4	-2.7	-27.4	-26.0
Green Subsidy	46.6	24.8	1.9	-0.5	-0.5	-27.6	-26.0
Useful Spending	52.8	1.4	2.4	-0.4	-0.4	-27.5	-26.0
Household Transfers	52.1	-	2.4	-0.4	-0.4	-27.4	-26.0

ment uses the carbon tax revenue to subsidize the green energy sector, then it will require a lower tax (51.7%) to achieve the same climate target. Compared to the wasteful spending scenario, the green energy sector almost doubles (with a 99.5% subsidy). Since the green sector is not associated with climate externalities, it enables the economy to reach its energy needs at a lower environmental cost. With a green subsidy, the fall in GDP is slightly larger (-0.8%) given the introduction of another distortion: a tax (wedge) on dirty energy production and a subsidy (another wedge) to green energy. However, the fall in consumption is now dampened to 0.8% (from 3.5% in the wasteful spending scenario).

A less distortionary alternative to the green subsidy scenario would be subsidizing the green sector as well as all the 14 non-energy sectors in the economy. This is akin to a public infrastructure subsidy for all sectors that are non-dirty energy, which in turn generates more economic activity. As such, a larger carbon tax is now needed (65.4%) in order to achieve the same climate target. The fall in GDP is now more comparable to the wasteful spending scenario, while the fall in consumption is largely offset (0.5% compared to 3.5% initially).

Finally, the government may rebate the tax revenue back to households as lump-sum transfers. Since these transfers are non-distortionary, nothing changes on the production side compared to the wasteful spending scenario, so we get the same carbon tax and change in GDP for the same target. The only difference is now consumption and GDP are aligned, so the drop in consumption is the same as that in GDP. From now on, we will abstract from the lump-sum transfers scenario in the sectoral economic analysis because it is basically the wasteful scenario in which the changes in consumption and GDP are the same.

4.1 China versus the United States

To capture cross-country heterogeneity, we replicate the same analysis for China, see Panel B of Table 1. The main insights across the different types of tax rebates found for the United States carry over to the Chinese case. The main differences are the magnitudes of those effects.

In order to achieve the same target of 26% reduction in emissions, China requires a smaller carbon tax (49.6% for the wasteful spending scenario). Despite being smaller than that of the US, this carbon tax generates larger aggregate output effects in China—roughly four times larger GDP and consumption drops than in the United States. The disparity in the economic effects of achieving the same climate target in the United States and China hinges on the varying importance of the taxed sectors in each country's economy. China is more polluting than the United States and is more reliant on dirty energy.

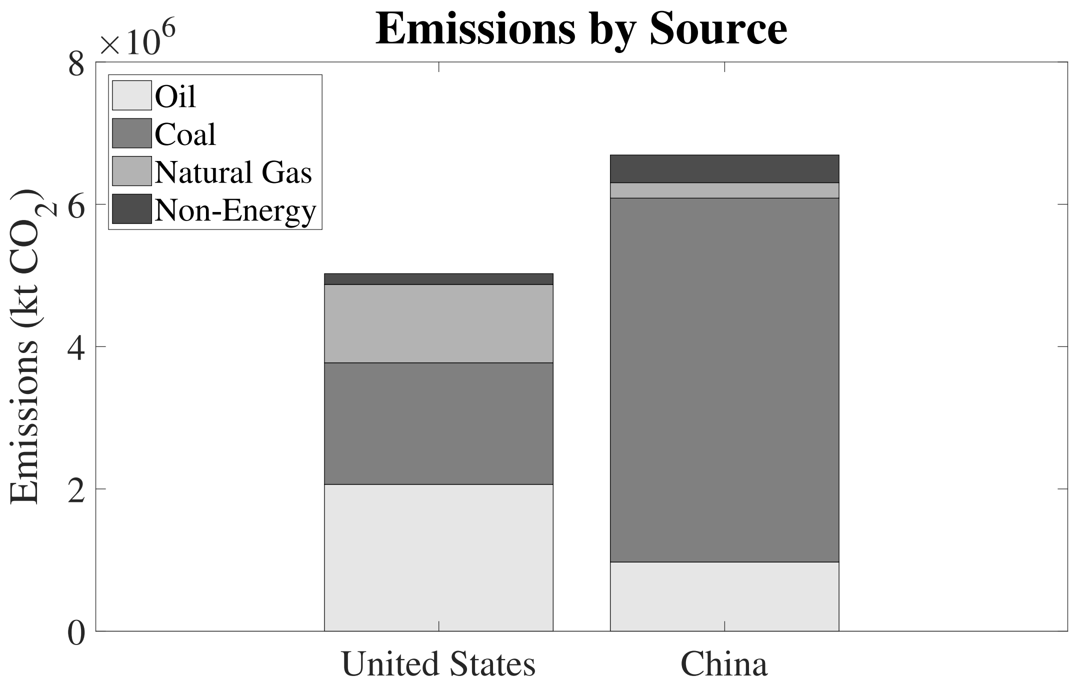
Figure 1 presents the breakdown of emissions for the United States and China. China generates more emissions than the United States: its fossil fuel emissions (oil, coal and natural gas combined) are 29.3% higher than the fossil fuel emissions in the United States, and its non-energy emissions are 156.9% higher than in the United States (albeit non-energy emissions constitute a small fraction of total emissions in both countries: 5.8% in China and 3% in the United States).

Figure 2 presents the breakdown of sales in each economy and shows that dirty energy production has a higher sales share in China (5.1%) than in the United States (2.4%). This drives its influence on the economy when shocked, in terms of its direct effect because of its size and its indirect effect because of its propagation via the production network (Acemoglu et al., 2012).[5]

One might argue that the divergence in results between the United States and China can also be due to varying levels of development. To assess this, we replicate the results for Brazil in Panel C of Table 1. While Brazil and China are both emerging economies, the difference in effects between Brazil and the United States is much less accentuated. For Brazil, achieving a 26% reduction in emissions requires a 52.1% carbon tax and comes with a comparable drop

[5] China also has a higher share of dirty energy in intermediate consumption (5.4% vs. 1.8% in US), value added (4.4% vs. 3.0% in US) and labor force composition (1.9% vs. 0.6% in US). See Table C15 for more details.

Figure 1: Breakdown of Emissions in United States vs. China.



Source: World Input Output Database, Environmental Accounts.

in GDP to the US economy and an even lower drop in consumption. Moreover, Figure C1 in Appendix C shows that sales shares of dirty energy sectors in Brazil are quite close to those observed in the United States. Given this, from now on, we will concentrate our analysis on the United States and China.

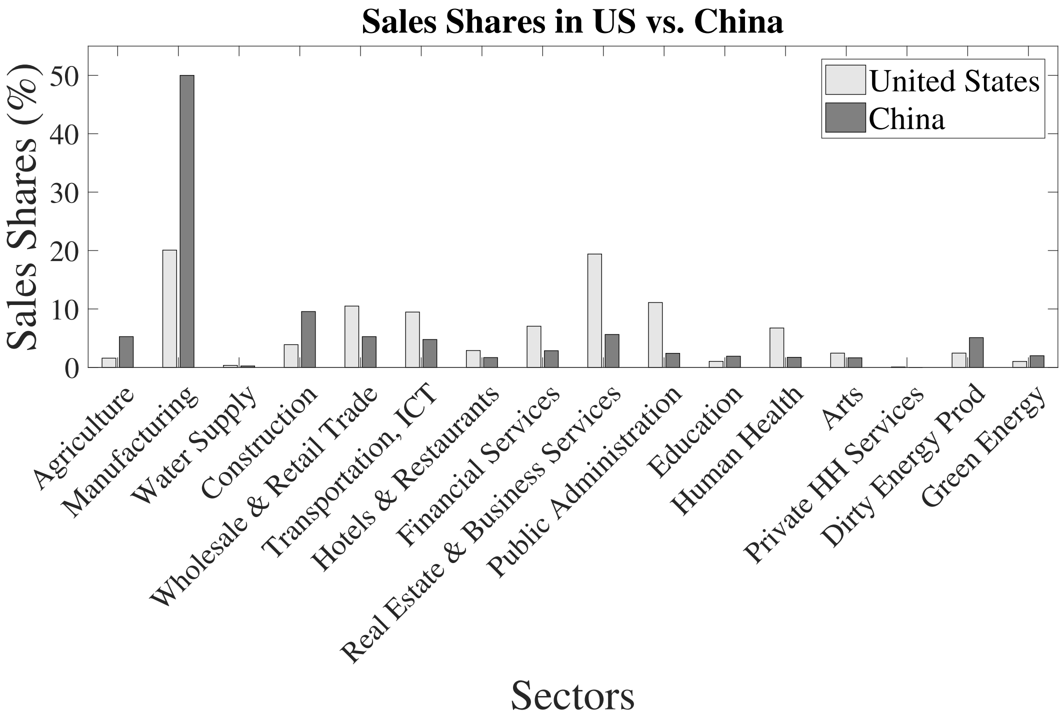
5 The Distributional Effects of Climate Change Mitigation Policies

This section investigates the sectoral- and individual-level effects of climate change mitigation policies to better understand the micro-underpinnings of the aggregate results of the previous section.

5.1 Sectoral-level Analysis

Introducing the carbon tax on oil, coal and natural gas causes these energy sectors to downsize as they become relatively more expensive. Given the input-output linkages, sectors

Figure 2: Sectoral Sales Shares in the United States vs. China.



Source: World Input Output Database, National Accounts.

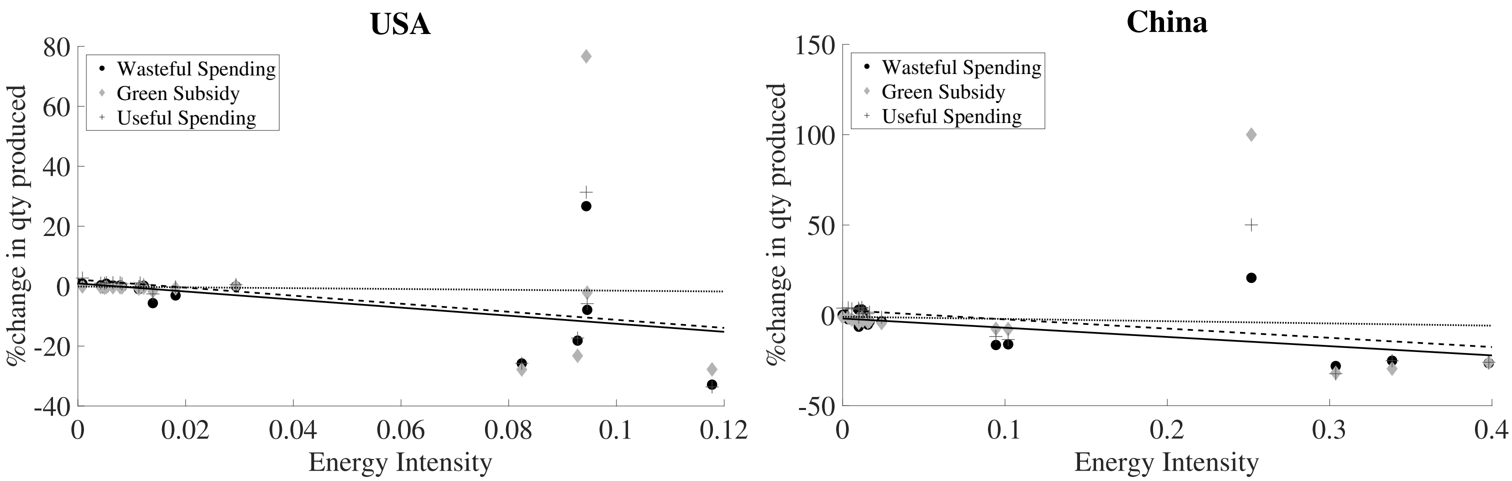
which are more reliant on dirty energy production witness a larger fall in their production. This is noticeable in Figure 3, which shows a negative correlation between the percentage change in production quantity and energy intensity across sectors.

Figure 4 exploits the richness of our production framework to present the percentage change in production quantity by sector. This figure highlights the largest drop in production by the dirty energy sectors as well as the heterogeneity in effects across sectors, scenarios, and countries. Production in green energy always increases, regardless of the recycling scheme. This is driven by the minimum requirement of energy for each intermediate good production and the substitutability between energy inputs within the energy bundle.

