STAFF REPORTS

NO. 1053
FEBRUARY 2023

REVISED
NOVEMBER 2025

Is the Green Transition Inflationary?

Marco Del Negro | Julian di Giovanni | Keshav Dogra

FEDERAL RESERVE BANK *of* NEW YORK

Is the Green Transition Inflationary?
Marco Del Negro, Julian di Giovanni, and Keshav Dogra
Federal Reserve Bank of New York Staff Reports, no. 1053
February 2023; revised November 2025
JEL classification: E12, E31, E52, Q54

Abstract

We develop a multisector New Keynesian model to analyze the macroeconomic effects of carbon taxes and show that they generate an inflation-output tradeoff whose size depends on the relative price flexibility of the sectors most affected (directly or indirectly) by the tax. When calibrated to U.S. input-output data and sectoral heterogeneity in emissions and price stickiness, the model matches empirical responses of price indices to an energy shock. A $100/metric ton CO2 tax substantially increases inflation if accommodated; curtailing this increase requires a prolonged contraction. Propagation via production linkages plays a key role.

Key words: green transition, inflation, input-output linkages

---

Del Negro, Giovanni, Dogra: Federal Reserve Bank of New York (emails: marco.delnegro@ny.frb.org, julian.digiovanni@ny.frb.org, keshav.dogra@ny.frb.org). The authors thank Neil Kapoor and Neel Lahiri for outstanding research assistance. They are very grateful to Diego Känzig for providing the codes in his paper and patiently addressing all their questions, as well as to Gianluigi Ferrucci, Stephie Fried, Basile Grassi, Sewon Hur, Anton Nakov, Conny Olovsson, and participants at various conferences, workshops, and seminars for their valuable feedback.

1 Introduction

Climate change will have widespread effects on the economy. One prescient concern is climate change's impact on price stability. Some policymakers have argued that we face a "new age of energy inflation" (Schnabel, 2022), whereby central banks may be forced to live with a persistently higher level of inflation as a result of both the physical effects of climate change and the transition to a low-carbon economy. While this idea may seem intuitive, as a general statement it is arguably incorrect: the adjustment in *relative* prices induced by climate change or policies can in principle occur under any level of inflation. Monetary policymakers still have the necessary levers to meet their inflation targets, though doing so may involve a tradeoff with other targets, such as the output gap.

We study these tradeoffs using both analytics and a rich quantitative input-output (henceforth I/O) model. We ask how the green transition, and specifically policies such as carbon taxes that reduce greenhouse gas emissions in order to limit global warming, affects monetary policymakers' ability to pursue price stability while stabilizing real activity. In contrast with much of the previous literature, we find that carbon taxes can have important macroeconomic consequences and thus create a serious tradeoff for policymakers. The interaction of the propagation of the effects of the tax via the *I/O network* and the heterogeneity in price stickiness across sectors is the key mechanism behind these results.

We begin by discussing analytically how these two factors interact using a simple multisector New Keynesian model à la Rubbo (2023). We show that if stickiness is the same across sectors, following the implementation of the carbon tax inflation either remains at target (in absence of a network) or can even go below target whenever policy closes the output gap. In other words, carbon taxes are simply not inflationary unless stickiness is heterogeneous across sectors. For carbon taxes to be inflationary, it has to be the case that the sectors that are directly or indirectly (via the network) affected by the tax are relatively more flexible than the rest of the economy.

Next, we investigate the effects of the carbon tax quantitatively using a non-linear, 69-sector version of the model with that is calibrated using I/O tables from the Bureau of Economic Analysis (BEA), Cotton and Garga (2022)'s data set on sectoral price stickiness based on Producer Price Index (PPI) microdata, and sector-level emissions data from the EIA and EPA derived using the methodology of Shapiro (2021). We assess the quantitative appeal of the model by comparing its responses to an oil price shock to those in Känzig (2021), and find that in spite of its simplicity, and the fact that none of its parameters are estimated, the model does a fairly good job at capturing the responses of various inflation indexes to the shock in the United States.[1]

[1] Känzig (2022) studies the impact of carbon policy shocks on economic activity and inflation. Such impulse responses would be closer to the exercise conducted in this paper than the responses to energy price shocks, except that they are obtained for the European economy, whose production network is different from that in the U.S., to

We find that in this I/O model an increase in carbon taxes creates a sizable tradeoff between stabilizing inflation and the output gap. The experiment we consider is a gradual increase in the carbon tax from 0 to \$100 (2012 dollars) per metric ton of CO_2 emissions—a magnitude based on the literature, e.g., Barron et al. (2018)—over 100 months, anticipated 20 months in advance. When policy accommodates the shock—that is, policy closes the output gap—the carbon tax has sizable inflationary implications: 12 month headline CPI is one percentage point or more above target for more than 6 years; 12 month core CPI is 50 basis points or more above target for about 10 years (and 80 basis points or more above target for about three years). If policymakers try to fight the inflationary consequences of the tax, the tradeoffs are non-negligible: controlling headline inflation—e.g., keeping inflation to less than 60 basis points on average—takes a one percent average output gap over the six year period, while controlling core inflation—e.g., keeping core inflation to less than 50 basis points on average—is associated with an average contraction of 0.6 percent of output relative to natural over the entire period.

These results are in stark contrast with those of much of the existing literature, which uses two-sector models (e.g., Olovsson and Vestin, 2023). The upshot of much of this work is that "climate policies have a limited impact on output and inflation and thus do not present a significant challenge for central banks" (WEO, chapter 3, Andaloussi et al., 2022). In these papers the well-known Aoki (2001) result applies: the carbon tax may have an effect on headline inflation, but its effect on core inflation is muted since the share of energy as an input for the economy is relatively small. Hence policymakers should ignore it. Accounting for the propagation via the production network reverses this conclusion.[2] In fact, we show that when we shut down the network propagation channel the macroeconomic effects of the carbon tax are quantitatively small, in line with the rest of the literature. The results in this paper emphasize the significance of taking the I/O network into account for many relevant macroeconomic questions.

Our analysis focuses on carbon taxes for a number of reasons. First, influential studies on climate change find that carbon taxes are an essential ingredient of the *optimal* response to global warming (Golosov et al., 2014). Further, Hassler et al. (2023) and Cruz and Rossi-Hansberg (2024) argue that carbon taxation is an essential ingredient of *any* solution for global warming, since green energy subsidies alone are not enough to reduce the use of fossil fuels. Second, the literature on the green transition, which also primarily focuses on carbon taxes, provides us with explicit magnitudes for our quantitative analysis. Carbon taxes are extensively studied partly because they have already been implemented in several countries in the European Union (EU). Furthermore,

which our model is calibrated.

[2]The propagation of the tax through the network depends crucially on the so-called Domar weights associated with the sectors being taxed, as discussed in section 4. These weights are not only function of the extent to which energy is a direct input to other sectors, which is accounted for in a two-sector model, but also on the extent to which these other sectors are inputs to other sectors in the economy, and so on. This additional channel of propagation is absent in a two-sector model of the economy.

the EU's Emissions Trading System (ETS), a cap-and-trade system, also places a price on using carbon and impact firms' production costs via supply chain linkages. Of course, in the near term a national carbon tax is extremely unlikely for the Unites States, though states such as California have implemented cap-and-trade systems. Nonetheless, if researchers like Hassler et al. (2023) are correct, a tax may eventually be needed if climate change is to be addressed. We calibrate our model to the U.S. economy because of data availability, especially regarding the I/O matrix. But the quantitative point that transmission via the I/O matrix is key for assessing the macroeconomic implications of the carbon tax arguably generalizes to other economies.

Subsidies for green technology are also a popular tool for the green transition. This paper does not explicitly model them for two reasons. First, while we have quantitative targets for carbon taxes from the literature, the corresponding targets for subsidies are less clear (e.g., which industries to subsidize, and by how much?). Second, modeling the effects of subsidies would require assumptions about how new green technologies affect the I/O matrix and the price flexibility of these technologies, for which there is little available data. We therefore leave the analysis of subsidies within a production network framework to future work. Finally, our work abstracts from the effects of innovation (Fornaro et al., 2024). The carbon tax may spur innovation in new technologies and therefore lessen the inflationary impact of the tax as alternative sources of energy become available.

Related Literature. Most recent studies on the impact of transition policies have focused on their effects on output, e.g., Metcalf and Stock (2023) and the literature surveyed in Bilal and Stock (2025), but a growing number also study the implications for inflation. Using VAR-based evidence, Känzig (2022) finds that a carbon policy shock in Europe leads to a persistent rise in energy prices (1 percent on impact, by construction) and a decline in emissions, as one would expect.[3] The responses of headline prices are about one-fifth of the response in energy prices, while the response of core prices is about half the response of headline prices. Industrial production declines for about two years after the shock. Using local projections, Konradt and Weder di Mauro (2021) find that while carbon taxes implemented in Europe and Canada impact relative prices, they have no significant impact on overall inflation.[4] However, they also find that for a subset of European countries where monetary policies are constrained, the effect on inflation is positive and significant, in line with Känzig (2022). Kapfhammer (2023) studies the impact of "effective" carbon taxes (that is, including taxes that are not explicitly aimed at reducing emissions) in Nordic countries and finds a sizable impact on emissions and economic activity, but a small and imprecisely estimated effect on inflation. Konradt et al. (2024) also find that the effect of carbon ETS on consumer price inflation

[3]Känzig (2022) uses a high-frequency identification approach based on changes in carbon future prices from the European Union Emissions Trading System immediately following regulatory events.

[4]This result is supported in recent work by Moessner (2022), who estimates the impact of emissions trading systems and carbon taxes on a broad set of price indexes using a dynamic panel model for 35 countries.

in the Euro area has been limited. Finally, Bettarelli et al. (2025) use sectoral data from several developed and developing economies to study the impact of climate change policies on inflation. They find that carbon taxes lead to inflation, but that carbon ETSs do not.[5]

Some authors, like us, have used New Keynesian frameworks to study the inflationary impact of transition policies. In particular, in contemporaneous work Olovsson and Vestin (2023) study optimal policy under a carbon tax and find that this would not generate a substantial output-inflation tradeoff for policymakers—in other words the Aoki (2001) result applies in their framework.[6] The aforementioned work by Fornaro et al. (2024) instead reach the conclusion that the green transition may be inflationary, as we do, using a model where climate policy takes the form of capacity constraints as opposed to carbon taxes. Garcia et al. (2024) study carbon taxes in a global context. A number of works perform normative analysis. Ferrari and Pagliari (2021) and Airaudo et al. (2023) consider optimal policy under the the green transition in the world economy and in a small open economy, respectively. Nakov and Thomas (2023) investigate the question of whether central banks should fight climate change by restraining economic activity.

Finally, our work draws heavily from the aforementioned recent literature on networks and monetary policy (Ghassibe, 2021; La'O and Tahbaz-Salehi, 2022; Rubbo, 2023; Afrouzi and Bhattarai, 2023) and the antecedent work on heterogeneity in price stickiness across sectors (Carvalho, 2006; Nakamura and Steinsson, 2010). It relates as well as to the literature on relative price adjustments under sticky prices (Guerrieri et al., 2021, 2023).

In the reminder of the paper, section 2 briefly introduces some evidence on energy use and price rigidities across U.S. sectors; section 3 presents the model; sections 4 and 5 discusses the analytical and quantitative results, respectively; section 6 concludes.

2 Energy Use and Price Rigidities in the Input-Output Network

In this section we document empirically i) the centrality of high CO_2 emission energy sectors in the U.S. I/O network, and ii) the relationship between sectoral total emissions over gross output, which in the model will be roughly proportional to the direct and indirect effect of the carbon tax on each sector, and price stickiness. Both facts play a key role for the results of this paper, as discussed analytically in section 4 and quantitatively in section 5. Figure 1 makes the first point. The figure is built using the 2012 BEA Input-Output Table for total requirements,[7] where we have

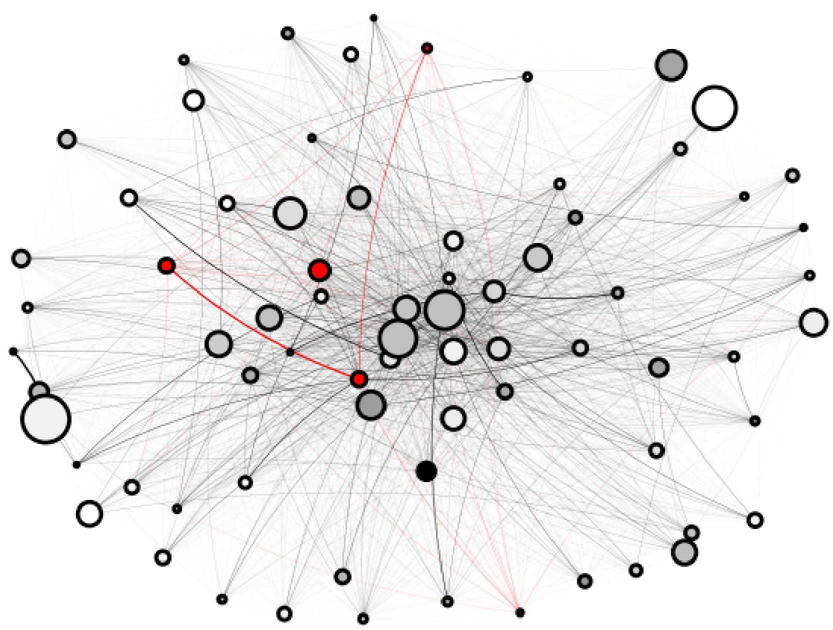
[5] As shown in section 4, the inflationary implications of a carbon tax depend on monetary policy, and also on the I/O structure and the relative price rigidity across sectors, all of which differ across countries.

[6] Other work using New Keynesian models to study the effects of climate policies include Bartocci et al. (2022), who use a two-country model with an energy sector, calibrated to the euro area and the rest of the world, and find that an increase in carbon taxes generates recessionary effects which are ameliorated by accommodative monetary policy. Ferrari and Nispi Landi (2024) focus instead on the role of expectations in determining whether emission taxes are inflationary or deflationary.

[7] We use the 2012 BEA I/O table rather than a more recent vintage given that the sectoral classification codes used in 2012 allow us to create a crosswalk to the price frequency data set's NAICS 2017 classification system.

aggregated up to 69 sectors (see section 5.1 for a discussion of the sectors' definition). Each node represents a sector with the size of the node proportional to the sector's value added; each edge represents the bilateral input usage of a sector pair deflated by the customer sector's gross output. One can readily see that many energy sectors (red nodes) occupy a central position in the network.[8] The darkness of other nodes is proportional to their price flexibility, that is, sticky price sectors are lighter.[9] Not surprisingly, the non-energy part of the economy—which in two-sector models is a monolithic sector—is composed of a multitude of sectors with varying stickiness that interact with one another and with energy.

Figure 1. The centrality of energy in the U.S. input-output network



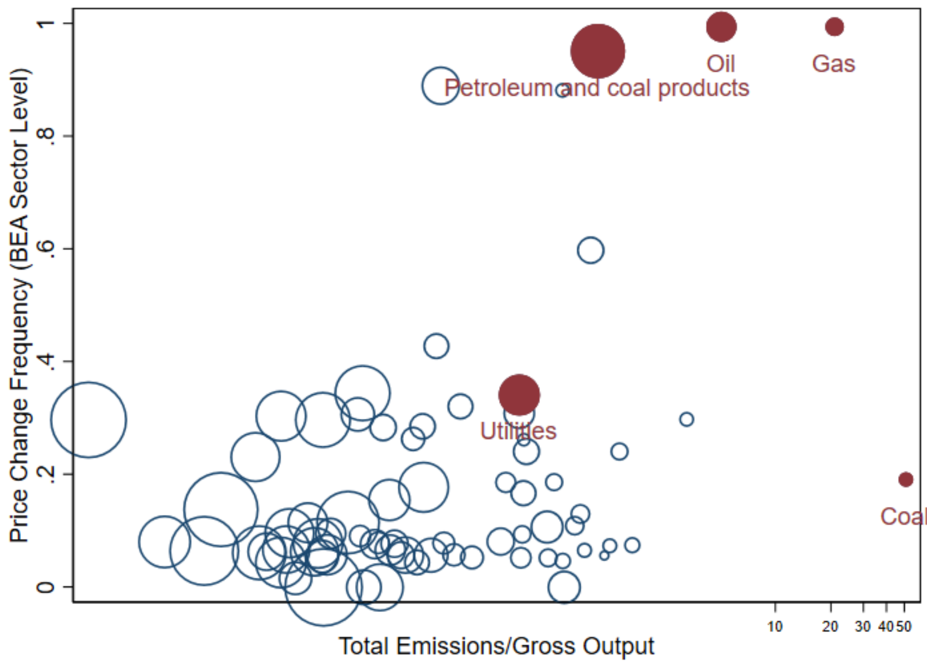
Notes: This figure is built using the 2012 BEA Input-Output Table for total requirements, where we have aggregated up to 73 sectors. Each node represents a sector with the size of the node proportional to the sector's value added. Each weighted edge represents the bilateral input usage of a sector pair deflated by the customer sector's gross output. The darkness of the nodes is proportional to their price flexibility (edges are red for energy sectors).

Figure 2 shows that energy sectors, and in general sectors whose output makes most use of

[8]Not all the energy sectors in our model—oil extraction, gas extraction, coal mining, petroleum and coal products, and utilities—involve high CO_2 emissions. In particular, the utilities sector includes zero-carbon electric power generation. Our model distinguishes between polluting sectors and energy sectors more broadly: only the first three of these sectors will be subject to the carbon tax.

[9]We source information on price rigidity from Cotton and Garga (2022), who calculate the frequency of price changes at the goods level as the ratio of the number of price changes to the number of sample months. Cotton and Garga (2022) construct their data set by using CPI and PPI price change data from Nakamura and Steinsson (2008) and then create a crosswalk for the goods and services with reported price frequency change data to 2017 NAICS in order to create sector-level measures of price changes.

Figure 2. Mean price change frequency of a good in a given sector vs CO_2 total emissions/gross output across 69 sectors in the United States



Notes: This figure plots a bin scatter of the sector-level mean price change frequency against the sector-level CO_2 total emissions to value added. The emissions ratio is expressed in terms of total kilotons of CO_2 emitted per millions of US$ gross output produced and is based on the total usage of fossil fuels (oil, gas, or coal) in production using the approach of Shapiro et al. (2018); Shapiro (2021), and is plotted on a log scale. Circle sizes are based on sector-level gross output within a bin.

energy either directly or indirectly, have more flexible prices on average than less energy-intensive sectors. The figure plots a bin scatter of the sector-level price rigidity measure against total CO_2 emissions/gross output ratio for 69 sectors, where sector-level total emissions are calculated using the methodology of Shapiro (2021). Intuitively, this measure captures the fossil fuels (oil, gas and coal) required to produce a dollar of output in each sector, including the fossil fuels required to produce the intermediate inputs used by that sector, the inputs required to produce those inputs, and so on. The direct and indirect use of fossil fuel, where fossil fuel emissions data is from the EPA and EIA, is computed using the I/O table's Leontief inverse; see Appendix A for details. Again, the size of each bin's circle corresponds to the sum of the value added of all sectors in a given bin, and the energy sectors are in red. Figure 2 shows that sectors with higher CO_2 total emissions (relative to gross output) tend to have a higher average frequency of price change. As discussed later, the total emissions to gross output ratio is roughly proportional to the extent to which sectors are directly or indirectly affected by the tax.[10]

[10]Figure A1 in the Appendix shows direct emissions over value added, as opposed to total emissions/gross output,

3 The Multisector Model

Our model is a multisector New Keynesian economy with sticky prices and wages, similar to Rubbo (2023), but augmented to include carbon taxes and to distinguish between energy and non-energy intermediate inputs. The economy consists of households, labor unions who set nominal wages, a continuum of monopolistically competitive firms in each sector $i = 1, ..., n$, a monetary authority, and a fiscal authority who sets carbon taxes. Next, we describe each agent in turn.

Households The representative household solves

$$\max_{\{C_t,\{C_t^i,C_t^i(\cdot)\}_{i=1}^n\}_{t=0}^\infty} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \ln C_t - \widetilde{b} \int_0^1 L_t(\iota) d\iota \right\} \tag{1}$$

$$\text{s.t.} \sum_{i=1}^{n} \int_0^1 P_t^i(j) C_t^i(j) dj + \frac{1}{1+i_t} B_{t+1} = \int_0^1 W_t(\iota) L_t(\iota) d\iota + T_t + B_t,$$

$$C_t = \left[\sum_i (\gamma_i)^{\frac{1}{\zeta}} (C_t^i)^{\frac{\zeta-1}{\zeta}} \right]^{\frac{\zeta}{\zeta-1}},$$

$$C_t^i = \left(\int_0^1 C_t^i(j)^{\frac{\varepsilon^i-1}{\varepsilon^i}} dj \right)^{\frac{\varepsilon^i}{\varepsilon^i-1}}, i = 1, ..., n,$$

where W_t denotes the nominal wage and T_t denotes net transfers from the government and monopolistically competitive firms. Consumption C_t is a CES aggregate of the products C_t^i produced by each of the n sectors, each of which is in turn a CES aggregate of the varieties $C_t^i(j)$ produced by a continuum of monopolistically competitive producers in that sector. The elasticity of substitution between sectors is ζ, and the elasticity of substitution between varieties in sector i is ε^i. As is standard, this implies that the consumer price index P_t equals $\left[\sum_{i=1}^{n} \gamma_i (P_t^i)^{-(\zeta-1)} \right]^{-\frac{1}{\zeta-1}}$, where $P_t^i = \left[\int_0^1 (P_t^i(j))^{-(\varepsilon^i-1)} dj \right]^{-\frac{1}{\varepsilon^i-1}}$ for all i and the demand for variety j of good i is $C_t^i(j) = C_t^i \left(\frac{P_t^i(j)}{P_t^i} \right)^{-\varepsilon^i}$.

Unions There are a continuum of differentiated labor varieties $L_t(\iota)$, $\iota \in [0, 1]$. Competitive labor packers combine these into "labor services" L_t using the CES technology

$$L_t = \left(\int_0^1 L_t(\iota)^{\frac{\varepsilon^w-1}{\varepsilon^w}} d\iota \right)^{\frac{\varepsilon^w}{\varepsilon^w-1}},$$

and sell labor services to the firms at nominal price W_t. This yields the standard demand curve $L_t(\iota) = L_t \left(\frac{W_t(\iota)}{W_t} \right)^{-\varepsilon^w}$ where $W_t = \left[\int_0^1 W_t(\iota)^{1-\varepsilon^w} d\iota \right]^{\frac{1}{1-\varepsilon^w}}$. The wage of each variety of labor ι is

and is broadly similar.

set by a monopolistically competitive union with Calvo frictions, which can adjust the wage with probability $1-\theta_w$ each period, and solves the problem

$$\max_{W_t^*} \sum_{k=0}^{\infty} (\theta_w \beta)^k \left[\frac{W_t^*}{P_{t+k} C_{t+k}} - \widetilde{b} \right] L_{t+k} \left(\frac{W_t^*}{W_{t+k}} \right)^{-\varepsilon^w} . \tag{2}$$

Firms Firms in sector i have the constant returns to scale production function

$$X_t^i = A_t^i \left[\alpha_i^{\frac{1}{\eta}} (L_t^i)^{\frac{\eta-1}{\eta}} + (1-\alpha_i)^{\frac{1}{\eta}} (I_t^i)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} ,$$

where A_t^i is a Hicks-neutral productivity shifter, η is the elasticity of substitution between labor and intermediate inputs, and I_t^i is a CES aggregate of "energy" E_t^i and "non-energy inputs" N_t^i:

$$I_t^i = \left[\varsigma_i^{\frac{1}{\nu}} (E_t^i)^{\frac{\nu-1}{\nu}} + (1-\varsigma_i)^{\frac{1}{\nu}} (N_t^i)^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}} ,$$

where ν is the elasticity of substitution between energy and non-energy inputs, and ς_i is the energy share of inputs for sector i. E_t^i and N_t^i are, in turn, aggregates of energy and non-energy intermediate goods, respectively:

$$E_t^i = \left[\sum_j (\omega_{ij}^E)^{\frac{1}{\xi}} (X_t^{ij})^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}} ,$$

$$N_t^i = \left[\sum_j (\omega_{ij}^N)^{\frac{1}{\xi}} (X_t^{ij})^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}} ,$$

where $\sum_{j=1}^{n} \omega_{ij}^E = \sum_{j=1}^{n} \omega_{ij}^N = 1$, $\omega_{ij}^E = 0$ if j is a non-energy good, and $\omega_{ij}^N = 0$ if j is an energy good. Here X_t^{ij} denotes the quantity of good j used by firms in sector i. Note that the share of different energy goods in the energy aggregate that is relevant for firms in sector i, E_t^i, may differ from sector to sector. The index of intermediate inputs used by firms in sector k and produced by a firm in sector i, is given by the same CES aggregate as household's consumption of sector i goods:

$$X_t^{ki} = \left(\int_0^1 X_t^{ki}(j)^{\frac{\varepsilon^i - 1}{\varepsilon^i}} dj \right)^{\frac{\varepsilon^i}{\varepsilon^i - 1}} ,$$

which yields the standard CES demand curve $X_t^{ki}(j) = X_t^{ki} \left(\frac{P_t^i(j)}{P_t^i} \right)^{-\varepsilon^i}$.