As oil, coal and natural gas energy sectors downsize, labor demand and wages in these sectors fall. Workers re-optimize their occupational decisions and some switch sectors. Figure 5 shows the changes in equilibrium labor in the energy sectors and the aggregate of all the non-energy sectors. Employment in the oil, coal and natural gas sectors drops, while it increases substantially in the green energy sector and marginally in the non-energy sectors of the economy.

The occupational decision of workers is driven by their innate abilities as well as the wage in

Figure 3: Energy Intensity vs. Change in Sectoral Production upon Targeting a 26% Reduction in Emissions.



Note: Each line displays the best linear fit for the corresponding case. The dotted line represents the green subsidy scenario, the dashed line represents the useful spending scenario, and the black line represents the wasteful spending scenario.

Figure 4: Change in Sectoral Production upon Targeting a 26% Reduction in Emissions

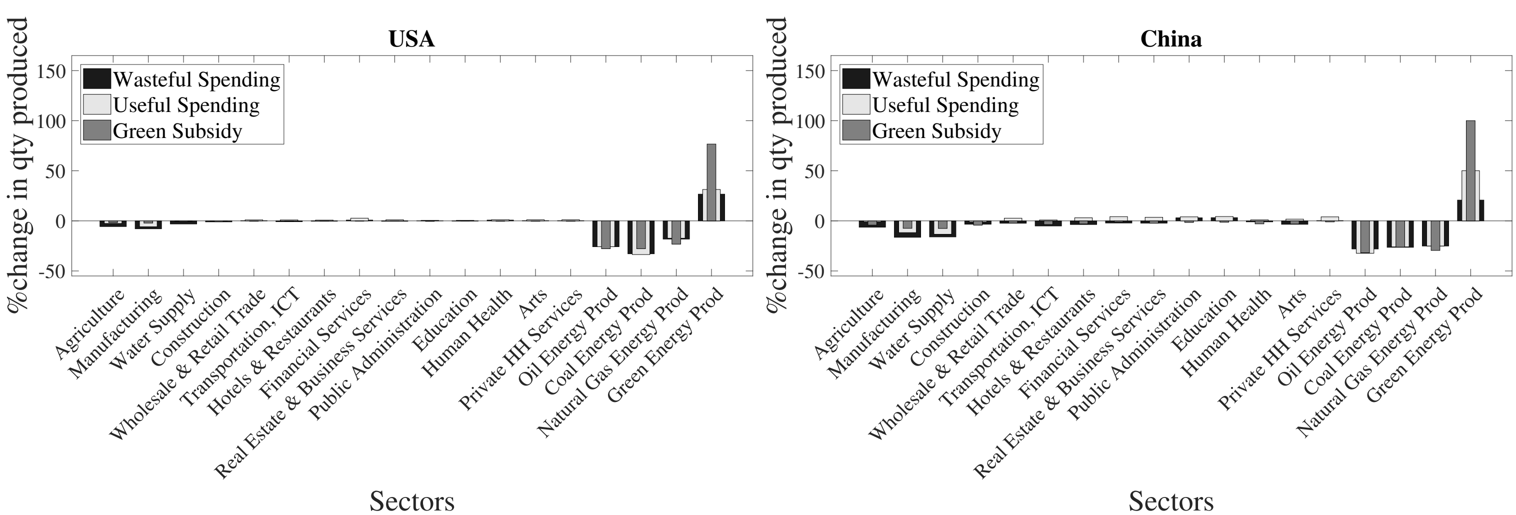


Figure 5: Percentage Change in Effective Labor upon a 26% Reduction in Emissions

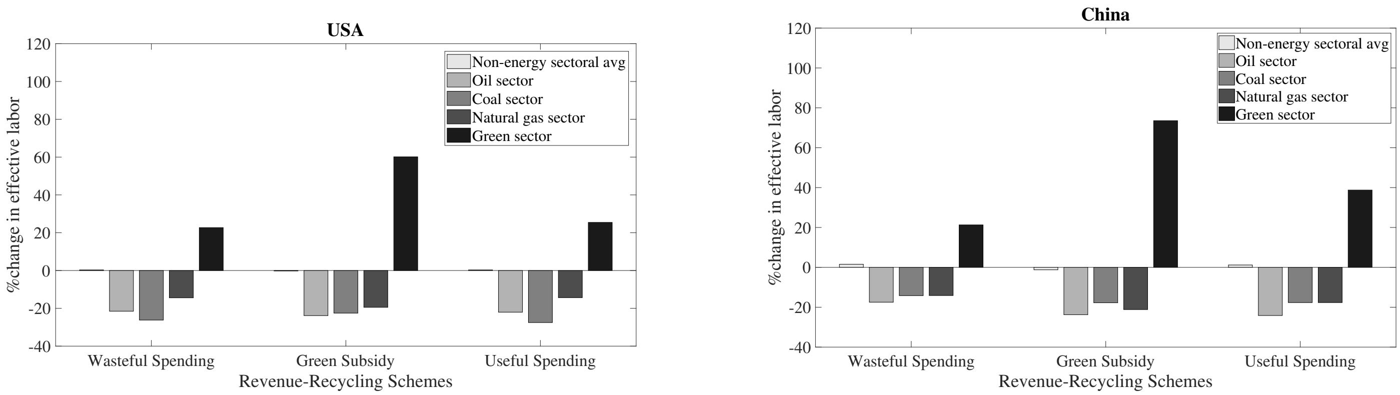
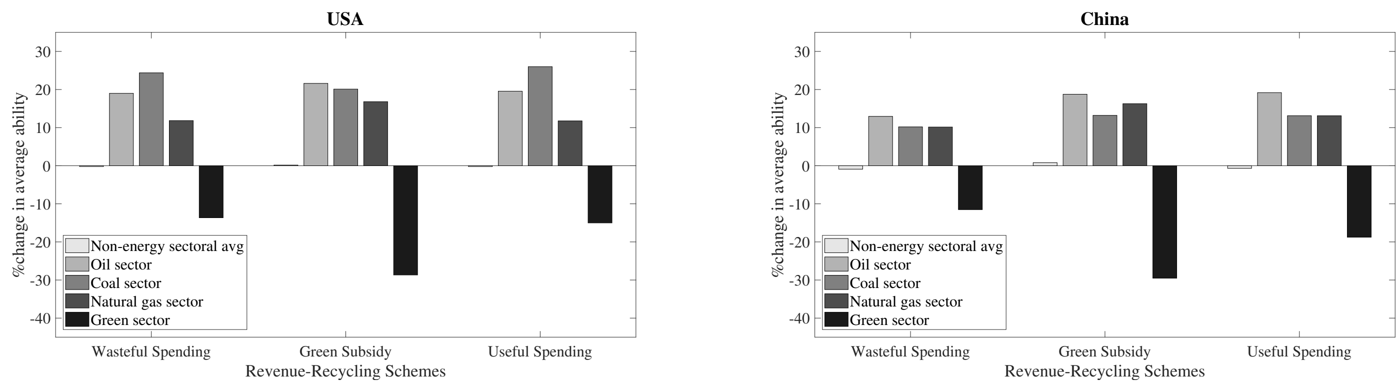


Figure 6: Percentage Change in Average Ability upon a 26% Reduction in Emissions



each occupation. Marginal workers with relatively low productivity in the dirty energy sectors reallocate to other sectors of the economy. Workers with a high comparative advantage in the dirty energy sectors remain in these sectors even after the policy change. Therefore, due to a selection effect, the average productivity of workers in the taxed sectors rises (see Figure 6). Average productivity drops significantly in the green sector due to the large inflow of workers to this sector in each scenario, as depicted in Figure 5.

5.2 Individual-level Analysis

We now investigate the distributional effects more closely by focusing on individual-level effects that arise after the introduction of a carbon tax. We split workers into six categories: i) those who remain in the non-energy sectors; ii) those who reallocate from the non-energy sectors; iii) those who remain in the dirty energy sectors; iv) those who reallocate from the dirty energy sectors; v) those who remain in the green energy sector; and vi) those who remain in the green energy sector. We then track how their welfare changes after the implementation of the policy. Welfare is measured by the change in consumption upon introducing the carbon tax relative to the baseline.

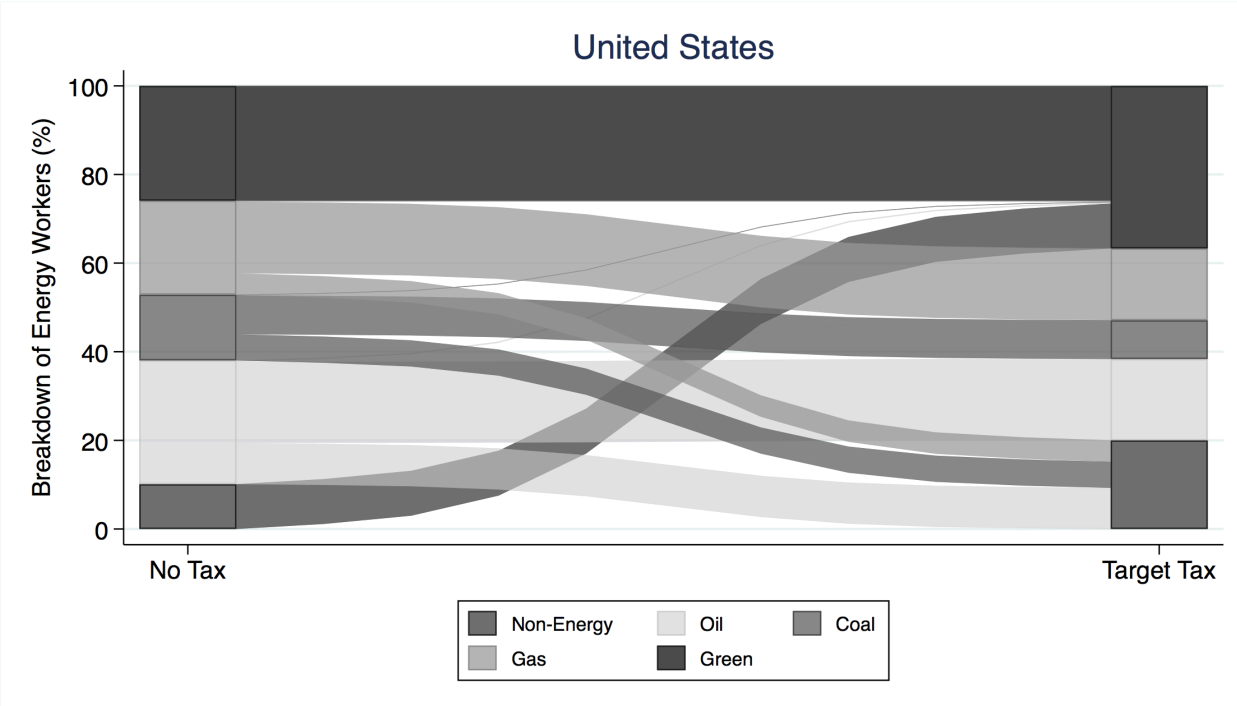
Table 2: Detailed Welfare Analysis

Panel A: United States	Wasteful Spending		Green Subsidy		Useful Spending		Household Transfers	
	CE (%)	LS (%)	CE (%)	LS (%)	CE CE (%)	LS (%)	CE CE (%)	LS (%)
Non-energy sectors, stayers	-3.3	94.5	-1.0	94.5	-0.2	94.6	0.8	94.5
Non-energy sectors, switchers	1.0	1.5	13.4	1.6	4.8	1.4	6.9	1.5
Dirty energy sectors, stayers	-18.4	1.9	-17.0	1.8	-16.2	1.9	-14.8	1.9
Dirty energy sectors, switchers	-10.3	0.9	-7.7	1.0	-7.6	0.9	-4.8	0.9
Green energy sector, stayers	11.7	1.1	39.1	1.1	17.1	1.1	15.9	1.1
Green energy sector, switchers	–	0.0	–	0.0	–	0.0	–	0.0
Panel B: China	Wasteful Spending		Green Subsidy		Useful Spending		Household Transfers	
	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)
Non-energy sectors, stayers	-11.3	89.4	-4.5	88.7	-1.6	88.7	2.3	89.4
Non-energy sectors, switchers	-8.3	3.6	10.3	4.3	5.8	4.4	10.7	3.6
Dirty energy sectors, stayers	-21.0	3.3	-17.0	3.0	-15.0	3.1	-8.6	3.3
Dirty energy sectors, switchers	-16.0	1.0	-8.1	1.3	-7.4	1.3	2.0	1.0
Green energy sector, stayers	-0.8	2.6	36.6	2.6	20.4	2.6	13.0	2.6
Green energy sector, switchers	–	0.0	–	0.0	–	0.0	–	0.0

Note: CE = consumption equivalents , LS = labor share in each sector.