The cost minimization problem of a sector i firm is

$$M^i X^i = \min_{L_t^i, I_t^i, E_t^i, N_t^i \{X_t^{ij}\}_{j=1}^n} W_t L_t^i + \sum_j P_t^j X_t^{ij} + \mathcal{T}_t e_i X_t^i \tag{3}$$

$$\text{s.t. } A_t^i \left[\alpha_i^{\frac{1}{\eta}} (L_t^i)^{\frac{\eta-1}{\eta}} + (1-\alpha_i)^{\frac{1}{\eta}} (I_t^i)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \geq X_t^i,$$

$$\left[\varsigma_i^{\frac{1}{\nu}} (E_t^i)^{\frac{\nu-1}{\nu}} + (1-\varsigma_i)^{\frac{1}{\nu}} (N_t^i)^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}} \geq I_t^i,$$

$$\left[\sum_j (\omega_{ij}^E)^{\frac{1}{\xi}} (X_t^{ij})^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}} \geq E_t^i,$$

$$\left[\sum_j (\omega_{ij}^N)^{\frac{1}{\xi}} (X_t^{ij})^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}} \geq N_t^i.$$

Here $\mathcal{T}_t$ is the nominal carbon tax per unit of emissions, and we calibrate e_i to raw emissions (which are nonzero only for oil and gas extraction and coal mining) as described in Appendix A. Thus, we assume that the carbon tax is imposed upstream, at the point of fuel production: crude oil is taxed at the point it leaves the well, gas at the point it enters a pipeline, coal as it leaves the mine. While in principle a carbon tax can be levied at various different points in the supply chain, and our model is well suited to study any tax system, it is often argued that an upstream system is best as the number of fuel distributors is much smaller than the number of end users, making an upstream tax much easier to administer (Metcalf and Weisbach, 2009). The tax is based on the imputed carbon emissions per unit of fuel.[11]

While we do compute the effect of the carbon tax on emissions, the focus of the paper is its direct effect on inflation over the medium term. We ignore the indirect effect of the reduction of emissions on climate and therefore on economic outcomes (eg, see Golosov et al., 2014; Känzig, 2022), including inflation, because the effect of policy on inflation via this channel is likely to be small compared to the direct effect over the horizon we are interested in.

Firms face Calvo-type price rigidities. Each period, a firm in sector i can change their price with probability $1-\theta_i$; otherwise it remains unchanged. The optimal price for a resetting firm in sector i at date t, P_t^{i*}, solves

$$\max \sum_{k=0}^{\infty} Q_{t+k|t} \theta_i^k [P_t^{i*} - M_t^i] X_{t+k}^i \left(\frac{P_t^{i*}}{P_{t+k}^i} \right)^{-\varepsilon^i}, \tag{4}$$

where $Q_{t+k|t} = \beta^k \dfrac{P_t C_t}{P_{t+k} C_{t+k}}$ denotes households' nominal stochastic discount factor between dates

[11]The tax in our model therefore differs from most existing carbon pricing schemes, which are imposed midstream on large point source emissions, rather than upstream. For example, the EU ETS covers CO_2 emissions from electricity and heat generation, energy-intensive heavy industry, aviation and maritime transport: it is firms operating in these sectors who must surrender an allowance for every ton of CO_2 they emit, and therefore directly face a price of carbon.

t and $t+k$.[12]

Monetary policy and carbon taxes For most of our analysis, we will assume that monetary policy follows a version of flexible inflation targeting,

$$\left(\frac{C_t}{C_t^*}\right)\Pi_t^{\psi} = 1,$$

where C_t^* denotes the level of aggregate consumption (and hence value added) in a counterfactual flexible-price economy where $\theta_i = 0$ for all i, and $\Pi_t := P_t/P_{t-1}$ denotes consumer price inflation. $\psi \geq 0$ measures the weight the monetary authority places on inflation, relative to closing the output gap: when $\psi \to \infty$, this policy becomes strict inflation targeting, while when $\psi = 0$, it is strict output gap targeting.

We model carbon taxes as an exogenously given path for the real carbon tax $\tau_t := \mathcal{T}_t/P_t$, which is announced at date 0.

Market clearing The market clearing conditions for each sector and for the labor market are

$$C_t^i + \sum_{j=1}^{n} X_t^{ji} = X_t^i, i = 1, ..., n, \tag{5}$$

$$\sum_{i=1}^{n} L_t^i = L_t. \tag{6}$$

4 Analytical Results

In this section we present analytical results which will help understand our quantitative results in Section 5. For ease of exposition, we focus on the case with flexible wages, $\theta_w = 1$.[13] Log-linearizing the supply side of the model around a zero-inflation steady state then yields the following system of equations (see Appendix B.2):

$$\boldsymbol{\pi_t} = K(\boldsymbol{\alpha} y_t - (I - \Omega)\boldsymbol{s_t} + \boldsymbol{\epsilon}\tau_t) + \beta\boldsymbol{\pi_{t+1}}, \tag{7}$$

$$\boldsymbol{s_t} = \boldsymbol{s_{t-1}} + \boldsymbol{\pi_t} - \mathbf{1}\pi_t^c, \tag{8}$$

$$\pi_t^c = \boldsymbol{\gamma}'\boldsymbol{\pi_t}, \tag{9}$$

where all the variables are expressed in log-deviations from steady state. In the above expressions, y_t denotes output, $\boldsymbol{\gamma} = (\gamma_1, ..., \gamma_n)'$ the vector of consumption shares (satisfying $\boldsymbol{\gamma}'\mathbf{1}$ where $\mathbf{1}$ denotes a $n \times 1$ vector of ones), and $\boldsymbol{\pi_t}$ the $n \times 1$ vector of sectoral inflation rates, so that $\pi_t^c = \boldsymbol{\gamma}'\boldsymbol{\pi_t}$ denotes

[12] Strictly speaking, since we have no aggregate shocks, this is known as of date t and is just the price of a k-period bond.

[13] As in Rubbo (2023), results extend immediately to the case with sticky wages if we reinterpret the labor union as a sector which supplies the intermediate input 'labor services' to other firms.

consumer price (henceforth, CPI) inflation.[14] K is a diagonal $n \times n$ matrix with ith diagonal element $\kappa_i = \frac{(1-\beta\theta_i)(1-\theta_i)}{\theta_i}$, where $1-\theta_i$ is the probability that a sector i firm gets to change its price, and higher κ_i of course implies more flexible prices and a steeper Phillips curve. The vector $\boldsymbol{\alpha}$ denotes the $n \times 1$ vector of sectoral labor shares in marginal cost, which multiplies the real wage w_t (note that we used the fact that with flexible wages $w_t = c_t = y_t$). Ω denotes intermediate input shares: Ω_{ij} equals i's expenditure on sector j's output, as a fraction of i's total cost. Since the production function has constant returns to scale it must be that $\boldsymbol{\alpha} + \Omega\mathbf{1} = \mathbf{1}$. Let us also define the row vector of Domar weights $\boldsymbol{\lambda}' := \boldsymbol{\gamma}'(I-\Omega)^{-1}$: $\boldsymbol{\lambda}'$ differs from the CPI weights $\boldsymbol{\gamma}'$ as they account for the total value added of each sector in the consumption basket, and not only the goods and services that are ultimately being consumed. $\boldsymbol{s_t}$ denotes the vector of relative prices, taking the consumer price level as numeraire (which implies $\boldsymbol{\gamma}'\boldsymbol{s}_t = 0$ for all $t \geq 0$ as long as the initial condition $\boldsymbol{s}_{-1}$ satisfies $\boldsymbol{\gamma}'\boldsymbol{s}_{-1} = 0$). Finally, $\boldsymbol{\epsilon}$ denotes the $n \times 1$ vector measuring the extent to which each sector is subject to the carbon tax τ_t (e.g., proportional to raw emissions, as in the quantitative application), scaled by marginal cost.

To close the system we need to specify monetary policy, which we will do below. But first we describe the flexible price equilibrium in this model, which does not depend on monetary policy.

The flexible price equilibrium. The flexible price levels of output y_t^* and relative prices $\boldsymbol{s}_t^*$ are given by the expressions:

$$y_t^* = -\boldsymbol{\gamma}'(I-\Omega)^{-1}\boldsymbol{\epsilon}\tau_t, \tag{10}$$

$$\boldsymbol{s}_t^* = \mathbf{1}y_t^* + (I-\Omega)^{-1}\boldsymbol{\epsilon}\tau_t. \tag{11}$$

Relative to the no carbon tax steady state, flexible price output (and therefore flexible price wages) is negative: the tax leads to a contraction in economic activity. Relative prices change as the result of two forces. For those sectors whose marginal costs are, directly or indirectly (via the input-output network), affected by taxation, relative prices rise ($(I-\Omega)^{-1}\boldsymbol{\epsilon}\tau_t > 0$), while they fall for the less affected sectors since y_t^* is negative, reflecting the fact that lower output implies lower real wages. Of course, $\boldsymbol{\gamma}'\boldsymbol{s}_t^* = 0$.

The introduction of a carbon tax therefore increases the relative price of goods which are either taxed directly, or rely indirectly on taxed goods via input output linkages. But under flexible prices, this adjustment in *relative* prices does not imply that the overall price level has to increase—in fact, it can be achieved alongside *any* level of aggregate inflation without generating any tradeoffs for the central bank. A tradeoff between stabilizing inflation and other objectives (in particular, closing the output gap) can therefore only arise when nominal rigidities are present. Proposition 1

[14] Note that PCE and CPI inflation in the model coincide.

sheds some light on the conditions under which such a tradeoff emerges. To see whether it does, we suppose the monetary authority closes the output gap (i.e., sets $y_t = y_t^*$) at all times, and ask whether under this policy CPI inflation is positive. If it is, then a tradeoff emerges: the central bank cannot close the output gap and stabilize CPI inflation at the same time. If instead CPI inflation is zero there is no tradeoff, while if it is negative such a tradeoff is "favorable" to the monetary authorities, in the sense that they can raise output above its flexible level while still keeping inflation at target.[15]

Before stating the proposition, note that using expression (B.24) we can rewrite the system of sectoral Phillips curves as:

$$\boldsymbol{\pi_t} = K\left(\boldsymbol{\alpha}(y_t - y_t^*) - (I - \Omega)(\boldsymbol{s_t} - \boldsymbol{s_t^*})\right) + \beta \mathbb{E}_t \boldsymbol{\pi_{t+1}}. \tag{12}$$

The above equation implies that whenever policy closes the output gap, the weighted average of sectoral inflation rates $\boldsymbol{\gamma}'(I-\Omega)^{-1}K^{-1}\boldsymbol{\pi_t} = \boldsymbol{\lambda}'K^{-1}\boldsymbol{\pi_t}$ is always zero. Rubbo (2023) therefore calls this inflation measure the "divine coincidence" index: the central bank can always target a zero value of this index while closing the output gap at the same time. Note that except in special cases divine coincidence and CPI inflation differ.

To obtain analytical results we consider the case where the tax rate grows indefinitely at a rate g, that is $\tau_t = \tau_{t-1} + g$, and the economy converges to a new steady state level of inflation, which is described in the proposition below. We consider this "perpetual tax growth" steady state because it reasonably approximates the very long transition period considered in the quantitative analysis of Section 5.

Proposition 1 *If policy closes the output gap, in response to a constantly growing carbon tax, the growth rates of relative prices converge to*

$$\Delta \boldsymbol{s} = \left(I - \mathbf{1}\boldsymbol{\gamma}'\right)(I - \Omega)^{-1}\boldsymbol{\epsilon} g,$$

while aggregate and sectoral inflation rates and the growth rate of relative prices converge to the following levels:

$$\pi^c = -\frac{\boldsymbol{\lambda}' K^{-1} \Delta \boldsymbol{s}}{\boldsymbol{\lambda}' K^{-1} \mathbf{1}},$$
$$\boldsymbol{\pi} = \Delta \boldsymbol{s} + \pi^c.$$

Proof: See Appendix B.6. ■

To help understand the implications of this Proposition, that is, the effects of the carbon tax on inflation, we first consider a number of special cases and then discuss the general case.

[15] To be clear, the term "favorable" is just shorthand: we are not claiming that setting $y > y^*$ increases welfare.

No I/O, homogenous price stickiness: Suppose first that price stickiness is the same across sectors ($K = \kappa I$) and there are no I/O linkages ($\boldsymbol{\alpha} = \mathbf{1}$, $\Omega = \mathbf{0}_{n\times n}$). In this case, the Proposition tells us there is no tradeoff: closing the output gap also implies zero consumer pice inflation, $\pi^c = 0$. One can readily see this because in this special case CPI and divine coincidence inflation are the same, so that when $y_t = y_t^*$ they are both zero. Relative prices are of course affected: goods with a higher than average ϵ_i share have increasing prices and vice versa:

$$\Delta \boldsymbol{s} = \left[\boldsymbol{\epsilon} - \left(\boldsymbol{\gamma}'\boldsymbol{\epsilon}\right)\mathbf{1}\right] g. \tag{13}$$

To understand the intuition behind this result, consider a two-sector version of the model ($n = 2$) and call the two sectors d (high-emissions, $\epsilon_d > 0$) and o (other/rest of the economy, $\epsilon_o = 0$). From (12) the two Phillips curves are

$$\begin{aligned}\pi_t^d &= \kappa(y_t - y_t^* - \underbrace{(s_t^d - s_t^{d*})}_{<0}) + \beta \mathbb{E}_t \pi_{t+1}^d,\\ \pi_t^o &= \kappa(y_t - y_t^* - \underbrace{(s_t^o - s_t^{o*})}_{>0}) + \beta \mathbb{E}_t \pi_{t+1}^o.\end{aligned}$$

If $y_t = y_t^*$ then $\pi_t^c = \gamma_o \pi_t^o + \gamma_d \pi_t^d = 0$ since $\boldsymbol{\gamma}'\boldsymbol{s}_t = \boldsymbol{\gamma}'\boldsymbol{s}_t^* = 0$. All the work is done by relative prices, which push inflation up in the high-emission sector and down in the rest of the economy. With the same κs the adjustment occurs at the same speed, and overall inflation remains zero.

I/O linkages, homogeneous price stickiness: Now suppose again that price stickiness is homogeneous ($K = \kappa I$), but there are I/O linkages ($\boldsymbol{\alpha} < \mathbf{1}$, $\Omega \neq \mathbf{0}_{n\times n}$). In this case, divine coincidence inflation coincides with the inflation index constructed using the Domar weights, $\boldsymbol{\lambda}'\boldsymbol{\pi_t}$, which we can loosely call PPI inflation as it measures the gross value added of each sector. When policy closes the output gap PPI inflation is therefore equal to zero, just like CPI inflation without I/O linkages. With I/O linkages CPI inflation is instead given by

$$\pi^c = -\frac{\boldsymbol{\lambda}'\Delta \boldsymbol{s}}{\boldsymbol{\lambda}'\mathbf{1}} = \left(\boldsymbol{\gamma}' - \frac{1}{\boldsymbol{\lambda}'\mathbf{1}}\boldsymbol{\lambda}'\right)(1-\Omega)^{-1}\boldsymbol{\epsilon} g.$$

CPI inflation will be negative to the extent that sectors that are more heavily taxed, either directly or indirectly via their inputs, have a lower consumption weight than their Domar weight (relative to the average Domar weight). That is, in the plausible case where carbon taxes disproportionately affect upstream sectors, inflation would be negative if all sectors had the same price stickiness. To gain intuition we again return to the two-sector example. In the case where the rest of the economy uses inputs from sector d but not vice versa, the two Phillips curves become:

$$\begin{aligned}\pi_t^d &= \kappa(y_t - y_t^* - (s_t^d - s_t^{d*})) + \beta \mathbb{E}_t \pi_{t+1}^d,\\ \pi_t^o &= \kappa((1-\omega_{od})(y_t - y_t^*) - (s_t^o - s_t^{o*}) + \omega_{od}\underbrace{(s_t^d - s_t^{d*})}_{<0}) + \beta \mathbb{E}_t \pi_{t+1}^o.\end{aligned}$$

These two Phillips curves are identical to those shown above, except for the term $\omega_{od}(s_t^d - s_t^{d*})$ in the rest of the economy Phillips curve. This term is negative while $s_t^d < s_t^{d*}$ so that $\pi_t^c = \gamma_o \pi_t^o + \gamma_d \pi_t^d = \gamma_o \kappa \omega_{od} \sum_{k=0}^{\infty} \beta^k \underbrace{(s_{t+k}^d - s_{t+k}^{d*})}_{<0}$.

The results so far make it clear that for carbon taxes to be "inflationary", as claimed by Schnabel, heterogeneity in price stickiness across sector must play a key role. The next special case illustrates this role.

No I/O, heterogeneous price stickiness: Now suppose price stickiness is heterogeneous across sectors ($K \neq \kappa I$), but there are no I/O linkages ($\boldsymbol{\alpha} = \mathbf{1}$, $\Omega = \mathbf{0}_{n\times n}$). Relative price changes are still given by (13). CPI inflation is given by

$$\pi^c = \left[\boldsymbol{\gamma}' - \frac{\boldsymbol{\gamma}' K^{-1}}{\boldsymbol{\gamma}' K^{-1}\mathbf{1}}\right] \boldsymbol{\epsilon} g \;=\; \frac{1}{\sum_j \gamma_j \kappa_j^{-1}} \sum_i \gamma_i \epsilon_i \left(\sum_j \gamma_j \kappa_j^{-1} - \kappa_i^{-1}\right) g.$$

Inflation is positive to the extent that the variance between ϵ_i and κ_i^{-1} is negative, i.e. sectors most affected by the carbon tax have more flexible prices than the average sector. In a two-sector model with fully flexible high-emission sector prices and sticky prices in the rest of the economy we have:

$$\begin{aligned}
s_t^d - s_t^{d*} &= y_t - y_t^*, \\
\pi_t^o &= \kappa^o(y_t - y_t^* - (s_t^o - s_t^{o*})) + \beta \mathbb{E}_t \pi_{t+1}^o, \\
\pi_t^c &= \pi_t^o - \Delta s_t^o.
\end{aligned}$$

If $y_t = y_t^*$ then $\pi_t^c = -\Delta s_t^o > 0$. Intuitively, if high-emission sector prices are flexible they rise immediately, and relative prices therefore adjust to their flexible price level. If policy closes the output gap then inflation in the rest of the economy is zero. CPI inflation therefore has to rise. Having $\pi_t^c = 0$ requires a negative output gap $y_t < y_t^*$ that pushes π_t^o into negative territory.

General case In the general case, CPI inflation is given by

$$\pi^c = \left[\boldsymbol{\gamma}' - \frac{\boldsymbol{\lambda}' K^{-1}}{\boldsymbol{\lambda}' K^{-1}\mathbf{1}}\right] (1 - \Omega)^{-1} \boldsymbol{\epsilon} g.$$

This formula calls for two observations. First, the role of propagation via the I/O network emerges clearly from the fact that the term $(I - \Omega)^{-1}\boldsymbol{\epsilon}$ can be quite different from the direct and first round effect of the tax $(I + \Omega)\boldsymbol{\epsilon}$—which is what a two-sector model of the economy such as those used by most of the previous literature would capture. Second, CPI inflation is positive if sectors that are more heavily taxed, either directly or indirectly, have a higher consumption weight γ_i than their divine coincidence weight λ_i/κ_i. This weight is low for flexible sectors (high κ_i), following the intuition of the previous special case, but is also high for upstream sectors. In sum, the formula highlights that the interaction between relative stickiness and the propagation via the I/O network is key to understand the inflationary impact of the carbon tax.

5 Quantitative Results

This section first describes the model's calibration. Next, it compares the calibrated model's response to an oil price shock to the VAR responses obtained by Känzig (2022) in order to assess the model's credibility in quantitative terms. We then describe the main results of the paper and study the inflationary consequences of a carbon tax.

5.1 Calibration

In order to perform the simulations we use a 69-sector version of the model. The BEA defines industries at two levels of aggregation: "detailed" (consisting of 402 industries) and "summary" (71 industries). To make the solution of the nonlinear model feasible, we work at the summary level, except that we break out oil extraction, gas extraction, and coal mining as distinct sectors, giving us 73 sectors.[16] We drop 4 industries (all in federal or state and local government) for which we have no data on frequency of price adjustment, leaving us with 69 sectors.[17] We manually classify each of our 69 sectors as either "goods" or "services", and classify some of them as "food", "energy", "goods", and "services".

While the model is *prima facie* heavily parameterized, the vast majority of the parameters are pinned down by the I/O tables and by sector-level micro estimates of price rigidities. For each industry i, the 2012 BEA I/O tables report gross output $P^i X^i$, compensation of employees WL^i, and that industry's usage of products produced by each industry j, $P^j X^{ij}$. We calibrate each sector's total costs in the initial steady state as the sum of that sector's compensation and intermediate inputs expenditure, starting from a steady state with zero carbon tax (and abstracting away from any other tax): $M^i X^i = WL^i + \sum_j P^j X_{ij}$. We use this information to calibrate each industry's labor share of total costs $\widetilde{\alpha}_i = \frac{WL^i}{M^i X^i}$, energy share of intermediate inputs $\widetilde{\varsigma}_i = \frac{\sum_{j\in\mathcal{E}} P^j X_{ij}}{\sum_j P^j X_{ij}}$, and its share of energy and nonenergy intermediate inputs spending allocated to each sector j, $\widetilde{\omega}^E_{ij} = \frac{P^j X^{ij}}{\sum_{k\in\mathcal{E}} P^j X^{ij}}$ and $\widetilde{\omega}^N_{ij} = \frac{P^j X^{ij}}{\sum_{k\in\mathcal{N}} P^j X^{ij}}$ respectively.[18] Consumption expenditure shares $\widetilde{\gamma}_i$ are simply calculcated as $\frac{P^i C^i}{\sum_j P^j C^j}$. Appendix B.4 shows that the full nonlinear dynamics

[16] Oil and gas extraction are combined into a single industry in both the detailed and summary tables, and coal mining is subsumed under 'Mining, except oil and gas' in the summary tables.

[17] See Appendix A for more details.

[18] Here $\mathcal{E}$ denotes the set of energy sectors and $\mathcal{N} = \{1, ..., n\} \setminus \mathcal{E}$ the set of nonenergy sectors.

of all variables of interest (expressed as a percentage change relative to the initial steady state) depend only on these share variables, and not on the structural parameters α_i, γ_i, etc.

Our model features a closed economy in which consumption is the only source of final demand. In the data, there are other sources of final demand, including net exports, and there are also imports and exports of intermediate goods. We deal with this by interpreting the data as a "fictitious closed economy" in which imports are produced by domestic producers, and model consumption equals the sum of consumption, investment, government purchases and exports (without subtracting imports) in the data. In addition, some of the output produced by our remaining 69 sectors is used as intermediate inputs by the 4 omitted sectors. To obtain a consistent I/O matrix, for each remaining sector, we subtract from its gross output the usage of its output by omitted sectors. That is, we set

$$P^i X^i = TotalOutput_i - \sum_{j \in Omitted} IntermediateUsage_{ij} + Imports_i,$$
$$P^i C^i = FinalDemand_i + Imports_i,$$

where $IntermediateUsage_{ij}$ denotes sector j's usage of i's product.

We calibrate the monthly frequency of price change $1 - \theta_i$ based on price adjustment data from Cotton and Garga (2022) as described in Appendix A. As described below, as a baseline we set the wage stickiness parameter $\theta_w = 0.9^{1/3}$ following Del Negro et al. (2015), but consider robustness to alternative values, including flexible wages ($\theta_w = 0$). We calibrate the model at a monthly frequency and set $\beta = 0.96^{(1/12)}$.