Table 2 shows that workers who remain in the dirty energy sectors (oil, coal and gas) experience the largest decline in welfare. Take the United States as an example—Panel A of this table. In the wasteful spending scenario, the welfare of stayers in the dirty energy sectors declines by 18.4%. This loss is approximately 1.8 times the one experienced by those who switch from the dirty sectors (10.3%) and almost six times the loss witnessed by workers staying in non-dirty sectors. This decline in welfare is due to the reduction in labor demand and wages in the taxed sectors. The measure of workers directly affected by the introduction of the carbon tax, however, is relatively small—at most 1.9% of the labor force in the United States. Due to general equilibrium effects, labor reallocation also takes place in the non-dirty sectors. Given the substitutability between dirty energy sectors and green energy, the green sector is expanding in all scenarios and therefore always witnesses a labor inflow. No worker is switching out of the green sector. Given the increase in wages, green energy stayers actually experience a welfare improvement, as do non-energy switchers who mostly go to the green energy sector. Non-energy stayers witness a welfare decline, although it is largely, and sometimes fully, offset when tax revenues are rebated back. Similar patterns are found for the other counterfactuals and for China, although welfare magnitudes differ

Figure 7: Reallocation of Dirty Energy Workers under Wasteful Spending



Note: This figure only reports the mass of workers switching into and out of the energy sectors for scaling purposes since workers in the non-energy sectors with and without the carbon tax constitute 96% of the labor force.

(see Table 2, Panel B).

Figure 7 presents the reallocation of workers into and out of the energy sectors. This corresponds to 4% of the total labor force as 96% of workers work in non-energy sectors with or without the carbon tax. The figure shows the fraction of workers in the dirty energy sectors (oil, coal and natural gas) that either remain in these sectors (the "stayers"), or switch to the non-energy sectors of the economy (the "switchers") after the introduction of the tax. A fraction of dirty energy workers switch to the green energy sector, albeit a small percentage. Meanwhile, workers who start off in the green sector stay in the green sector. Lastly, there is a noticeable inflow of workers from the non-energy sectors to the green sector, in line with the significant increase in effective labor supply in the green sector depicted in Figure 5.

Figure C2 repeats the same analysis for China under the wasteful spending scenario. Similar patterns emerge except that the breakdown of energy workers across sectors is different in China, with bigger emphasis on coal and green energy production, as noted in Table C15. Finally, Figure C3 presents labor reallocation in the United States and China under a green subsidy scenario. Unsurprisingly, heavier flows into the green sector materialize compared to the wasteful spending scenario. See Appendix C.4 for more details.

6 Decomposing the Mechanisms

To better understand the key mechanisms behind our main results, we disentangle in the following subsections the roles played by energy substitutability, input-output linkages, and worker heterogeneity.

6.1 The Role of Energy Substitutability

In the benchmark model, we assumed that the energy bundle and the non-energy bundle are perfect complementary factors in the production of intermediate goods, as in Fried and Lagakos (2020). In this subsection, we change this assumption and consider a Cobb-Douglas production technology for each intermediate good j, represented by:

$$Y_j = L_j^{\beta_j^L} \prod_{k=1}^{J} x_{jk}^{\beta_{jk}^M},\ \beta_j^L, \beta_{jk} \in [0,1], \tag{10}$$

such that $\beta_j^L + \sum_k \beta_{jk}^M = 1$. The bundle $\prod_{k=1}^{J} x_{jk}^{\beta_{jk}^M}$ now includes the four energy goods. In this case, the elasticity of substitution between each energy type and any other input is equal to one. The calibration details for this economy are presented in Appendix B.

Table 3 presents similar patterns to the results displayed in Table 1, but with the Cobb-Douglas intermediate production function (10), instead of the Leontief function defined by equations (4)-(6). Two main features stand out. First, a lower carbon tax is needed to achieve the original Paris Agreement pledge of reducing total emissions by 26%. The higher substitutability of energy relative to other inputs implies that, for a given carbon tax, it is easier for firms in intermediate sectors to shift away from dirty energy. Given the easier reallocation of resources from dirty energy types to other inputs, the economic costs are lower in the Cobb-Douglas environment. For instance, in the wasteful spending scenario, GDP falls by 0.2 percentage points relative to 0.4 in the benchmark case for the United States. In China, the fall in GDP is reduced by a third relative to the benchmark case for the wasteful spending scenario (0.5% here versus 1.5% in the baseline). The difference in economic costs of a carbon tax between the United States and China is reduced relative to the world in which the energy bundle and the non-energy bundle are perfect complements in production. This again is explained by China's reliance on its energy sectors, and their influence being accentuated when energy is less substitutable. Therefore, achieving a 26% reduction in emissions comes with a spectrum of economic losses ranging between 0.8% and 0.2% drops in GDP for the United States, and between 3.7% and 0.5% for China.

Table 3: Macroeconomic Effects of Targeting a 26% Reduction in Emissions in a Cobb-Douglas World

	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Consumption (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Panel A: United States							
Wasteful Spending	41.1	-	1.39	-0.2	-1.6	-26.6	-26.0
Green Subsidy	44.6	85.4	1.5	-0.6	-0.6	-26.8	-26.0
Useful Spending	41.4	0.8	1.42	-0.2	-0.2	-26.7	-26.0
Household Transfers	41.1	-	1.39	-0.2	-0.2	-26.6	-26.0
Panel B: China	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Consumption (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	22.2	-	2.9	-0.5	-3.3	-27.4	-26.0
Green Subsidy	28.0	62.0	3.8	-1.2	-1.2	-27.5	-26.0
Useful Spending	23.6	1.1	3.1	-0.5	-0.5	-27.5	-26.0
Household Transfers	22.2	-	2.9	-0.5	-0.5	-27.4	-26.0

Second, for the benchmark case, there is a major reallocation of resources from dirty energy sectors to the green energy sector. In the Cobb-Douglas case, resources from the taxed dirty energy sectors are reallocated to all the other sectors. In order to highlight the role of susbtitutability in more detail, Tables C16 and C17 in the Appendix report the percentage change in production quantity by sector upon introducing the carbon tax required to achieve a 26% reduction in emissions. The green sector is hit similarly to non-energy sectors in the Cobb-Douglas world (when not subsidized). In the Leontief benchmark, the green sector always expands since it must supply the essential energy bundle. This has implications for the tax needed under a green subsidy compared to the wasteful spending scenario. A larger tax is needed compared to wasteful spending in the Cobb-Douglas economy (44.6% under green subsidy in US compared to 41.1% under wasteful spending), while a smaller tax is needed compared to the wasteful spending scenario in the Leontief benchmark (51.7% compared to 63.9% under wasteful spending). The response of the green sector and associated tax needed also affect labor reallocation and welfare as detailed in Table C18 in Appendix C.

6.2 The Role of Input-Output Linkages

To evaluate the role of input-output linkages in propagating the effects of the carbon tax, we solve a version of the model without the network structure of the benchmark. That is, we solve the equilibrium for a horizontal economy. More precisely, we change the model environment presented in our benchmark case and define the production technology of the intermediate good j by:

$$Y_j = min\left\{\frac{L_j}{\eta_j}, \frac{E_j}{1-\eta_j}\right\},\ \eta_j \in (0,1), \tag{11}$$

The final good production is represented by the same technology as before—equation (8)—and the energy bundle aggregator is also similar to the benchmark environment—equation (6). Therefore, the difference in this alternative environment and the benchmark environment is that only energy goods are inputs for intermediate goods and final good production while the non-energy intermediate goods are only inputs in the final good production. We again calibrate the model to match similar moments as in the benchmark case—details are described in Appendix B.

The main results for this horizontal economy are presented in Table 4. A larger carbon tax is now needed to reduce total emissions by 26% relative to the benchmark. For the United States and the wasteful spending scenario, the carbon tax to reach the original Paris agreement pledge is 69.5% instead of 63.9%. For the case of the green subsidy in the United States the carbon tax rate is 58.1% instead of 51.7%. This result materializes because the production network structure amplifies the effects of a carbon tax by affecting both the taxed sectors and the sectors that use energy intensively, then the sectors that use those sectors, and so on.

Table 4: Macroeconomic Effects of Targeting a 26% Reduction in Emissions in a Horizontal Economy

Panel A: United States	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Cons. (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	69.5	-	1.7	-0.3	-1.9	-26.7	-26.0
Green Subsidy	58.1	128.2	1.1	-0.4	-0.4	-26.8	-26.0
Useful Spending	68.6	1.7	1.7	-0.3	-0.3	-26.7	-26.0
Household Transfers	69.5	-	1.7	-0.3	-0.3	-26.7	-26.0
Panel B: China	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Cons. (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	75.4	-	10.0	-1.4	-11.3	-27.1	-26.0
Green Subsidy	64.4	176.3	4.8	-2.3	-2.3	-27.4	-26.0
Useful Spending	74.3	9.6	10.1	-1.4	-1.4	-27.2	-26.0
Household Transfers	75.4	-	10.0	-1.4	-1.4	-27.1	-26.0

Despite the larger required carbon tax rate, the reduction in GDP for the US economy is about one third and one half lower than in the benchmark for the wasteful spending and green subsidy scenarios, respectively. The revenue generated from the carbon tax is smaller, implying a much smaller fall in consumption for the wasteful spending scenario.

As discussed in Section 4.1, China is more reliant on dirty energy, as is evident from its sales shares. This is apparent again in this exercise, as China now requires a much higher tax increase to hit the 26% reduction in emissions compared to the benchmark (75.4% vs. 49.6% in the benchmark), while the United States did not require such a tax hike (69.5% vs. 63.9 in the benchmark). This highlights a stronger role of input-output linkages in propagating the tax in China than in the United States. This happens since manufacturing, an energy-intensive sector, constitutes almost half of Chinese gross output.

6.3 The Role of Worker Heterogeneity

In our baseline, workers have different abilities to work in each sector. For instance, some are more productive in dirty energy sectors while others have a comparative advantage in non-energy sectors. Heterogeneous abilities might represent different skills for particular tasks, which can be sector-specific. We now explore the role that this worker heterogeneity plays in our main results.

In our benchmark model, workers' abilities are distributed according to a Frechét distribution. In this subsection, we drop the heterogeneity in individual skills. As such, we consider a setup with a single labor market, such that total labor supply is fixed at 1. So the equilibrium conditions for labor are now:

$$(P_j - (1-\eta_j)P_j^E)Y_j = wL_j,$$
$$\sum_{j=1}^{18} L_j = 1.$$

Table 5 reports the results of introducing a carbon tax aimed at reducing emission by 26%. Compared to the benchmark results, a smaller tax is required in each scenario to achieve the 26% reduction in emissions. This happens because labor reallocation is less costly in the environment with homogeneous workers relative to the benchmark case. With "less (labor) friction" in this economy, a smaller tax is needed to achieve the same target (47.3% tax vs. 69.3% in the benchmark wasteful spending scenario in the United States), and therefore less adverse economic effects as witnessed by the smaller drops in GDP (0.3% vs. 0.4% in the benchmark) and consumption (2.8% vs. 3.5% the benchmark). Similar insights carry through to the other tax revenue schemes and the Chinese case.

Table 5: Macroeconomic Effects of Targeting a 26% Reduction in Emissions with Homogeneous Workers

Panel A: United States	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Cons. (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	53.7	-	2.4	-0.3	-2.8	-26.6	26.0
Green Subsidy	40.0	77.6	1.5	-0.6	-0.6	-26.8	-26.0
Useful Spending	54.8	1.5	2.6	-0.4	-0.4	-26.6	-26.0
Household Transfers	53.7	-	2.4	-0.3	-0.3	-26.6	-26.0
Panel B: China	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Cons. (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	47.3	-	10.2	-1.5	-11.5	-26.6	-26.0
Green Subsidy	43.4	103.4	8.1	-3.7	-3.7	-27.2	-26.0
Useful Spending	59.8	6.2	18.2	-2.1	-2.1	-26.9	-26.0
Household Transfers	47.3	-	10.2	-1.5	-1.5	-26.6	-26.0

In regard to welfare, with homogeneous workers, welfare losses are equalized among all individuals by construction. All individuals witness a decline of 2.8% in welfare in the United States under the wasteful spending scenario. This is in contrast to our benchmark case, where heterogeneity is featured and we classify workers into six different groups (see Table 2). The losses in consumption in the benchmark vary from -18.4% (dirty energy sectors, stayers) to +11.7% (green energy sectors, stayers). Consequently, modeling worker heterogeneity is key, both to understand the distributional effects and to correctly quantify the aggregate effects of climate change mitigation policies. The distributional impacts of carbon taxes can strongly influence their political acceptability. It is therefore critical to identify who are the biggest losers after the introduction of a carbon tax.