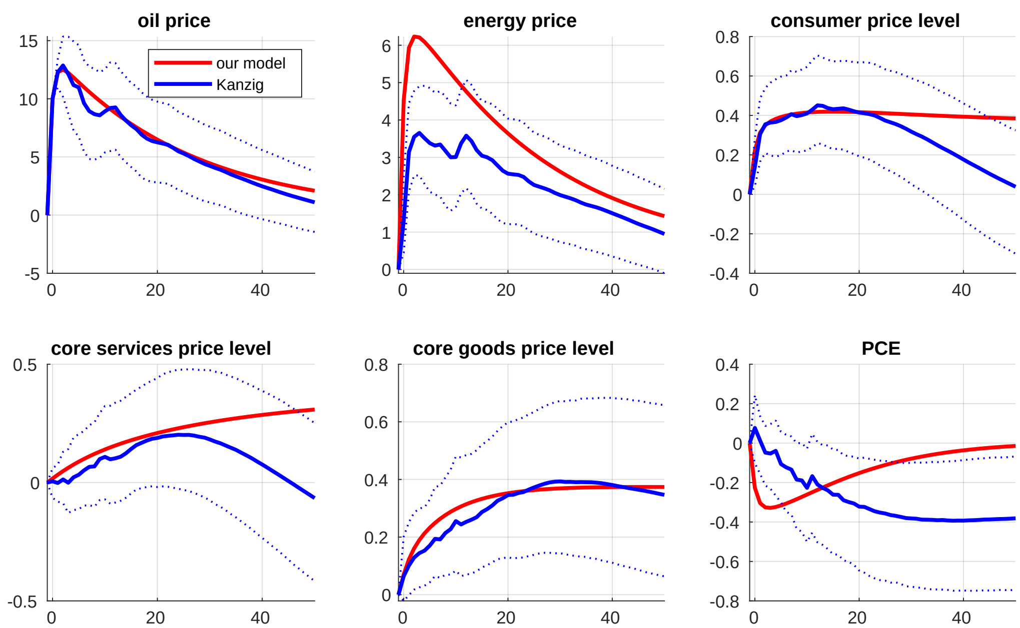
The only remaining aggregate parameters to calibrate are the elasticities. We set the elasticity of substitution between consumption goods $\eta = 2$, in line with Carvalho et al. (2021) and within the range of estimates for upper-level elasticities of substitution in Hobijn and Nechio (2019). We set the elasticity of substitution between labor and intermediate inputs $\eta = 0.6$, in line with the elasticities of substitution between materials and non-materials for manufacturing plants in 2007 estimated by Oberfield and Raval (2021). The elasticity of substitution between energy and non-energy inputs ν can also be interpreted as the elasticity of businesses' demand for energy. As summarized by Bachmann et al. (2022), estimates of the short-run price elasticity of gas and energy demand mostly lie between 0.15 and 0.25; we therefore set $\nu = 0.2$. Finally, we set the elasticity of substitution between intermediate inputs $\xi = 0.1$, towards the upper end of the range of estimates reported by Atalay (2017).

Last, we calibrate e_i based on each sector's total raw CO_2 emissions, which are calculated using EIA and EPA data as described in Appendix A. Again, raw emissions are nonzero for only three sectors: oil and gas extraction and coal mining.

5.2 Model Validation: The Propagation of Oil Shocks Through the Input-Output Network

In this section we compare the impulse response to oil price shocks from a linearized version of the calibrated model to those obtained by Känzig (2021) using a structural VAR. We do so for two reasons. First, this exercise empirically validates the quantitative network model by comparing its IRFs to Känzig's empirical IRFs. The second purpose of this exercise is to understand the role played by the network in propagating the effect of energy price shocks.

Figure 3. Känzig's WTI oil shocks responses: model vs SVAR



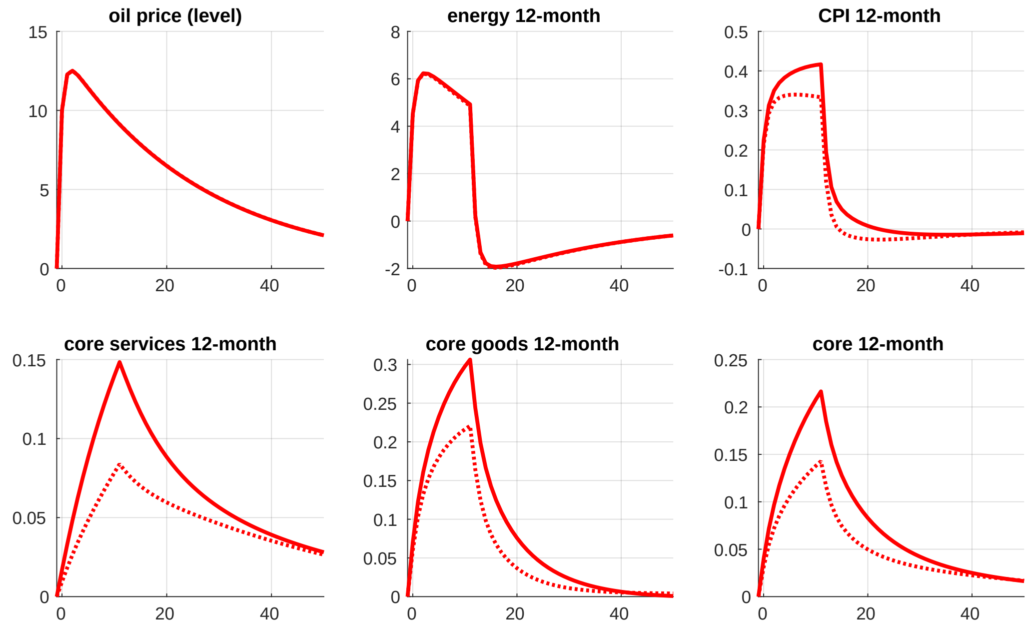
Notes: Solid/dotted blue lines: Känzig (2021)'s WTI oil shocks responses of various price indexes with 90 percent coverage intervals (log levels). Solid red lines: 400 sector model responses.

Figure 3 plots Känzig's empirical IRFs in blue (the solid lines show the posterior mean; the dotted lines the 90 percent coverage intervals). The responses for all variables are shown in (log) levels to be consistent with Känzig. The model's responses are in red, and are generated by assuming that oil prices are subject to an AR(2) markup shock whose parameters are chosen to match as well as possible the WTI oil price responses in Känzig—hence the red and blue responses in the upper left panel of Figure 3 are close by construction. For this exercise, we assume monetary policy follows an inertial Taylor rule.[19]

In spite of the fact that no other parameter in this calibrated model is selected to match any empirical properties of inflation, the model seems to broadly capture the responses to oil price shocks of energy, overall CPI, core goods, and core services relatively well, at least up to two years

[19]See Appendix B.5 for details.

Figure 4. Känzig's WTI oil shocks responses: the role of propagation through the IO network



Notes: Solid red: same IRFs as Figure 3 but in terms of 12-month inflation (except for oil). Dotted red: counterfactual without IO network *except* for energy.

out.[20] The magnitude of the response of economic activity, as measured by consumption, is in line with the empirical evidence, even though its timing is off, which is not surprising in this model without habit formation and other features that may delay the response of economic activity.

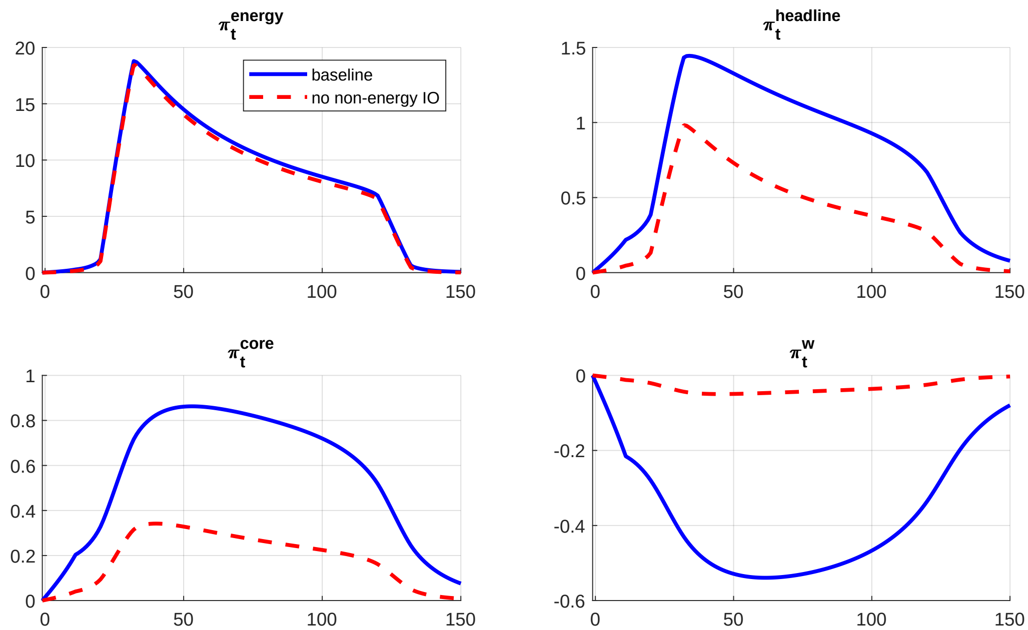
The solid red lines in Figure 4 display the same impulse responses as Figure 3, but expressed in terms of 12-month inflation as opposed to the price level (except for oil prices). The dotted lines show the responses to the same shock in a counterfactual model where the *direct* impact of energy on goods and services is the same as in the original model, but otherwise the input/output network is shut down in that we assume that each sector is an "island" (except, again, for energy inputs). The difference between the solid and dotted lines measures the importance of the IO network in propagating the shock. For the overall CPI propagation via the IO network amounts to less than one fourth of the responses after one year, but for core services inflation it accounts for about half of the responses to oil shocks, and about one third for core goods and overall core CPI.[21]

[20] Känzig (2021)'s paper did not include responses to core goods' and core services' prices. We therefore used his code to compute these impulse responses.

[21] Figures A2 and A3 in the Appendix perform the same exercise using a 396-sector, as opposed to 72-sector, linearized version of the model, to see to what extent aggregation impacts the results. We find that the responses in the more disaggregated model to be very similar. However, in the disaggregated model the difference between the solid and the dotted lines in Figure A3 are larger than in Figure 4, reinforcing the argument that propagation via the IO network is important.

5.3 The Inflationary Consequences of the Carbon Tax

Figure 5. The inflationary consequences of the carbon tax: dynamics under *output gap* targeting



Notes: Solid blue lines: baseline response. Dashed red lines: counterfactual without IO network *except* for energy.

The experiment we consider is a linear increase in the carbon tax from 0 to \$100 over 100 months, anticipated 20 months in advance (Figure A4 in the Appendix shows the path for the carbon tax). This trajectory is broadly similar to those which have been studied in the climate literature (e.g., Barron et al., 2018).[22] As mentioned, we solve the 69 sector version of model non-linearly. The blue lines in Figure 5 show the effect of the carbon tax on inflation—energy, headline CPI, core CPI, and wage inflation—for the case when monetary policy closes the output gap. We find that the carbon tax has sizable inflationary implications: 12 month headline CPI is one percentage point or more above target for more than 6 years; 12 month core CPI is 50 basis points or more above target for about 10 years (and 80 basis points or more above target for about 3 years). This result stands in contrast with the message from the literature mentioned in the introduction, which finds that the inflationary effects of the carbon tax are small.[23]

[22]As mentioned above, we exogenously specify this path for the *real* carbon tax $\tau_t = \mathcal{T}_t/P_t$, and so the nominal carbon tax changes endogenously with the consumer price index. For comparison, the \$100 value is well below the domestic cost of carbon estimate of \$215 in 2024 computed by Bilal and Känzig (2024), which is about \$157 in 2012 dollars.