7 Concluding Remarks

This paper quantifies the aggregate and distributional effects of climate change mitigation policies within and across countries. Our results for the United States show that achieving its original Paris Agreement goal of reducing emissions by 26% leads to, at most, a 0.8% drop in output. Applying the same climate target to China leads to a much larger loss in economic activity (-3.7%, at most). The heterogeneity in the results between the United States and China is due to varying degrees of importance of the taxed energy sectors in the production network of each economy. The differences are not due to disparity in levels of development since Brazil, also an emerging economy, loses at most 0.5% of its GDP when applying the same target. Nevertheless, regardless of the country under study, the adverse effects on GDP and welfare can be partially offset through tax rebates.

Behind these aggregate results lies significant heterogeneity at the sectoral and individual levels. The dirty energy sectors exposed to the carbon tax witness the largest drop in production, and consequently the largest labor outflow. However, by examining the skill distribution, we find that less talented workers in dirty energy production reallocate away from the taxed sectors into other sectors in the economy. Meanwhile, workers with a comparative advantage in dirty energy production remain and end up bearing most of the cost from the lower wages. These workers, however, constitute a small fraction of total employment. Workers in the green energy sector, on the other hand, benefit from a carbon tax.

We present a detailed inspection of the main mechanism of our model environment by dissecting the roles played by substitutability between energy and non-energy goods, input-output linkages and worker heterogeneity. All three features are important for our understanding on how a carbon tax impacts the economy. Relaxing each assumption affects both the quantitative results and the underlying mechanisms. For instance, in our benchmark model in which energy is essential for production, the carbon tax reduces the size of dirty energy sectors and expands the green energy sector. With a higher elasticity of substitution between energy and non-energy goods, the reduction in the dirty energy sectors is not followed by a rise in the green energy sector.

This paper therefore provides a rich unified framework integrating worker heterogeneity within a multi-sectoral general equilibrium model with input-output linkages. This framework allows us to quantify in detail the aggregate and distributional effects of distinct climate change mitigation policies. In the future, this framework can be applied to assess the effects of different policies, such as revised nationally determined contributions of the Paris Agreement, or the effects of these policies for other regions of the world.

References

Acemoglu, D., Carvalho, V. M., Ozdaglar, A., and Tahbaz-Salehi, A. (2012). The network origins of aggregate fluctuations. *Econometrica*, 80(5):1977–2016.

Atalay, E. (2017). How important are sectoral shocks? *American Economic Journal: Macroeconomics*, 9(4):254–80.

Aubert, D. and Chiroleu-Assouline, M. (2019). Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82.

Baqaee, D. R. and Farhi, E. (2020). Productivity and misallocation in general equilibrium. *The Quarterly Journal of Economics*, 135(1):105–163.

Barrage, L. (2020). Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy. *The Review of Economic Studies*, 87(1):1–39.

Bosetti, V. and Maffezzoli, M. (2013). Taxing carbon under market incompleteness.

Castellanos, K. A. and Heutel, G. (2019). Unemployment, labor mobility, and climate policy. Technical report, National Bureau of Economic Research.

Chateau, J., Bibas, R., and Lanzi, E. (2018). Impacts of green growth policies on labour markets and wage income distribution: a general equilibrium application to climate and energy policies.

Dietz, S. and Stern, N. (2015). Endogenous growth, convexity of damage and climate risk: how nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, 125(583):574–620.

Dissou, Y. and Siddiqui, M. S. (2014). Can carbon taxes be progressive? *Energy Economics*, 42:88–100.

Eaton, J. and Kortum, S. (2002). Technology, geography, and trade. *Econometrica*, 70(5):1741–1779.

Fried, S. and Lagakos, D. (2020). Electricity and firm productivity: A general-equilibrium approach. *NBER Working Paper No. 27081*.

Fried, S., Novan, K. M., and Peterman, W. (2022). Understanding the inequality and welfare effects of carbon tax policies.

Garg, A., Kazunari, K., and Pulles, T. (2006). Ipcc guidelines for national greenhouse gas inventories. volume 2: energy. chapter 1: introduction. *Available from Intergovernmental Panel on Climate Change website: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html*.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Goulder, L. H., Hafstead, M. A., Kim, G., and Long, X. (2019). Impacts of a carbon tax across us household income groups: What are the equity-efficiency trade-offs? *Journal of Public Economics*, 175:44–64.

Grainger, C. A. and Kolstad, C. D. (2010). Who pays a price on carbon? *Environmental and Resource Economics*, 46(3):359–376.

Hafstead, M. A. and Williams III, R. C. (2018). Unemployment and environmental regulation in general equilibrium. *Journal of Public Economics*, 160:50–65.

Hassler, J., Krusell, P., and Olovsson, C. (2012). Energy-saving technical change. *NBER Working Paper No. 18456*.

Hassler, J., Krusell, P., and Olovsson, C. (2018). The consequences of uncertainty: climate sensitivity and economic sensitivity to the climate. *Annual Review of Economics*, 10:189–205.

Hsieh, C.-T., Hurst, E., Jones, C. I., and Klenow, P. J. (2019). The allocation of talent and us economic growth. *Econometrica*, 87(5):1439–1474.

Jones, C. I. (2011). Misallocation, economic growth, and input-output economics. Technical report, National bureau of economic research.

King, M., Tarbush, B., and Teytelboym, A. (2019). Targeted carbon tax reforms. *European Economic Review*, 119:526–547.

Minnesota Population Center. (2019). Integrated Public Use Microdata Series, International: Version 7.2. [Dataset]. Minneapolis, MN: IPUMS.

Nordhaus, W. D. (1994). *Managing the global commons: the economics of climate change*, volume 31. MIT press Cambridge, MA.

Ramstein, C., Dominioni, G., Ettehad, S., Lam, L., Quant, M., Zhang, J., Mark, L., Nierop, S., Berg, T., Leuschner, P., et al. (2019). *State and Trends of Carbon Pricing 2019*. The World Bank.

Roy, A. D. (1951). Some thoughts on the distribution of earnings. *Oxford Economic Papers*, 3(2):135–146.

Stern, D. I. (2012). Interfuel substitution: a meta-analysis. *Journal of Economic Surveys*, 26(2):307–331.

Tol, R. S. (2018). The economic impacts of climate change. *Review of Environmental Economics and Policy*, 12(1):4–25.

Appendix

A Appendix – Theory

A.1 Proposition 1 - Occupational Shares

The fraction of workers choosing to work in sector j is denoted by q_j. For simplicity, we present below the fraction of people who choose to work in sector 1, and this calculation procedure can be replicated to all sectors without loss of generality (WLOG).

$$\begin{aligned} q_1 &= Pr(w_1 z_1 > w_j z_j \ \ \forall \ \ j \neq 1) \\ &= \mathbb{E}\left[Pr(w_1 z_1 > w_j z_j \ \ \forall \ \ j \neq 1 \ \mid \ z_1)\right] \\ &= \mathbb{E}\left[Pr(z_j < \frac{w_1 z_1}{w_j} \ \ \forall \ \ j \neq 1 \ \mid \ z_1)\right] \\ &= \int f(z_1)F(\beta_2 z_1)F(\beta_3 z_1)..F(\beta_j z_1)..F(\beta_J z_1)dz_1 \ \ where \ \ \beta_j = \frac{w_1}{w_j} \end{aligned}$$

This is as if we are taking the derivative with respect to the first argument of the new joint distribution $F(z_1, \beta_2 z_1, ..., \beta_J z_1)$, so q_1 is now:

$$\begin{aligned} q_1 &= \int_0^\infty F_1(z_1, \beta_2 z_1, \beta_3 z_1, .., \beta_j z_1, .., \beta_J z_1)dz_1 \\ &= \int_0^\infty F_1(z, \beta_2 z, \beta_3 z, .., \beta_j z, .., \beta_J z)dz \end{aligned}$$

We know that $F(z_1, z_2, ..z_J) = \exp\Big(-\sum_{j=1}^J z_j^{-\lambda}\Big)$, so:

$$F(z, \beta_2 z, ..., \beta_J z) = \exp\Big(-\sum_{j=1}^J \beta_j^{-\lambda} z^{-\lambda}\Big)$$

$$F_1(z, \beta_2 z, ..., \beta_J z) = (-)(-\lambda)z^{-\lambda-1}\exp\Big(-\sum_{j=1}^J \beta_j^{-\lambda} z^{-\lambda}\Big)$$

$$F_1(z, \beta_2 z, ..., \beta_J z) = \lambda z^{-\lambda-1}\exp\Big(-\sum_{j=1}^J \beta_j^{-\lambda} z^{-\lambda}\Big)$$

q_1 is now:

$$
\begin{aligned}
q_1 &= \int_0^\infty \lambda z^{-\lambda-1} \exp\Big(- \sum_{j=1}^{J} \beta_j^{-\lambda} z^{-\lambda}\Big) dz \\
&= \int_0^\infty \lambda z^{-\lambda-1} \exp\Big(- z^{-\lambda}\bar{\beta}\Big) dz, \text{ where } \bar{\beta} = \sum_{j=1}^{J} \beta_j^{-\lambda} \\
&= \int_0^\infty \lambda z^{-\lambda-1} \exp\Big(- \Big[(\bar{\beta})^{\frac{-1}{\lambda}} z\Big]^{-\lambda}\Big) dz
\end{aligned}
$$

We proceed with integration by change of variables, let $z' = (\bar{\beta})^{\frac{-1}{\lambda}} z$, then $dz' = \big(\bar{\beta}\big)^{\frac{-1}{\lambda}} dz$, so if we replace z with z':

$$
\begin{aligned}
q_1 &= \int_0^\infty \lambda \Big[\big(\bar{\beta}\big)^{\frac{1}{\lambda}} z'\Big]^{-\lambda-1} \exp\Big(- (z')^{-\lambda}\Big) \big(\bar{\beta}\big)^{\frac{1}{\lambda}} dz' \\
&= \big(\bar{\beta}\big)^{-1} \int_0^\infty \lambda (z')^{-\lambda-1} \exp\Big(- (z')^{-\lambda}\Big) dz' \\
&= \big(\bar{\beta}\big)^{-1} \int_0^\infty dF(z') \\
&= \big(\bar{\beta}\big)^{-1} \\
&= \frac{1}{\bar{\beta}} \\
&= \frac{1}{\sum_{j=1}^{J} \Big(\frac{w_1^{-\lambda}}{w_j^{-\lambda}}\Big)} \\
&= \frac{w_1^{\lambda}}{\sum_{j=1}^{J} w_j^{\lambda}}
\end{aligned}
$$

More generally:

$$
q_j = \frac{w_j^{\lambda}}{\sum_{k=1}^{J} w_k^{\lambda}} \text{ for } j \in \{1, ..., J\}
$$

q_j therefore represents the equilibrium share of workers in sector j.

A.2 Proposition 2: Effective Labor

Following Hsieh et al. (2019), the total efficiency units in each occupation (including both talent) is number of workers in every sector, given by q_j, multiplied by average individual productivity given by $\mathbb{E}[z_j]$.