[23]Importantly, the tax increase we study is of a similar magnitude to that generally considered in the literature: we are not finding larger inflationary effects simply because we study a larger tax. To give one example, Olovsson and Vestin (2023) consider an ad valorem tax on the dirty sector which rises from 0 to 65%. We study a per unit tax: one way to compare this to Olovsson and Vestin (2023)'s tax is to calculate total tax revenue as a fraction of the value of fossil fuel production in our steady state with taxes, which is only 18%. This fraction includes behavioral

In order to highlight the role played by the network for these results, the dashed red lines in Figure 5 show the results in the counterfactual economy where only the direct impact of the increased cost of energy is considered while the network is otherwise shut down (this is the same counterfactual experiment performed in Figure 4 of section 5.2). Figure 5 shows that the impact of the network is substantial: for headline inflation the network accounts for between one third and one half of the responses, while for core inflation the network is about two thirds of the impact. In sum, because of propagation via the I/O the network the Aoki (2001) view of the world is incomplete when it comes to assessing the inflationary effects of climate policy: the carbon tax has first order effects on core inflation even if the *direct* effect of the tax on the economy is limited.

How do these findings square with the analytical results in section 4? Recall that according to those results the effect of the tax on inflation is captured by the formula $\pi^c = \left[\boldsymbol{\gamma}' - \frac{\boldsymbol{\lambda}' K^{-1}}{\boldsymbol{\lambda}' K^{-1}\mathbf{1}}\right](1 - \Omega)^{-1}\boldsymbol{\epsilon} g$. First of all, the evidence in section 2 shows that the energy sector is central to the network (see Figure 1). If it were not, the direct effect of the tax $\boldsymbol{\epsilon}$ would be very similar to the total effect including propagation via the network $(I - \Omega)^{-1}\boldsymbol{\epsilon}$, hence the blue and dashed red lines in Figure 5 would be similar: setting certain elements of Ω to zero, as we do in the counterfactual represented by the dashed red line, would have no effect. Specifically, suppose that the sectors that *use energy as an input* were not central to the network. In this case, the direct plus first-round effects of the tax, $(I + \Omega)\boldsymbol{\epsilon}$, would be similar to the total effect; therefore, setting I/O linkages between nonenergy sectors to zero, as we do in the counterfactual, would have no effect. The large differences between the blue and dashed red lines show that, instead, these I/O linkages—which a two-sector model would abstract from—are important.

Second, the evidence also shows that high-emission energy sectors, as well as sectors with higher total emissions over gross output, tend to be more flexible than prices in the rest of the economy (see Figure 2).[24] This is important because if these sectors were sticky, the term $-\frac{\boldsymbol{\lambda}' K^{-1}}{\boldsymbol{\lambda}' K^{-1}\mathbf{1}}$ would prevail so that the inflationary consequences of the tax could even be negative.[25]

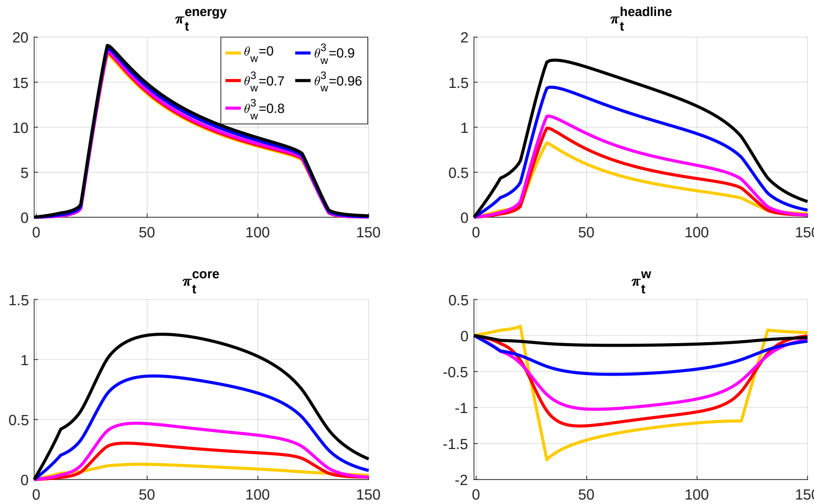
Figure 6 speaks to the importance of wage stickiness for the quantitative results. Recall that

responses since fossil fuel production and emissions fall in response to taxes, while the relative price of fossil fuels rises. If instead we shut off these behavioral responses by computing the tax rate times emissions in the pre-tax steady state divided by the value of fossil fuel production in the pre-tax steady state, this number is 67%, similar to Olovsson and Vestin (2023).

[24]Since total emissions are computed using the Leontief inverse matrix, total emissions over gross output $(I - \Omega)^{-1}\frac{e_i X^i}{P^i X^i}$ are roughly proportional to the direct and indirect effect of the tax, which is given by $(I - \Omega)^{-1} P \frac{e_i X^i}{M^i X^i}$.

[25]Implicitly, these results are obtained under the assumption that sectoral price stickiness remains the same, in spite of the large carbon tax levied on some sectors and its repercussions on the sectors that are downstream with respect to high-emissions energy. One might therefore wonder how our results would change if prices become more flexible in response to large shocks. In defense of our assumption, recall that, first, the tax increases are gradual, although fully anticipated. Second, and more important, the sectors that are directly taxed are almost all assumed to have nearly flexible prices as shown in Figure 2, with the only exception being coal. Third, and equally important, the analytical results in section 4 make plain that if *all* the sectors directly or indirectly affected by the tax had flexible prices, the effect of the tax on inflation would be *larger* than that shown in Figure 5.

Figure 6. Importance of wage stickiness

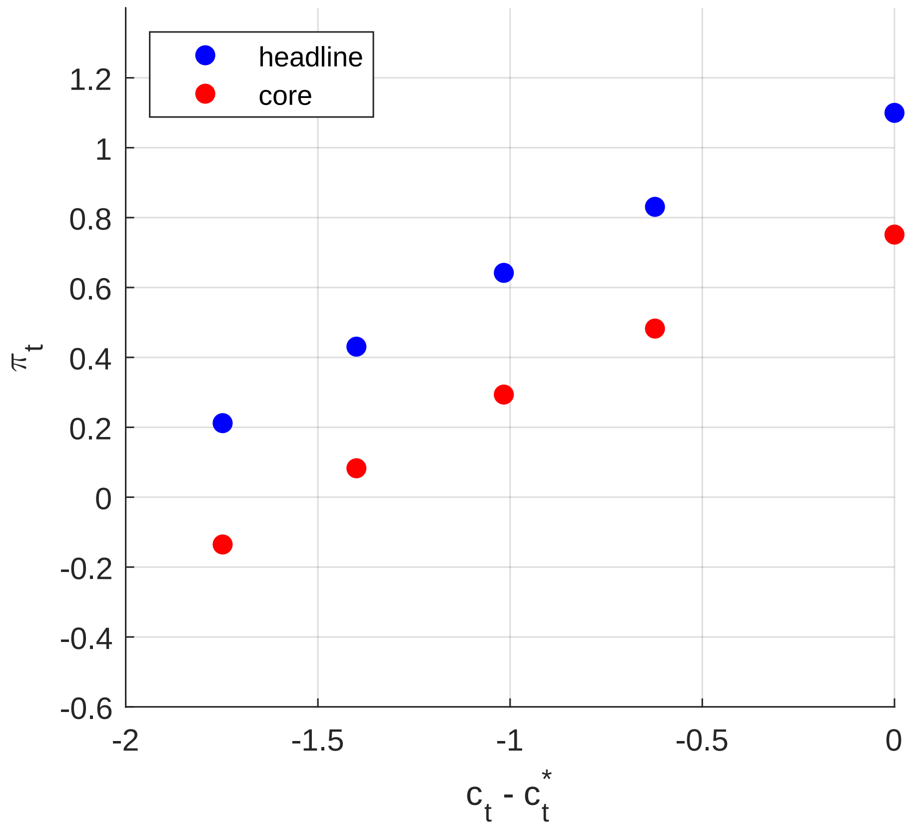


Notes: The solid blue lines display the baseline response, with $\theta^w = .9$. The other lines show the responses under alternative assumptions about wages stickiness (yellow, red, purple, and black correspond to $\theta^w = 0, .7, .9, .96$ respectively)

under the flexible price equilibrium real wages decline along with output following the introduction of the carbon tax. Under flexible wages (yellow lines in Figure 6), nominal wages fall substantially as soon as the carbon tax is introduced, and continue falling for much of the period under consideration. For the many sectors for which labor is an important input, this decline in wages compensates the increase in marginal costs due to the increased cost of energy, resulting in a muted response of core inflation relative to the baseline responses (blue lines). The stickier the wages, the more gradual the decline in labor costs, which implies that this compensating effect on marginal costs is dampened and hence core inflation is higher. Although the analytical results in section 4 were derived for an economy with flexible wages, they can be interpreted as relating to the sticky wages economy as well using Rubbo (2023)'s approach of interpreting the "labor union" as just another sector, whose output (labor services) is used by all other sectors of the economy. This labor union sector is not affected by the tax at all as it does not use any input other than labor. Its degree of stickiness is important because it affects the denominator in the the term $-\frac{\boldsymbol{\lambda}' K^{-1}}{\boldsymbol{\lambda}' K^{-1}\mathbf{1}}$—that is, the *relative* network-adjusted stickiness of the sectors that are affected by the tax. The labor union sector has a large λ_i—it is of course upstream. If sticky, it also has a large κ_i^{-1} thereby making the denominator, and therefore the inflationary consequences of the tax, larger.

The results in Figure 5 obtain when policy accommodates the shock and closes the output gap. How costly is it for the central bank to fight the effects of the carbon tax on inflation in terms of economic activity? Figure 7 addresses this question, as it shows *average* inflation and *average* output gap over the 100 months during which taxes are increasing under alternative

Figure 7. Tradeoffs in the quantitative IO model



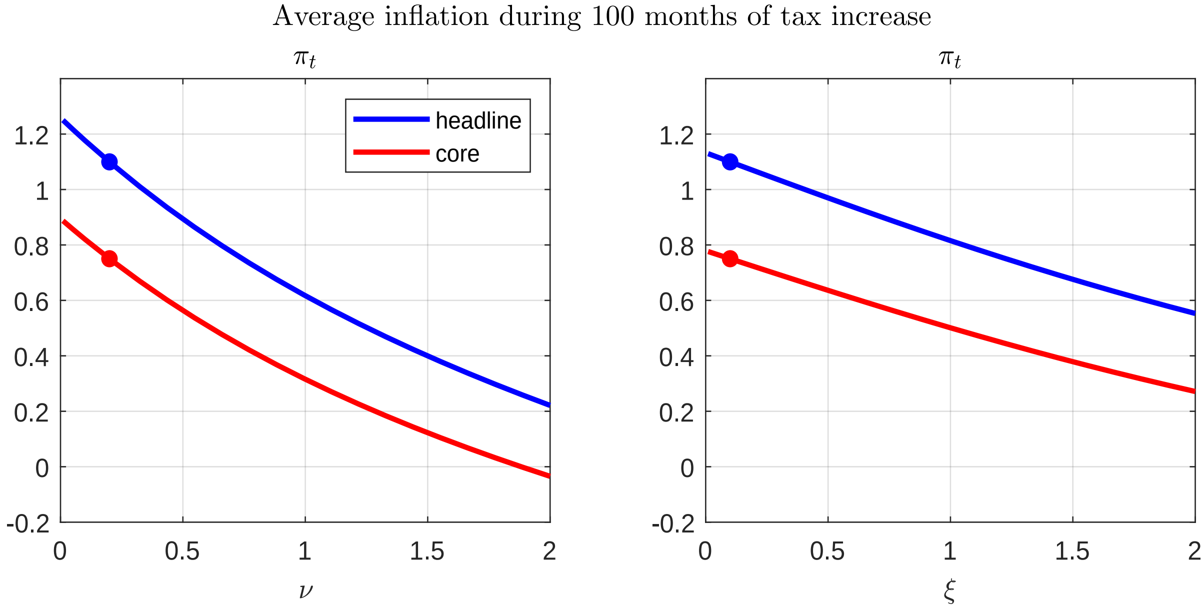
Notes: The dots compute average inflation and output gap over 100 months after the announcement of the tax increase for different policy rules.

reaction functions that place also weight on the inflation gap.[26] It shows that these tradeoffs are non-negligible: controlling headline inflation—e.g., keeping inflation to less than 60 basis points on average—takes a 1 percent average output gap over the same period, while controlling core inflation—e.g., keeping core inflation to less than 50 basis points on average—is associated with an average contraction of .6 percent of output over the entire period. Using a simple Okun law formulation, this amounts to .5 and .3 percentage points of higher unemployment on average during this 100 month period.