Total efficiency units of labor supplied to sector j is:

$$\begin{aligned} L_j^e &= E[z_j| \text{ worker chooses sector j}] \\ &= E[z_j | w_j z_j > w_s z_s \ \ \forall \ \ s \neq j] \\ &= E[z_j | z_j > \frac{w_s z_s}{w_j} \ \ \forall \ \ s \neq j] \end{aligned}$$

For simplicity, we present below the expected value of effective labor supply in sector 1 (WLOG):

$$\begin{aligned} L_1^e &= \int_0^\infty z_1 F_1(z_1, \beta_2 z_1, .., \beta_J z_1) dz_1 \\ &= \int_0^\infty z \lambda z^{-\lambda-1} \exp(-z^{-\lambda} \bar{\beta}) dz \\ &= \int_0^\infty \lambda z^{-\lambda} \exp(-[z(\bar{\beta})^{\frac{-1}{\lambda}}]^{-\lambda}) dz \end{aligned}$$

We proceed with integration by change of variables, let $y = [z(\bar{\beta})^{\frac{-1}{\lambda}}]^{-\lambda}$ then $z = y^{\frac{-1}{\lambda}}(\bar{\beta})^{\frac{1}{\lambda}}$, so:

$$\begin{aligned} dy &= -\lambda \bar{\beta}^{\frac{-1}{\lambda}} [z(\bar{\beta})^{\frac{-1}{\lambda}}]^{-\lambda-1} dz \\ dz &= \frac{-dy}{\lambda \bar{\beta}^{\frac{-1}{\lambda}} [z(\bar{\beta})^{\frac{-1}{\lambda}}]^{-\lambda-1}} \\ dz &= \frac{-dy}{\lambda \bar{\beta}^{\frac{-1}{\lambda}} ([z(\bar{\beta})^{\frac{-1}{\lambda}}]^{-\lambda})^{\frac{-\lambda-1}{-\lambda}}} \\ dz &= \frac{-dy}{\lambda \bar{\beta}^{\frac{-1}{\lambda}} y^{\frac{\lambda+1}{\lambda}}} \end{aligned}$$

By plugging the new variable into the labor supply equation, we get:

$$\begin{aligned}
L_1^e &= \int_{\infty}^{0} -\lambda[y^{\frac{-1}{\lambda}}(\bar{\beta})^{\frac{1}{\lambda}}]^{-\lambda}\exp(-y)\frac{dx}{\lambda(\bar{\beta})^{\frac{-1}{\lambda}}y^{\frac{\lambda+1}{\lambda}}} \\
&= -\int_{\infty}^{0} y^{1-\frac{\lambda+1}{\lambda}}(\bar{\beta})^{-1+\frac{1}{\lambda}}\exp(-y)dy \\
&= \int_{0}^{\infty} y^{\frac{-1}{\lambda}}(\bar{\beta})^{\frac{1}{\lambda}-1}\exp(-y)dy \\
&= (\bar{\beta})^{\frac{1}{\lambda}-1}\int_{0}^{\infty} y^{(1-\frac{1}{\lambda})-1}\exp(-y)dy \\
&= (\bar{\beta})^{\frac{1}{\lambda}-1}\Gamma(1-\frac{1}{\lambda}) \\
&= \left(\frac{1}{q_1}\right)^{\frac{1}{\lambda}-1}\Gamma(1-\frac{1}{\lambda}) \\
&= q_1^{1-\frac{1}{\lambda}}\Gamma(1-\frac{1}{\lambda})
\end{aligned}$$

More generally:

$$L_j^e = q_j^{1-\frac{1}{\lambda}}\Gamma(1-\frac{1}{\lambda}) \text{ for } j \in \{1, ..., J\}$$

L_j^e can also be interpreted as the sum of all individual productivities (efficiency units of labor) employed in sector j, where average individual productivity in sector j is $q_j^{-\frac{1}{\lambda}}\Gamma(1-\frac{1}{\lambda})$.

B Details on Calibration

Table B1 lists all the model's parameters and classifies them according to the required calibration procedure.

The calibration relies on two major data sources: World Input Output Database (WIOD) and the Integrated Public Use Micro-data Series (IPUMS). Both databases present the sectors according to the International Standard Industrial Classification (ISIC) of all economic activities developed by the United Nations. However, IPUMS conforms to a top level aggregation of 15 intermediate goods sectors, to which we will refer when aggregating the data of the 56 sectors in the WIOD input-output tables. In order to do so, we first collapse the 56 sectors in the WIOD tables into the top-level ISIC Rev. 4 classification as presented in the first column of Table B2. Second, we collapse the 21 resulting sectors into the 15 sectors

Table B1: List of Parameters

	Externally Calibrated Parameters	Data Source
J	number of sectors	WIOD data
α_j	labor shares	WIOD data
ν_{jk}	input-output shares	WIOD data
$g_{\text{oil}} = 84.6\%$	carbon intensity of oil	Golosov et al. (2014)
$g_{\text{coal}} = 71.6\%$	carbon intensity of coal	Golosov et al. (2014)
$g_{\text{natural gas}} = 73.4\%$	carbon intensity of natural gas	IPCC (2006)
$g_{\text{green}} = 0\%$	carbon intensity of green	Golosov et al. (2014)
	Internally Calibrated Parameters	**Moment(s) Targeted**
σ_j	expenditure shares in final good	Sectoral value added from WIOD data
η_j	non-energy expenditure in intermediate good	Non-energy expenditure from WIOD data
λ	Fréchet dispersion parameter	Coefficient of variation in earnings from IPUMS data

presented in IPUMS databases. Additionally, since the focus of this paper is on taxing dirty energy-producing sectors in the economy, we create an aggregate energy sector by merging 'Mining and Quarrying' and 'Electricity' sectors; the sectoral breakdown is reported in the second column of Table B2. Third, we split the aggregate energy sector into four energy producing sectors: oil, coal, natural gas and green according to the WIOD environmental accounts on gross energy use by sector and energy commodity. As such, we end up with 18 intermediate goods sectors ($J = 18$), which are presented in the third column of Table B2.

Table B2: Intermediate Goods Sectors

	Sectors (J=21) ISIC Rev4: Top-level Aggregation		Sectors (J=15) IPUMS Aggregation		Sectors (J=18) Authors' Aggregation
A	Agriculture, hunting, forestry and fishing	A	Agriculture, hunting, forestry and fishing	1.	Agriculture, hunting, forestry and fishing
B	Mining and Quarrying	C	Manufacturing	2.	Manufacturing
C	Manufacturing	E	Water supply	3.	Water supply
D	Electricity, gas, steam and air conditioning supply	F	Construction	4.	Construction
E	Water supply; sewerage, waste management and remediation activities	G	Wholesale and retail trade	5.	Wholesale and retail trade
F	Construction	H,J	Transport, storage and communications	6.	Transport, storage and communications
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	I	Accommodation and food service activities	7.	Accommodation and food service activities
H	Transportation and storage	K	Financial and insurance activities	8.	Financial and insurance activities
I	Accommodation and food service activities	L,M,N	Real estate, renting and business activities	9.	Real estate, renting and business activities
J	Information and communication	O	Public administration and defence	10.	Public administration and defence
K	Financial and insurance activities	P	Education	11.	Education
L	Real estate activities	Q	Health and social work	12.	Health and social work
M	Professional, scientific and technical activities	R,S,U	Arts and other service activities	13.	Arts and other service activities
N	Administrative and support service activities	T	Private household services	14.	Private household services
O	Public administration and defence; compulsory social security	B,D	Total Energy	15.	Oil Energy Production
P	Education			16.	Coal Energy Production
Q	Human health and social work activities			17.	Natural Gas Energy Production
R	Arts, entertainment and recreation			18.	Green Energy Production
S	Other service activities				
T	Activities of households as employers; undifferentiated goods - and services-producing activities of households for own use				
U	Activities of extraterritorial organizations and bodies				

Parameters α_j and $\{\nu_{jk}\}$ – for the Leontief economy – and parameters β_j^L and $\{\beta_{jk}^M\}$ – for the Cobb-Douglas economy, are externally calibrated as discussed in Section 3. They are not presented in the Appendix for space purposes.

As for the internally calibrated estimates, Table B6 presents the final expenditure shares of each intermediate good alongside the value added shares of each of the intermediate good sectors in the model and in the data. We have to adjust the final expenditure shares as we collapsed the national input-output tables from open economy to closed economy. We use those final expenditure shares across all models. Value added shares in the model match exactly the data in the Cobb-Douglas world by construction, and also exactly in the Leontief and Homogenous Economy, given our exact calibration to intermediate consumption. Value added shares only deviate from the data in the Horizontal Economy. We did not re-calibrate in the Horizontal Economy setup in order not to distort the final expenditure side. Tables B7, B8 and B9 present more details on the value added shares in the four models and their correlation with the data. Table B10 presents the Fréchet Parameter and variation coefficient of wages for each country in our sample. Those λ estimates hold for the Leontief, Cobb-Douglas and Horizontal Economy setups. The Homogeneous Workers setup is akin to having $\lambda = \infty$. Finally, Tables B3, B4, B5 present the $\{\eta_j\}$ that target the non-energy expenditure shares in the Leontief, Horizontal Economy and Homogeneous Worker setups. In the Cobb-Douglas case, the intermediate expenditure shares (non-energy and energy) are given by β_{jk}^M.

Table B3: Value Added Shares in the United States

	Data	United States: Non-Energy Expenditure Shares					
		Leontief		Horizontal Economy		Homogeneous Workers	
		Model	η_j	Model	η_j	Model	η_j
1. Agriculture, hunting, forestry and fishing	98.6%	98.6%	0.971	99.1%	0.996	98.6%	0.974
2. Manufacturing	90.5%	90.3%	0.830	93.1%	0.936	90.5%	0.908
3. Water supply	98.2%	98.2%	0.988	98.5%	0.999	98.2%	0.987
4. Construction	98.9%	98.9%	0.977	99.2%	0.987	98.9%	0.985
5. Wholesale and retail trade	99.6%	99.6%	0.995	99.6%	0.994	99.6%	0.998
6. Transport, storage and communications	99.5%	99.5%	0.988	99.5%	0.993	99.5%	0.994
7. Hotels and restaurants	99.2%	99.2%	0.991	99.2%	0.994	99.2%	0.994
8. Financial services and insurance	99.9%	99.9%	0.999	99.9%	0.999	99.9%	0.999
9. Public administration and defense	98.8%	98.8%	0.988	98.8%	0.985	98.8%	0.995
10. Real estate, renting and business activities	98.8%	98.8%	0.989	98.8%	0.985	98.8%	0.995
11. Education	97.1%	97.1%	0.978	97.1%	0.982	97.1%	0.980
12. Health and social work	99.5%	99.5%	0.993	99.5%	0.993	99.5%	0.996
13. Other services activities	99.2%	99.2%	0.992	99.2%	0.994	99.2%	0.994
14. Private households services	99.4%	99.4%	0.999	99.3%	0.999	99.3%	0.997
15. Oil energy production	91.8%	91.8%	0.980	91.8%	0.972	91.8%	0.981
16. Coal energy production	88.2%	88.2%	0.955	88.2%	0.959	88.2%	0.953
17. Natural gas energy production	90.7%	90.8%	0.975	90.7%	0.975	90.7%	0.975
18. Green energy production	90.6%	90.6%	0.972	90.6%	0.969	90.6%	0.974

Table B4: Value Added Shares in China

		China					
		Non-Energy Expenditure Shares					
	Data	**Leontief**		**Horizontal Economy**		**Homogeneous Workers**	
		Model	η_j	**Model**	η_j	**Model**	η_j
1. Agriculture, hunting, forestry and fishing	99.0%	99.0%	0.998	99.0%	0.995	99.0%	0.999
2. Manufacturing	90.6%	90.6%	0.917	90.2%	0.917	90.6%	0.942
3. Water supply	89.8%	89.7%	0.954	89.5%	0.980	89.8%	0.932
4. Construction	97.6%	97.8%	0.968	97.4%	0.970	97.6%	0.976
5. Wholesale and retail trade	98.7%	98.9%	0.998	98.6%	0.992	98.7%	0.998
6. Transport, storage and communications	98.5%	98.6%	0.991	98.4%	0.986	98.5%	0.993
7. Hotels and restaurants	99.0%	99.3%	0.997	99.0%	0.996	99.0%	0.997
8. Financial services and insurance	99.7%	99.7%	1.000	99.6%	0.998	99.7%	1.000
9. Public administration and defense	99.4%	99.4%	0.999	99.4%	0.997	99.4%	0.999
10. Real estate, renting and business activities	99.0%	99.2%	0.999	99.0%	0.996	99.0%	0.999
11. Education	98.8%	98.9%	0.998	98.8%	0.994	98.8%	0.998
12. Health and social work	98.8%	98.8%	0.996	98.7%	0.995	98.8%	0.995
13. Other services activities	98.4%	98.6%	0.996	98.3%	0.995	98.4%	0.996
14. Private households services	100.0%	100.0%	1.000	100.0%	1.000	100.0%	1.000
15. Oil energy production	69.6%	70.3%	0.916	69.9%	0.872	69.6%	0.892
16. Coal energy production	60.2%	60.2%	0.731	60.2%	0.765	60.2%	0.739
17. Natural gas energy production	66.2%	66.3%	0.880	65.6%	0.913	66.2%	0.840
18. Green energy production	74.8%	74.9%	0.951	74.8%	0.892	74.8%	0.946

Table B5: Value Added Shares in Brazil

		Brazil Non-Energy Expenditure Shares					
	Data	**Leontief**		**Horizontal Economy**		**Homogeneous Workers**	
		Model	η_j	**Model**	η_j	**Model**	η_j
1. Agriculture, hunting, forestry and fishing	98.3%	97.2%	0.986	98.6%	0.992	98.3%	0.993
2. Manufacturing	92.2%	86.6%	0.811	92.2%	0.899	92.2%	0.923
3. Water supply	96.1%	94.7%	0.987	96.1%	0.989	96.1%	0.984
4. Construction	98.4%	97.4%	0.971	98.4%	0.979	98.4%	0.987
5. Wholesale and retail trade	98.8%	98.2%	0.991	98.8%	0.988	98.8%	0.996
6. Transport, storage and communications	99.5%	99.2%	0.991	99.5%	0.995	99.5%	0.996
7. Hotels and restaurants	99.2%	98.7%	0.993	99.1%	0.995	99.2%	0.995
8. Financial services and insurance	99.7%	99.6%	0.998	99.7%	0.998	99.7%	0.999
9. Public administration and defense	99.5%	99.2%	0.997	99.5%	0.995	99.5%	0.999
10. Real estate, renting and business activities	99.3%	99.0%	0.998	99.3%	0.994	99.3%	0.999
11. Education	99.2%	98.8%	0.998	99.2%	0.994	99.2%	0.999
12. Health and social work	99.4%	99.1%	0.997	99.4%	0.996	99.4%	0.998
13. Other services activities	98.4%	97.5%	0.985	98.4%	0.990	98.4%	0.990
14. Private households services	100.0%	100.0%	1.000	100.0%	1.000	100.0%	1.000
15. Oil energy production	85.6%	86.4%	0.956	85.9%	0.940	85.6%	0.948
16. Coal energy production	79.5%	82.7%	0.936	79.7%	0.978	79.5%	0.855
17. Natural gas energy production	79.7%	80.8%	0.911	79.9%	0.957	79.7%	0.866
18. Green energy production	83.1%	82.8%	0.916	83.1%	0.902	83.1%	0.925

Table B6: Intermediate Goods Sectors: Value-Added Shares and Final Expenditure Shares

Sector	Brazil VA (%)	Brazil σ_j	China VA (%)	China σ_j	United States VA (%)	United States σ_j
1. Agriculture, hunting, forestry and fishing	5.2%	0.0381	9.4%	0.0360	1.2%	0.0051
2. Manufacturing	14.6%	0.2220	30.1%	0.3293	12.4%	0.1314
3. Water supply	0.7%	0.0041	0.3%	0.0018	0.3%	0.0004
4. Construction	6.7%	0.1073	6.8%	0.2610	3.8%	0.0554
5. Wholesale and retail trade	12.4%	0.0937	9.7%	0.0478	12.2%	0.1312
6. Transport, storage and communications	8.0%	0.0566	7.2%	0.0364	9.1%	0.0788
7. Hotels and restaurants	2.4%	0.0315	1.9%	0.0209	2.8%	0.0394
8. Financial services and insurance	6.3%	0.0442	6.0%	0.0133	7.0%	0.0548
9. Public administration and defense	16.6%	0.0893	9.7%	0.0611	23.1%	0.1492
10. Real estate, renting and business activities	9.6%	0.1253	4.0%	0.0669	13.1%	0.1788
11. Education	5.5%	0.0660	3.3%	0.0501	1.1%	0.0155
12. Health and social work	4.2%	0.0596	1.8%	0.0486	7.1%	0.116
13. Other services activities	1.8%	0.0274	2.3%	0.0211	2.6%	0.0313
14. Private households services	1.1%	0.0111	0.0%	0.0000	0.1%	0.0009
15. Oil energy production	1.7%	0.0128	1.2%	0.0057	1.3%	0.0024
16. Coal energy production	0.1%	0.0000	2.8%	0.0000	0.7%	0.0073
17. Natural gas energy production	0.3%	0.0004	0.3%	0.0000	0.9%	0
18. Green energy production	2.9%	0.0109	3.2%	0.0000	1.2%	0.0021

Table B7: Value Added Shares in the United States

Sector	**Data**	**United States**			
		Model			
		Leontief	**Cobb Douglas**	**Horizontal Economy**	**Homogeneous Workers**
1. Agriculture, hunting, forestry and fishing	1.2%	1.2%	1.2%	0.5%	1.2%
2. Manufacturing	12.4%	13.1%	12.4%	12.2%	13.2%
3. Water supply	0.3%	0.3%	0.3%	0.0%	0.3%
4. Construction	3.8%	3.9%	3.8%	5.5%	3.9%
5. Wholesale and retail trade	12.2%	12.0%	12.1%	13.1%	12.0%
6. Transport, storage and communications	9.1%	9.1%	9.1%	7.8%	9.1%
7. Hotels and restaurants	2.8%	2.8%	2.8%	3.9%	2.8%
8. Financial services and insurance	7.0%	7.0%	7.0%	5.5%	7.0%
9. Public administration and defense	23.1%	22.9%	23.0%	14.8%	22.9%
10. Real estate, renting and business activities	13.1%	13.0%	13.1%	17.7%	13.0%
11. Education	1.1%	1.1%	1.1%	1.5%	1.1%
12. Health and social work	7.1%	7.1%	7.1%	11.5%	7.1%
13. Other services activities	2.6%	2.6%	2.6%	3.1%	2.6%
14. Private households services	0.1%	0.1%	0.1%	0.1%	0.1%
15. Oil energy production	1.3%	1.2%	1.3%	0.8%	1.2%
16. Coal energy production	0.7%	0.7%	0.7%	0.8%	0.7%
17. Natural gas energy production	0.9%	0.9%	1.0%	0.5%	0.9%
18. Green energy production	1.2%	1.2%	1.2%	0.7%	1.1%
Correlation between Model and Data		100.0%	100.0%	90.6%	100.0%

Table B8: Value Added Shares in China

Sector	Data	China Model: Leontief	Cobb Douglas	Horizontal Economy	Homogeneous Workers
1. Agriculture, hunting, forestry and fishing	9.4%	9.5%	9.3%	3.6%	9.5%
2. Manufacturing	30.1%	30.3%	29.8%	29.7%	30.3%
3. Water supply	0.3%	0.3%	0.3%	0.2%	0.3%
4. Construction	6.8%	6.7%	6.7%	25.4%	6.7%
5. Wholesale and retail trade	9.7%	9.7%	9.6%	4.7%	9.7%
6. Transport, storage and communications	7.2%	7.3%	7.1%	3.6%	7.3%
7. Hotels and restaurants	1.9%	1.9%	1.9%	2.1%	1.9%
8. Financial services and insurance	6.0%	6.3%	6.0%	1.3%	6.3%
9. Public administration and defense	9.7%	9.8%	9.6%	6.1%	9.8%
10. Real estate, renting and business activities	4.0%	3.9%	3.9%	6.6%	3.9%
11. Education	3.3%	3.2%	3.2%	5.0%	3.2%
12. Health and social work	1.8%	1.8%	1.8%	4.8%	1.8%
13. Other services activities	2.3%	2.3%	2.3%	2.1%	2.3%
14. Private households services	0.0%	0.0%	0.0%	0.0%	0.0%
15. Oil energy production	1.2%	0.9%	1.2%	1.1%	1.0%
16. Coal energy production	2.8%	3.0%	3.6%	2.4%	3.1%
17. Natural gas energy production	0.3%	0.4%	0.5%	0.2%	0.4%
18. Green energy production	3.2%	2.6%	3.3%	1.2%	2.7%
Correlation between Model and Data		100.0%	100.0%	77.3%	100.0%

Table B9: Value Added Shares in Brazil

Sector	**Data**	**Brazil Model**			
		Leontief	**Cobb-Douglas**	**Horizontal Economy**	**Homogeneous Workers**
1. Agriculture, hunting, forestry and fishing	5.2%	4.7%	5.2%	2.3%	5.0%
2. Manufacturing	14.6%	14.9%	14.6%	22.8%	16.1%
3. Water supply	0.7%	0.7%	0.7%	0.4%	0.7%
4. Construction	6.7%	6.7%	6.7%	10.3%	6.8%
5. Wholesale and retail trade	12.4%	11.8%	12.4%	9.2%	12.0%
6. Transport, storage and communications	8.0%	7.9%	8.0%	5.9%	7.9%
7. Hotels and restaurants	2.4%	2.4%	2.4%	3.5%	2.4%
8. Financial services and insurance	6.3%	6.3%	6.3%	4.5%	6.3%
9. Public administration and defense	16.6%	16.4%	16.6%	9.2%	16.4%
10. Real estate, renting and business activities	9.6%	9.5%	9.6%	12.2%	9.6%
11. Education	5.5%	5.4%	5.5%	6.4%	5.5%
12. Health and social work	4.2%	4.1%	4.2%	5.8%	4.1%
13. Other services activities	1.8%	1.8%	1.8%	2.7%	1.8%
14. Private households services	1.1%	1.1%	1.1%	1.1%	1.1%
15. Oil energy production	1.7%	2.0%	1.7%	1.3%	1.5%
16. Coal energy production	0.1%	0.1%	0.1%	0.1%	0.1%
17. Natural gas energy production	0.3%	0.4%	0.3%	0.3%	0.3%
18. Green energy production	2.9%	3.8%	2.9%	2.5%	2.6%
Correlation between Model and Data		99.8%	100.0%	82.8%	99.7%

Table B10: Fréchet Parameter and Variation Coefficient of Wages by Country

Country	Data Sample Size	Data Estimate of Variation Coefficient	Model Estimate of Variation Coefficient	Fréchet Parameter λ
Brazil	8,241,143	6.37	6.37	2.10
China	24,915	0.91	0.91	2.58
United States	1,488,316	1.41	1.41	2.39

Table B11: Untargeted Sectoral Labor Shares by Country

Sector	**Brazil**		**China**		**United States**	
	LS Data (%)	LS Model (%)	LS Data (%)	LS Model (%)	LS Data (%)	LS Model (%)
1. Agriculture, hunting, forestry and fishing	10.2	4.7	23.8	9.5	1.0	1.2
2. Manufacturing	11.9	14.9	19.6	30.3	8.7	13.1
3. Water supply	0.5	0.7	0.0	0.3	0.3	0.3
4. Construction	9.6	6.7	8.4	6.7	4.3	3.9
5. Wholesale and retail trade	16.8	11.8	11.2	9.7	15.1	12.0
6. Transport, storage and communications	5.3	7.9	3.9	7.3	7.1	9.1
7. Hotels and restaurants	4.6	2.4	2.6	1.9	8.7	2.8
8. Financial services and insurance	1.3	6.3	2.0	6.3	4.0	7.0
9. Public administration and defense	9.3	16.4	3.2	9.8	14.6	22.9
10. Real estate, renting and business activities	5.9	9.5	5.4	3.9	16.7	13.0
11. Education	7.0	5.4	5.3	3.2	2.3	1.1
12. Health and social work	4.4	4.1	3.0	1.8	12.5	7.1
13. Other services activities	5.6	1.8	8.9	2.3	3.8	2.6
14. Private households services	7.1	1.1	0.0	0.0	0.2	0.1
15. Oil energy production	0.2	2.0	0.4	0.9	0.3	1.2
16. Coal energy production	0.0	0.1	1.4	3.0	0.2	0.7
17. Natural gas energy production	0.0	0.4	0.1	0.4	0.2	0.9
18. Green energy production	0.3	3.8	0.7	2.6	0.3	1.2
Model Fit (Correlation between actual and model LS series)	69.7%		71.7%		84.8%	

Table B12: Data Sources by Country

Country	Data	Year	Source
Brazil	Input Output Table	2014	WIOD
	Environmental Accounts to get energy input mix by sector	2009	WIOD
	CO_2 Emissions	2009	WIOD
	Sectoral Labor Shares	2014	WIOD
	Sectoral Labor Compensation	2014	WIOD
	Data on Income Earned	2010	IPUMS
	Total Labor Force Participation Rate (%)	2019	WDI
China	Input Output Table	2014	WIOD
	Environmental Accounts to get energy input mix by sector	2009	WIOD
	CO_2 Emissions	2009	WIOD
	Sectoral Labor Shares	2014	WIOD
	Sectoral Labor Compensation	2014	WIOD
	Data on Income Earned	2013	CHIP
	Total Labor Force Participation Rate (%)	2019	WDI
United States	Input Output Table	2014	WIOD
	Environmental Accounts to get energy input mix by sector	2009	WIOD
	CO_2 Emissions	2009	WIOD
	Sectoral Labor Shares	2014	WIOD
	Sectoral Labor Compensation	2014	WIOD
	Data on Income Earned	2015	IPUMS
	Total Labor Force Participation Rate (%)	2019	WDI

C Additional Results

C.1 Robustness to λ

In Table 1, we present the results of the United States for $\lambda = 2.39$ as presented in Table B10. In what follows, we present robustness of the main result by setting λ to be smaller by 10% ($\lambda = 2.15$) and larger by 10% ($\lambda = 2.63$). We find that the results are robust on both accounts.