Figure 8 shows the extent to which the inflationary dynamics shown in Figure 5 depend on the two most important elasticity of substitution parameters: the elasticity of substitution between different inputs of a given type ξ, and the elasticity between energy and non-energy inputs ν. Specifically, the panels plot average annualized headline and core inflation over the 100 months during which taxes are increasing, as a function of ν and ξ. The bottom left panel shows that

[26]The reaction functions we consider are of the type $(y_t - y_t^*) - \psi(\pi_t - \pi^*) = 0$ where y_t^* is flexible output and π^* is the inflation target, which is 0 without loss of generality in these simulations. In Figure 5 the parameter ψ was set to 0.

Figure 8. Robustness to the elasticity of substitution



Notes: Lines show average headline (blue line) and core (red line) inflation over the 100 months during which taxes are increasing, as a function of as a function of the elasticity of substitution between energy and non-energy inputs ν (left panel) and the elasticity of substitution between intermediate input varieties ξ (right panel), fixing all other parameters at their baseline calibration. Circles indicate our baseline calibration.

average inflation very much depends on the assumption regarding ν. This is not surprising since for elevated values of ν it is easy to substitute away from highly-taxed energy in favor of less taxed intermediate inputs, so the effect of the tax is lower. However, the inflationary effects of the tax are really not all that sensitive to variations of ν within the range considered plausible according to the literature, namely between 0.15 and 0.25 (see Bachmann et al., 2022). Moreover, much larger values of ν would also imply degrees of reduction in emissions that seem implausibly high, as discussed later. The inflationary effects of the tax are much less sensitive to changes in ξ, the elasticity of substitution between intermediate inputs. In any case, as mentioned in section 5.1, our calibration for ξ is towards the upper bound of the range of estimates reported by Atalay (2017).

The paper focuses on the consequences of the carbon tax for the tradeoffs faced by monetary policymakers, as opposed to its implications for emissions and climate change, which the model is not designed to investigate. Still, for full disclosure Figure A6 in the Appendix shows the effect of the carbon tax on emissions. Specifically, it shows the long-run level of emissions, as well as output/usage of fossil fuels, after the tax is fully implemented as a fraction of emissions/usage prior to the introduction of the tax, as a function of as a function of the elasticity of substitution parameters. For our baseline choice of elasticities, which are quite low, we obtain an eventual reduction in emissions, and fossil fuel usage, of about 70 percent, a figure that is somewhat optimistic in light of estimates in the literature. Increasing these elasticities would further increase the reduction in eventual emissions induced by the carbon tax, obtaining for instance emission reductions greater than 80 percent when $\nu = 1$.[27]

6 Conclusion

It has been argued that the green transition will be inflationary. In this paper we investigated this question focusing on the effects of a carbon tax using a model with production networks. We obtain analytical results showing that the interaction of propagation via the I/O network and heterogeneity in sectoral nominal rigidities is key for the answer. In particular, we show that if price stickiness were the same across all sectors the tax would have no inflationary consequences or may even imply inflation below the target, even when monetary policy closes the output gap. For the carbon tax to be inflationary it is necessary that the sectors that are most affected by the tax, either directly or indirectly via the production network, have a higher CPI weight than their "divine coincidence" weight (Rubbo, 2023), where the latter is high if the sector is sticky and/or upstream. In other words, the carbon tax will be inflationary under two conditions. First, energy must be central to the network, which means it directly or indirectly affects sectors with a significant weight in the CPI index. Second, sectors that are directly or indirectly energy-intensive must have relatively more flexible prices than the rest of the economy.

Using a quantitative, non-linear version of the model with 69 sectors calibrated to data on input-output linkages and sectoral heterogeneity in price stickiness we then show that the carbon tax can create a sizable tradeoff between stabilizing inflation and the output gap. Specifically, a gradual increase in the carbon tax from 0 to \$100 over 100 months has sizable inflationary implications when monetary policy accommodates the shock—that is, it closes the output gap: 12 month headline CPI is one percentage point or more above target for more than 6 years; 12 month core CPI is 50 basis points or more above target for about 10 years (and 80 basis points or more above target for about three years). If policymakers try to fight the inflationary consequences of the tax, controlling headline inflation—e.g., keeping inflation to less than 60 basis points on average—takes a one percent average output gap over the six year period, while controlling core inflation—e.g., keeping core inflation to less than 50 basis points on average—is associated with an average contraction of 0.6 percent of output relative to natural over the entire period. These results are in stark contrast with those of the existing literature that generally ignores propagation via the I/O network, and finds that the impact of the tax is negligible. As such, this paper highlights the

[27] The dependence of emissions on ν is easy to explain: the impact of the carbon tax is larger if energy can be substituted away with other intermediate inputs. The dependence on ξ can be rationalized as follows. Within energy, ξ determines the substitutability of different fossil fuels. Increasing ξ leads to more usage for those fuels that are comparatively less polluting, and therefore less taxed. Outside of energy, ξ also determines the substitutability among non-energy intermediate goods and services. Hence increasing ξ implies a higher substitution away from those intermediates that are more heavily affected by the tax, either directly or indirectly, and therefore more pollutant in terms of total emissions over gross output.

importance of taking the I/O network into account for many relevant macroeconomic questions.

References

Afrouzi, Hassan and Saroj Bhattarai, "Inflation and GDP Dynamics in Production Networks: A Sufficient Statistics Approach," Technical Report, National Bureau of Economic Research 2023.

Airaudo, Florencia S, Evi Pappa, and Hernán D Seoane, *The green metamorphosis of a small open economy*, Centre for Economic Policy Research, 2023.

Andaloussi, Mehdi Benatiya, Benjamin Carton, Christopher Evans, Florence Jaumotte, Dirk Muir, Jean-Marc Natal, Augustus J. Panton, and Simon Voigts, "Chapter 3, World economic outlook, Near-term macroeconomic impact of decarbonization policies," *International Monetary Fund*, 2022.

Aoki, Kosuke, "Optimal monetary policy responses to relative-price changes," *Journal of Monetary Economics*, 2001, *48* (1), 55–80.

Atalay, Enghin, "How important are sectoral shocks?," *American Economic Journal: Macroeconomics*, 2017, *9* (4), 254–280.

Bachmann, Ruediger, David Baqaee, Christian Bayer, Moritz Kuhn, Andreas Löschel, Benjamin Moll, Andreas Peichl, Karen Pittel, and Moritz Schularick, "What if? The economic effects for Germany of a stop of energy imports from Russia," Technical Report, ECONtribute Policy Brief 2022.

Barron, Alexander R, Allen A Fawcett, Marc AC Hafstead, James R McFarland, and Adele C Morris, "Policy insights from the EMF 32 study on US carbon tax scenarios," *Climate change economics*, 2018, *9* (01), 1840003.

Bartocci, Anna, Alessandro Notarpietro, and Massimiliano Pisani, ""Green" fiscal policy measures and non-standard monetary policy in the Euro Area," 2022. Bank of Italy Temi di Discussione (Working Paper) No. 1377.

Bettarelli, Luca, Davide Furceri, Loredana Pisano, and Pietro Pizzuto, "Greenflation: Empirical evidence using macro, regional and sectoral data," *European Economic Review*, 2025, *174*, 104983.

Bilal, Adrien and Diego R Känzig, "The macroeconomic impact of climate change: Global vs. local temperature," *National Bureau of Economic Research*, 2024, *32450.*

_ and James H Stock, "Macroeconomics and climate change," *National Bureau of Economic Research*, 2025, *33567.*

Carvalho, Carlos, “Heterogeneity in price stickiness and the real effects of monetary shocks,” *Frontiers in Macroeconomics*, 2006, *2* (1).

—, Jae Won Lee, and Woong Yong Park, “Sectoral price facts in a sticky-price model,” *American Economic Journal: Macroeconomics*, 2021, *13* (1), 216–256.

Cotton, Christopher D. and Vaishali Garga, “The Role of Industrial Composition in Driving the Frequency of Price Change,” Junes 2022. Federal Reserve Bank of Boston Research Department Working Papers No. 22-9.

Cruz, José-Luis and Esteban Rossi-Hansberg, “The economic geography of global warming,” *Review of Economic Studies*, 2024, *91* (2), 899–939.

Del Negro, Marco, Marc P Giannoni, and Frank Schorfheide, “Inflation in the great recession and new keynesian models,” *American Economic Journal: Macroeconomics*, 2015, *7* (1), 168–196.

Ferrari, Alessandro and Valerio Nispi Landi, “Will the green transition be inflationary? Expectations matter,” *IMF Economic Review*, 2024, pp. 1–64.

Ferrari, Massimo Minesso and Maria Sole Pagliari, “No country is an island. International cooperation and climate change.,” *International Cooperation and Climate Change.(June 2021). Banque de France Working Paper*, 2021, (815).

Fornaro, Luca, Veronica Guerrieri, and Lucrezia Reichlin, “Monetary Policy for the Energy Transition,” Technical Report, Working Paper 2024.

Garcia, Pablo, Pascal Jacquinot, Črt Lenarčič, Kostas Mavromatis, Niki Papadopoulou, and Edgar Silgado-Gómez, “Green transition in the Euro area: domestic and global factors,” *De Nederlandsche Bank Working Paper*, 2024.

Ghassibe, Mishel, “Monetary policy and production networks: an empirical investigation,” *Journal of Monetary Economics*, 2021, *119*, 21–39.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski, “Optimal taxes on fossil fuel in general equilibrium,” *Econometrica*, 2014, *82* (1), 41–88.

Guerrieri, Veronica, Guido Lorenzoni, Ludwig Straub, and Iván Werning, “Monetary policy in times of structural reallocation,” *Proceedings of the Jackson Hole Symposium*, 2021.

—, Michala Marcussen, Lucrezia Reichlin, and Silvana Tenreyro, “Geneva Report: The art and science of patience: relative prices and inflation,” 2023.

Hassler, John, Per Krusell, and Conny Olovsson, "Climate policy in the wide world," *Manuscript*, 2023.

Hobijn, Bart and Fernanda Nechio, "Sticker shocks: using VAT changes to estimate upper-level elasticities of substitution," *Journal of the European Economic Association*, 2019, *17* (3), 799–833.

Känzig, Diego R, "The macroeconomic effects of oil supply news: Evidence from OPEC announcements," *American Economic Review*, 2021, *111* (4), 1092–1125.

Känzig, Diego R., "The unequal economic consequences of carbon pricing," 2022. Mimeo, Northwestern University.

Kapfhammer, Felix, "The economic consequences of effective carbon taxes," *American Economic Journal: Macroeconomics*, 2023.

Konradt, Maximilian and Beatrice Weder di Mauro, "Carbon Taxation and Greenflation: Evidence from Europe and Canada," September 2021. CEPR Discussion Paper DP16396.

_ , Thomas McGregor, and Mr Frederik G Toscani, "Carbon prices and inflation in the Euro Area," *International Monetary Fund Working Paper*, 2024, *24-31.*

La'O, Jennifer and Alireza Tahbaz-Salehi, "Optimal monetary policy in production networks," *Econometrica*, 2022, *90* (3), 1295–1336.

Metcalf, Gilbert E. and James H. Stock, "The Macroeconomic Impact of Europe's Carbon Taxes," *American Economic Journal: Macroeconomics*, 2023, *15* (3), 265–286.

Metcalf, Gillbert E and David Weisbach, "The design of a carbon tax," *Harv. Envtl. L. Rev.*, 2009, *33*, 499.

Moessner, Richhild, "Effects of Carbon Pricing on Inflation," February 2022. CESifo Working Paper No. 9563.

Nakamura, Emi and Jón Steinsson, "Five Facts about Prices: A Reevaluation of Menu Cost Models," *Quarterly Journal of Economics*, 11 2008, *123* (4), 1415–1464.

_ and Jon Steinsson, "Monetary non-neutrality in a multisector menu cost model," *The Quarterly Journal of Economics*, 2010, *125* (3), 961–1013.

Nakov, Anton and Carlos Thomas, "Climate-Conscious Monetary Policy," 2023.

Oberfield, Ezra and Devesh Raval, "Micro data and macro technology," *Econometrica*, 2021, *89* (2), 703–732.

Olovsson, Conny and David Vestin, *Greenflation?*, Sveriges Riksbank, 2023.

Rubbo, Elisa, "Networks, Phillips curves, and monetary policy," *Econometrica*, 2023, *91* (4), 1417–1455.