Table C13: Macroeconomic Effects of Targeting a 26% Reduction in Emissions

Panel A: United States ($\lambda = 2.15$)							
	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Consumption (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	65.3	-	3.0	- 0.4	- 3.4	- 26.6	- 26.0
Green Subsidy	53.3	103.4	1.9	- 0.8	- 0.8	- 26.8	- 26.0
Useful Spending	66.7	1.8	3.2	- 0.4	- 0.4	- 26.6	- 26.0
Household Transfers	65.3	-	3.0	- 0.4	- 0.4	- 26.6	- 26.0
Panel B: United States ($\lambda = 2.63$)							
	Tax (%)	Subsidy (%)	Tax Revenue (% of GDP)	GDP (% change)	Consumption (% change)	Fossil Emissions (% change)	Total Emissions (% change)
Wasteful Spending	62.7	-	3.2	- 0.5	- 3.6	- 26.5	- 26.0
Green Subsidy	50.4	96.6	2.1	- 0.8	- 0.8	- 26.8	- 26.0
Useful Spending	64.3	2.0	3.4	- 0.5	- 0.5	- 26.6	- 26.0
Household Transfers	62.7	-	3.2	- 0.5	- 0.5	- 26.5	- 26.0

C.2 Detailed Results on Emissions

Table C14: Percentage Change in CO_2 Emissions by Source, Country and Recycling Scheme

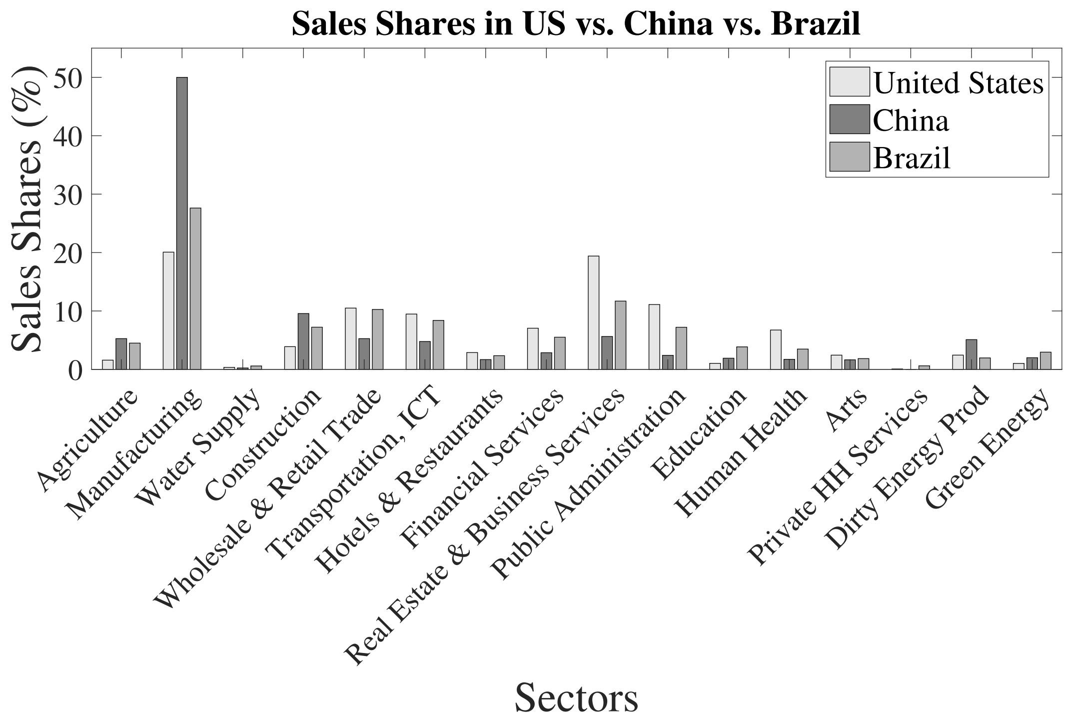
	Carbon Tax (%)	%Δ Oil Emissions	%Δ Coal Emissions	%Δ Natural Gas Emissions	%Δ Green Emissions	%Δ Non-energy Emissions	%Δ Fossil Fuel Emissions	%Δ Total Emissions
United States								
Wasteful Spending	63.9	-25.8	-32.9	-18.2	-	-8.2	-26.6	-26.0
Green Subsidy	51.7	-27.8	-27.8	-23.2	-	-1.3	-26.8	-26.0
Useful Spending	65.4	-25.8	-33.6	-17.3	-	-6.3	-26.6	-26.0
Household Transfers	63.9	-25.8	-32.9	-18.2	-	-8.2	-26.6	-26.0
China								
Wasteful Spending	49.6	-28.1	-26.4	-25.1	-	-15.9	-26.6	-26.0
Green Subsidy	46.4	-31.9	-26.2	-29.5	-	-7.0	-27.2	-26.0
Useful Spending	62.0	-32.3	-26.0	-25.1	-	-11.2	-26.9	-26.0
Household Transfers	49.6	-28.1	-26.4	-25.1	-	-15.9	-26.6	-26.0
Brazil								
Wasteful Spending	52.1	-27.8	-25.4	-26.0	-	-3.3	-27.4	-26.0
Green Subsidy	46.6	-27.5	-28.2	-28.1	-	0.0	-27.6	-26.0
Useful Spending	52.8	-28.0	-24.9	-25.6	-	-1.5	-27.5	-26.0
Household Transfers	52.1	-27.8	-25.4	-26.0	-	-3.3	-27.4	-26.0

C.3 More Economic Facts

Table C15: Sectoral Breakdown of Output, VA, Intermediate Consumption and Labor Share by Country

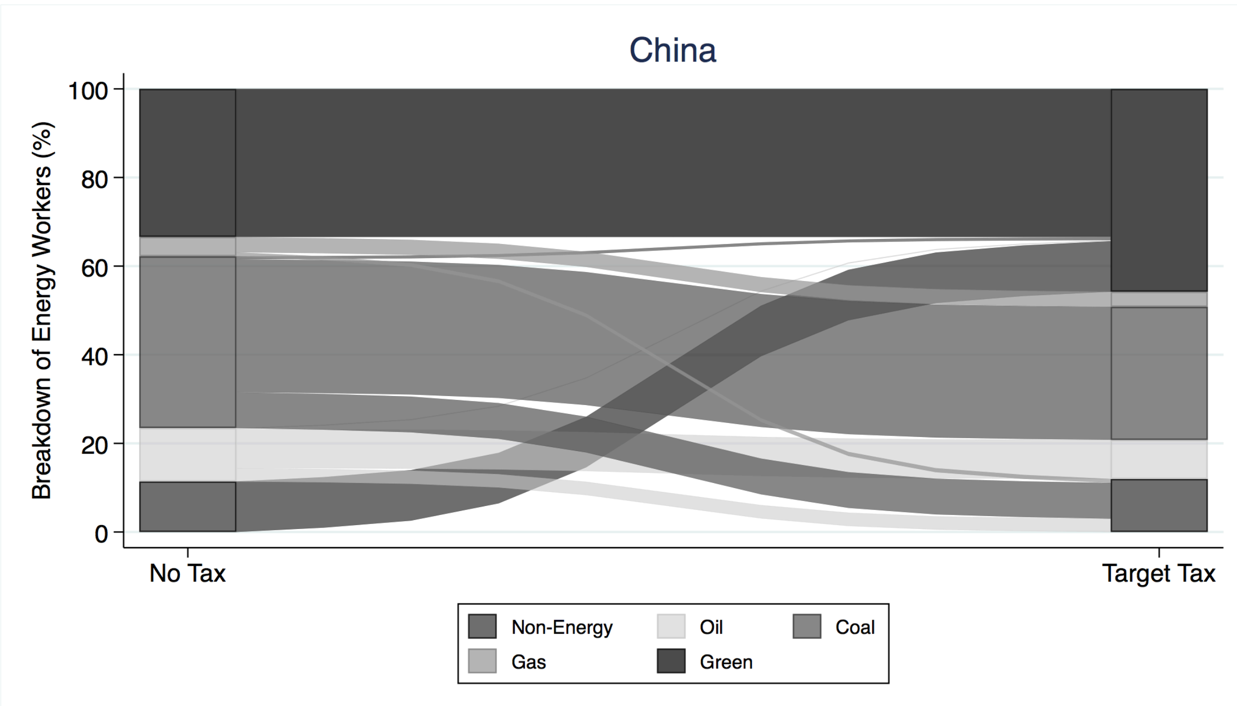
	Brazil				**China**				**United States**			
	Sales	**VA**	**Int. Cons.**	**LS**	**Sales**	**VA**	**Int. Cons.**	**LS**	**Sales**	**VA**	**Int. Cons.**	**LS**
1. Agriculture, hunting, forestry and fishing	4.5%	5.2%	3.7%	10.2%	5.3%	9.4%	3.2%	23.8%	1.6%	1.2%	2.0%	1.0%
2. Manufacturing	27.6%	14.6%	43.6%	11.9%	50.0%	30.1%	59.7%	19.6%	20.1%	12.4%	29.9%	8.7%
3. Water supply	0.6%	0.7%	0.4%	0.5%	0.2%	0.3%	0.2%	0.0%	0.3%	0.3%	0.4%	0.3%
4. Construction	7.2%	6.7%	7.8%	9.6%	9.6%	6.8%	10.9%	8.4%	3.9%	3.8%	4.0%	4.3%
5. Wholesale and retail trade	10.3%	12.4%	7.6%	16.8%	5.3%	9.7%	3.1%	11.2%	10.5%	12.2%	8.4%	15.1%
6. Transport, storage and communications	8.4%	8.0%	8.8%	5.3%	4.8%	7.2%	3.6%	3.9%	9.5%	9.1%	9.9%	7.1%
7. Hotels and restaurants	2.3%	2.4%	2.3%	4.6%	1.7%	1.9%	1.6%	2.6%	2.9%	2.8%	3.0%	8.7%
8. Financial services and insurance	5.5%	6.3%	4.5%	1.3%	2.9%	6.0%	1.3%	2.0%	7.0%	7.0%	7.1%	4.0%
9. Public administration and defense	11.7%	16.6%	5.7%	9.3%	5.6%	9.7%	3.7%	3.2%	19.4%	23.1%	14.7%	14.6%
10. Real estate, renting and business activities	7.2%	9.6%	4.2%	5.9%	2.4%	4.0%	1.6%	5.4%	11.1%	13.1%	8.5%	16.7%
11. Education	3.9%	5.5%	1.8%	7.0%	1.9%	3.3%	1.2%	5.3%	1.0%	1.1%	0.9%	2.3%
12. Health and social work	3.5%	4.2%	2.6%	4.4%	1.7%	1.8%	1.7%	3.0%	6.7%	7.1%	6.3%	12.5%
13. Other services activities	1.8%	1.8%	1.9%	5.6%	1.6%	2.3%	1.3%	8.9%	2.4%	2.6%	2.3%	3.8%
14. Private households services	0.6%	1.1%	0.0%	7.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.2%
15. Oil energy production	1.5%	1.7%	1.3%	0.2%	1.0%	1.2%	0.8%	0.4%	1.0%	1.3%	0.6%	0.3%
16. Coal energy production	0.1%	0.1%	0.1%	0.0%	3.8%	2.8%	4.3%	1.4%	0.7%	0.7%	0.6%	0.2%
17. Natural gas energy production	0.4%	0.3%	0.4%	0.0%	0.3%	0.3%	0.3%	0.1%	0.8%	0.9%	0.5%	0.2%
18. Green energy production	2.9%	2.9%	3.0%	0.3%	2.0%	3.2%	1.4%	0.7%	1.0%	1.2%	0.7%	0.3%
Sum of total dirty energy production shares	2.0%	2.0%	1.9%	0.2%	5.1%	4.4%	5.4%	1.9%	2.4%	3.0%	1.8%	0.6%

Figure C1: Sectoral Sales Shares in the United States vs. China vs. Brazil



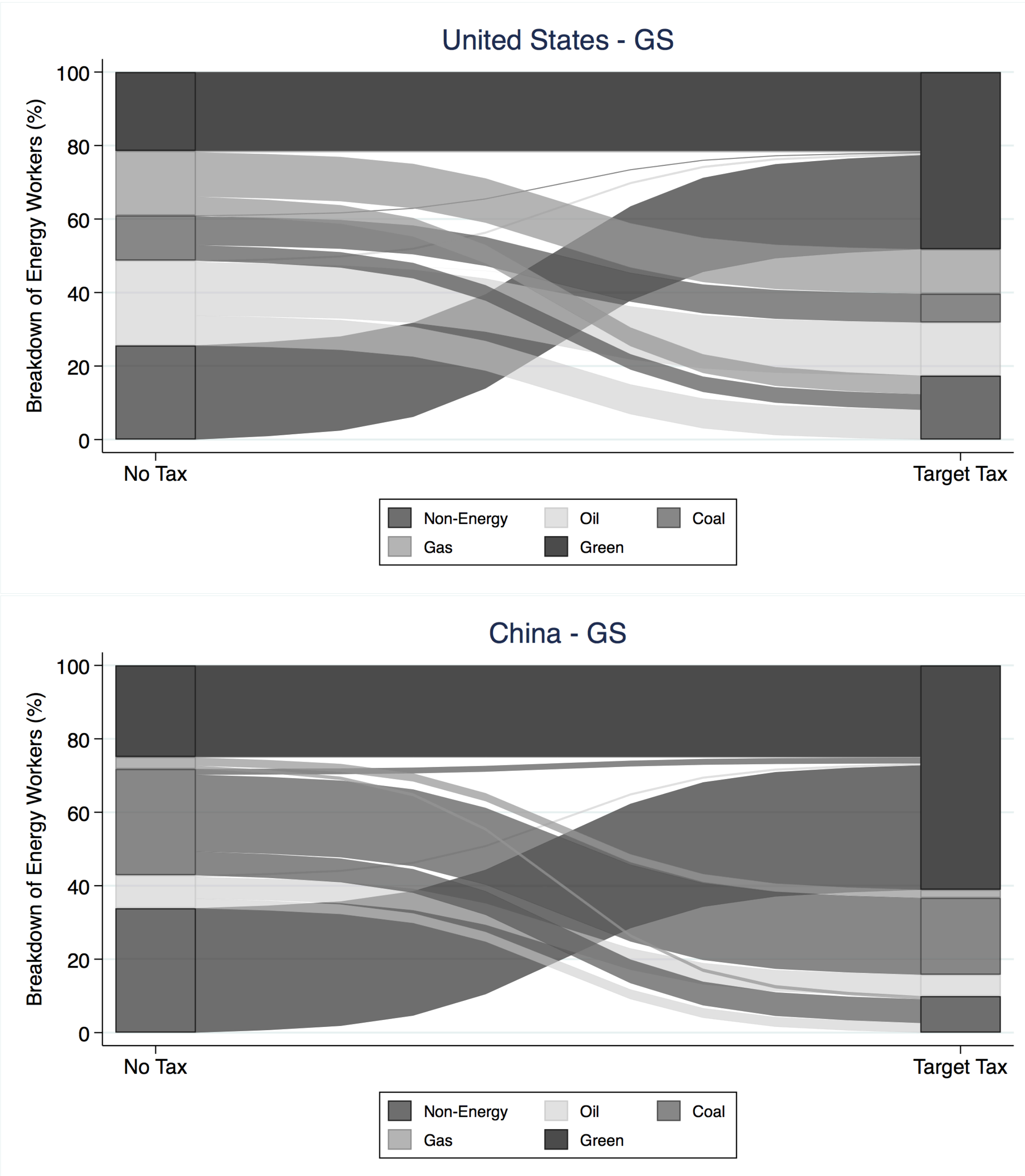
C.4 Worker Reallocation

Figure C2: Reallocation of Dirty Energy Workers under Wasteful Spending



Note: This figure only reports the mass of workers switching into and out of the energy sectors for scaling purposes since workers in the non-energy sectors with and without the carbon tax constitute 93% of the labor force.

Figure C3: Reallocation of Dirty Energy Workers under Green Subsidy



Note: This figure only reports the mass of workers switching into and out of the energy sectors for scaling purposes since workers in the non-energy sectors with and without the carbon tax constitute 96% and 93% of the labor force in the United States and China, respectively.

C.5 Sectoral Production

Table C16: Sectoral Changes in Production Qty (%) Upon Reducing Emissions by 26% in US.

	United States					
	Wasteful Spending		**Green Subsidy**		**Useful Spending**	
	Leontief %Change	Cobb Douglas %Change	Leontief %Change	Cobb Douglas %Change	Leontief %Change	Cobb Douglas %Change
Agriculture, forestry and fishing	-5.7	-0.6	-1.7	-0.4	-2.6	1.0
Manufacturing	-7.9	-2.6	-2.2	-1.1	-5.9	-1.4
Water Supply; sewerage, waste management and remediation activities	-3.1	-0.9	-0.7	-0.4	-0.3	0.4
Construction	-1.0	-0.4	-0.8	-0.6	-0.1	0.0
Wholesale and retail trade; repair of motor vehicles and motorcycles	0.2	0.3	-0.3	-0.2	1.0	0.7
Transportation and storage; Information and communication	-0.8	-0.2	-0.5	-0.4	1.0	0.6
Hotels and restaurants	-0.2	0.0	-0.4	-0.2	0.8	0.4
Financial services and insurance	0.8	0.4	-0.1	-0.1	2.7	1.2
Real estate and business services	-0.3	0.1	-0.3	-0.1	1.1	0.6
Public administration and defense; compulsory social security	0.1	0.1	-0.5	-0.3	0.5	0.2
Education	0.0	0.1	0.0	0.3	0.5	0.3
Human health and social work activities	0.8	0.4	-0.3	-0.2	1.2	0.5
Arts, entertainment and recreation; Other services	0.2	0.2	-0.4	-0.2	1.1	0.6
Private household services	0.2	0.2	-0.4	-0.2	1.1	0.6
Oil Energy production	-25.8	-26.8	-27.8	-28.6	-25.8	-26.8
Coal Energy Production	-32.9	-27.5	-27.8	-25.6	-33.6	-27.8
Natural Gas Energy Production	-18.2	-24.9	-23.2	-25.1	-17.3	-24.7
Green Energy Production	26.7	-3.4	76.7	54.4	31.3	-2.4

Table C17: Sectoral Changes in Production Qty (%) Upon Reducing Emissions by 26% in China.

	China					
	Wasteful Spending		**Green Subsidy**		**Useful Spending**	
	Leontief %Change	Cobb Douglas %Change	Leontief %Change	Cobb Douglas %Change	Leontief %Change	Cobb Douglas %Change
Agriculture, forestry and fishing	-6.3	-0.3	-4.2	-1.0	-1.0	1.4
Manufacturing	-16.4	-3.4	-7.4	-2.3	-11.7	-1.0
Water Supply; sewerage, waste management and remediation activities	-16.0	-5.1	-7.6	-4.1	-13.4	-3.4
Construction	-3.3	-0.9	-4.3	-1.4	-1.1	-0.2
Wholesale and retail trade; repair of motor vehicles and motorcycles	-2.4	0.0	-2.2	-0.6	2.7	1.0
Transportation and storage; Information and communication	-5.1	-1.1	-3.7	-1.5	0.9	0.4
Hotels and restaurants	-3.6	-0.9	-3.1	-1.2	3.1	0.5
Financial services and insurance	-2.1	-1.1	-1.2	-1.2	4.2	0.0
Real estate and business services	-2.2	-0.4	-2.4	-1.0	3.6	0.7
Public administration and defense; compulsory social security	3.1	0.8	-1.6	-0.5	4.0	0.6
Education	3.2	0.8	-1.3	-0.4	4.3	0.7
Human health and social work activities	-1.0	-0.3	-3.0	-0.9	1.0	0.1
Arts, entertainment and recreation; Other services	-3.4	-0.9	-3.1	-1.3	1.7	0.2
Private household services	0.3	0.2	-1.0	-0.7	4.0	0.8
Oil Energy production	-28.1	-21.7	-31.9	-25.5	-32.3	-22.4
Coal Energy Production	-26.4	-28.7	-26.2	-27.9	-26.0	-28.7
Natural Gas Energy Production	-25.1	-22.6	-29.5	-24.8	-25.1	-22.5
Green Energy Production	20.8	-8.3	100.0	37.0	50.1	-6.7

C.6 Additional Welfare Results

Table C18: Detailed Welfare Analysis in a Cobb-Douglas World

United States	Wasteful Spending		Green Subsidy		Useful Spending		Household Transfers	
	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)
Non-energy sectors, stayers	-1.2	95.6	-0.6	94.7	0.2	95.7	0.7	95.6
Non-energy sectors, switchers	-1.1	0.1	11.7	1.0	0.3	0.1	1.6	0.1
Dirty energy sectors, stayers	-16.6	2.0	-16.5	2.0	-15.6	2.0	-15.0	2.0
Dirty energy sectors, switchers	-8.7	1.0	-7.6	1.1	-7.4	1.0	-6.2	1.0
Green energy sector, stayers	-2.3	1.2	28.7	1.2	-0.6	1.2	-0.5	1.2
Green energy sector, switchers	-1.8	0.03	-	0.0	-0.2	0.02	0.9	0.0
China	Wasteful Spending		Green Subsidy		Useful Spending		Household Transfers	
	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)
Non-energy sectors, stayers	-2.8	91.0	-1.4	89.5	-0.1	91.2	0.9	91.0
Non-energy sectors, switchers	-2.7	0.3	6.6	1.8	0.0	0.2	2.5	0.3
Dirty energy sectors, stayers	-11.2	4.2	-11.0	4.1	-9.2	4.1	-7.9	4.2
Dirty energy sectors, switchers	-7.0	1.1	-5.1	1.3	-4.5	1.2	-2.1	1.1
Green energy sector, stayers	-4.4	3.2	18.0	3.3	-1.1	3.2	-0.8	3.2
Green energy sector, switchers	-3.6	0.1	-	0.0	-0.5	0.1	1.5	0.1

Note: CE = consumption equivalents , LS = labor share in each sector.

Table C19: Detailed Welfare Analysis in a Horizontal Economy

Panel A: United States	Wasteful Spending		Green Subsidy		Useful Spending		Household Transfers	
	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)
Non-energy sectors, stayers	-1.6	96.4	-0.5	96.0	0.1	96.4	0.7	96.4
Non-energy sectors, switchers	3.0	0.8	18.1	1.2	4.8	0.8	6.2	0.8
Dirty energy sectors, stayers	-20.6	1.2	-19.9	1.2	-19.2	1.2	-18.7	1.2
Dirty energy sectors, switchers	-10.5	0.9	-8.9	0.9	-9.0	0.9	-7.6	0.9
Green energy sector, stayers	13.4	0.7	47.9	0.7	15.5	0.7	15.7	0.7
Green energy sector, switchers	-	0.0	-	0.0	-	0.0	-	0.0
Panel B: China	Wasteful Spending		Green Subsidy		Useful Spending		Household Transfers	
	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)	CE (%)	LS (%)
Non-energy sectors, stayers	-10.0	89.3	-3.1	90.1	-0.3	89.7	2.6	89.3
Non-energy sectors, switchers	-0.2	5.7	20.2	5.0	11.8	5.4	17.5	5.7
Dirty energy sectors, stayers	-28.8	2.1	-22.7	2.1	-21.1	2.1	-18.5	2.1
Dirty energy sectors, switchers	-18.5	1.6	-9.0	1.6	-9.4	1.6	-2.4	1.6
Green energy sector, stayers	22.9	1.2	74.4	1.2	39.6	1.2	35.7	1.2
Green energy sector, switchers	-	0.0	-	0.0	-	0.0	-	0.0

Note: CE = consumption equivalents , LS = labor share in each sector.