Schnabel, Isabel, "A new age of energy inflation: climateflation, fossilflation and greenflation," in "Speech given at a panel on "Monetary Policy and Climate Change" at The ECB and its Watchers XXII Conference, March" 2022.

Shapiro, Joseph S, "The environmental bias of trade policy," *The Quarterly Journal of Economics*, 2021, *136* (2), 831–886.

Shapiro, Joseph S., Eva Lyubich, and Reed Walker, "Regulating Mismeasured Pollution: Implications of Firm Heterogeneity for Environmental Policy," *AEA Papers and Proceedings*, May 2018, *108*, 136–42.

Appendix A Data Construction

This appendix describes our procedure to construct and merge price frequency change and emissions data with BEA input-output tables.

Price change frequencies. Sectoral price change frequency data are sourced from Cotton and Garga (2022), who use price change frequencies from Nakamura and Steinsson (2008). Specifically, Cotton and Garga (2022) use the price change frequencies of CPI and PPI products from Nakamura and Steinsson (2008), and transform these product price change frequencies into *sectoral* price change frequencies, with sectors defined at the 2017 six-digit NAICS level.

Emissions and input-output tables. Emissions data are constructed from a combination of data from the Bureau of Economic Analysis (BEA), Energy Information Administration (EIA), and Environmental Protection Agency (EPA). We follow the methods used by Shapiro (2021) to compute total emissions by sector and direct emissions by sector.

First, we construct augmented versions of the 2012 BEA input-output tables, in which we work at the summary level of aggregation (71 industry groups), but expand the number of industries to distinguish between oil extraction, gas extraction and coal mining. We begin with the BEA's industry-by-commodity "make" table M and commodity-by-industry "use" table U, defined at the 'detail' level of aggregation: square 405×405 matrices originally, respectively representing the production and use of each commodity by each industry in dollar terms. Specifically, each element M_{ij} of M represents the production of commodity j by industry i, while each element U_{ij} of U represents the use of commodity i by industry j. We then aggregate these matrices up to the 'summary' level by summing across all the 'detail' industries contained within a 'summary' industry.[28] The only exception is that we keep the 'detail' industry 'Coal mining' separate from the rest of the 'summary' industry 'Mining, except oil and gas'. This leaves us with aggregated make and use tables with dimensions 72×72.

We then split industry 211 (Oil and gas extraction) into two. We update the "make" table by assigning output in the new sectors such that the oil industry produces all of the old industry's output of commodity 324110 (Petroleum refineries), the gas industry produces all of the old industry's output of commodity 325120 (Industrial gas manufacturing), and the residual output is assigned to make the new oil and gas sectors' relative level of production line up with production of oil and gas per the EIA.[29] We then update the "use" table by splitting the commodity usage of the old

[28] As an example, 'Support activities for mining' (at the summary level) contains both 'Drilling oil and gas wells' and 'Other support activities for mining'.

[29] Since the EIA's data are in terms of energy produced, rather than dollars spent, we transform the EIA energy use data into dollar amounts using the 2012 average prices of Brent crude and natural gas per energy unit (pulled from Haver).

industry again in line with the relative output of the sector a choice that assumes the new oil and gas sectors individually have the same commodity mix in inputs as the old combined sector. The new make and use tables $\overline{M}$ and $\overline{U}$ thus have dimensions of 73×72 and 72×73 respectively.

We then follow the standard method of constructing an industry-level input-output coefficients matrix by normalizing each column of $\overline{M}$ by total commodity usage (i.e., the sum of the elements in that column) to create a "market shares" matrix m, and similarly normalize each column of $\overline{U}$ by total industry output (once again, the sum of elements in that column) to create a "direct requirements" matrix u. Multiplying m by u then gives us the industry-by-industry technical coefficients matrix A, in which each element A_{ij} represents the dollars of industry i's commodity production that industry j must use in order to produce a dollar of output.[30] This matrix helps define the following (rather famous) equilibrium:

$$X = AX + Y \implies X = (I - A)^{-1}Y,$$

where for a number of industries N, X denotes the N-dimensional vector of industry gross output, Y denotes a given N-dimensional vector of final demand, and $(I - A)^{-1}$ denotes the $N \times N$ Leontief inverse or "total requirements matrix", which shows the amount of output required from each industry in total (not merely directly, but throughout the supply chain) to meet the given vector of final demand Y.

We compute total and direct emissions by sector using the Leontief inverse $(I - A)^{-1}$ and IO coefficients matrix A respectively. To do so, we construct a N-dimensional row vector c of 'raw' CO_2 emissions by energy type, which is 0 everywhere except for the entries associated with the oil, gas, and coal industries from the BEA tables. In those three entries, we take the EIA energy production data for each source, and multiply it by the corresponding emissions intensity factor from the EPA, where these intensities show the amount of CO_2 emitted per unit of energy produced for a given energy source. This vector c corresponds to $\{e_i X_i\}$ in the quantitative model presented in section 3, so that c divided by nominal gross output is proportional to the vector of $\{e_i/P^i\}$'s. We then premultiply the Leontief inverse and the IO coefficients matrix by c, producing in each case an N-dimensional row vector showing carbon emissions associated with each industry. The row vector cA gives emissions associated with energy usage in the production process for each industry, while the row vector $c(I - A)^{-1}$ shows *total* emissions associated with an industry's production, all the way upstream in its supply chain.

Crosswalk. In order to combine the price change frequencies with the emissions data described above, we create a crosswalk between the BEA's 2012 input-output sector definitions for the 405×405 I/O matrix and the 2017 six-digit NAICS sectors in which terms Cotton and Garga (2022)

[30] In terms of our notation in the main text, A is the inverse of Ω.

present their price change frequencies. The BEA's sectors are closely related to the 2012 NAICS sectors, and a concordance is provided in the I/O tables between those two types of codes. We thus follow two steps. First, we link the 2017 and 2012 six-digit NAICS codes using an existing concordance between them. Then, we use the 2012 BEA-2012 NAICS concordance to complete the link.

The first caveat is that the link between the 2012 NAICS and the BEA input-output codes is not perfect, in the sense that the NAICS codes vary in the level of aggregation at which they map into the BEA codes. While some NAICS codes map into the BEA codes at the six-digit level, others only map in at the five- or four-digit level, with some going as low as at the two-digit level. This is an issue in the sense that each six-digit NAICS code has a price change frequency associated with it, which means that BEA codes have multiple price change frequencies associated with them if they concord with multiple six-digit NAICS codes. To resolve this issue, we take an average across the "candidate" price change frequencies for each BEA code, which then leaves us with a unique code for each input-output sector.

The other caveat is that even after conducting the merge described above, some BEA codes did not have any candidate price change frequencies associated with them due to the Cotton and Garga (2022) data not covering the entire set of NAICS six-digit codes. To deal with this issue, we apply the average price change frequency across the closest set of comparable BEA codes to any BEA code which lacks a match. Specifically, we cut the BEA codes from six digits down to five, search for sectors that match with them at this five-digit level, take the average price change frequency across these "comparable" sectors, and apply it to the unmatched sector. If no five-digit match with price change frequency data exists, we try four digits, three digits, and so on until a price change frequency is assigned to the sector. Using this method, we are able to assign to each BEA sector (with the exception of a few BEA industries operating in the public sector) a price change frequency.

The procedure just described gives us the frequency of price adjustment for sectors at the "detailed" level of aggregation. We aggregate to the "summary" level by taking the gross output weighted average of the inverse frequency of price adjustment among all "detailed" sectors contained in each "summary" sector.

Appendix B Multisector model

B.1 Optimality conditions

The household's optimization problem (1) implies the following. First, the demand for each sector is given by

$$C_t^i = \gamma_i C_t \left(\frac{P_t^i}{P_t}\right)^{-\zeta} \tag{B.1}$$

where the consumer price index P_t is given by

$$P_t = \left[\sum_{i=1}^{n} \gamma_i (P_t^i)^{-(\zeta-1)}\right]^{-\frac{1}{\zeta-1}} \tag{B.2}$$

Second, the demand for variety j in sector i is given by

$$C_t^i(j) = C_t^i \left(\frac{P_t^i(j)}{P_t^i}\right)^{-\zeta} \tag{B.3}$$

where each sectoral price index P_t^i is an aggregate of prices set by producers in that sector:

$$P_t^i = \left[\int_0^1 (P_t^i(j))^{-(\varepsilon^i-1)} dj\right]^{-\frac{1}{\varepsilon^i-1}} \tag{B.4}$$

The solution to the union's optimization problem (2) yields the optimality condition

$$W_t^* = b \frac{\sum_{k=0}^{\infty} (\theta_w \beta)^k N_{t+k} \left(\frac{W_t^*}{W_{t+k}}\right)^{-\varepsilon^w}}{\sum_{k=0}^{\infty} (\theta_w \beta)^k \frac{1}{P_{t+k} C_{t+k}} N_{t+k} \left(\frac{W_t^*}{W_{t+k}}\right)^{-\varepsilon^w}} \tag{B.5}$$

where we define $b = \dfrac{\varepsilon^w}{\varepsilon^w - 1}\widetilde{b}$. Note that in zero-inflation steady state, or in the flexible-wage limit with $\theta_w = 0$, we have $\dfrac{W_t}{P_t} = bC_t$. The wage W_t evolves according to

$$W_t = \left[\theta_w (W_{t-1}^i)^{1-\varepsilon^w} + (1-\theta_w)(W_t^*)^{1-\varepsilon^w}\right]^{\frac{1}{1-\varepsilon^w}} \tag{B.6}$$

Attaching multipliers $\widetilde{M}_t^i, P_t^{I,i}, P_t^{E,i}, P_t^{N,i}$ to the constraints, the firm's cost minimization problem (3) yields the optimality conditions

$$L_t^i = (A_t^i)^{\eta-1} X_t^i \alpha_i \left(\frac{W_t}{\widetilde{M}_t^i}\right)^{-\eta}$$

$$I_t^i = (A_t^i)^{\eta-1} X_t^i (1-\alpha_i) \left(\frac{P_t^{I,i}}{\widetilde{M}_t^i}\right)^{-\eta}$$

$$E_t^i = \varsigma_i I_t^i \left(\frac{P_t^{E,i}}{P_t^{I,i}}\right)^{-\nu}$$

$$N_t^i = (1-\varsigma_i) I_t^i \left(\frac{P_t^{N,i}}{P_t^{I,i}}\right)^{-\nu}$$

$$X_t^{ij} = \omega_{ij}^E E_t^i \left(\frac{P_t^j}{P_t^{E,i}}\right)^{-\xi} + \omega_{ij}^N N_t^i \left(\frac{P_t^j}{P_t^{N,i}}\right)^{-\xi}$$

which implies that

$$
\begin{aligned}
\widetilde{M}_t^i &= \frac{1}{A_t^i}\left[\alpha_i\left(W_t\right)^{-(\eta-1)}+\left(1-\alpha_i\right)\left(P_t^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} \\
P_t^{I,i} &= \left[\varsigma_i\left(P_t^{E,i}\right)^{-(\nu-1)}+\left(1-\varsigma_i\right)\left(P_t^{N,i}\right)^{-(\nu-1)}\right]^{-\frac{1}{\nu-1}} \\
P_t^{E,i} &= \left[\sum_j \omega_{ij}^E\left(P_t^j\right)^{-(\xi-1)}\right]^{-\frac{1}{\xi-1}} \\
P_t^{N,i} &= \left[\sum_j \omega_{ij}^N\left(P_t^j\right)^{-(\xi-1)}\right]^{-\frac{1}{\xi-1}}
\end{aligned}
$$

$\widetilde{M}_t^i$ can be interpreted as the nominal marginal cost excluding the carbon tax. The full nominal marginal cost is

$$
\begin{aligned}
M_t^i &= \frac{1}{A_t^i}\left[\alpha_i\left(W_t\right)^{-(\eta-1)}+\left(1-\alpha_i\right)\left(P_t^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}}+\mathcal{T}_t e_i \\
&= \frac{1}{A_t^i}\left[\alpha_i\left(W_t\right)^{-(\eta-1)}+\left(1-\alpha_i\right)\left[\sum_j \omega_{ij}\left(P_t^j\right)^{-(\xi-1)}\right]^{\frac{\eta-1}{\xi-1}}\right]^{-\frac{1}{\eta-1}}+\mathcal{T}_t e_i
\end{aligned}
$$

The solution to the firm's optimal pricing problem (4) implies that the price set by a resetting firm in sector i at date t, P_t^{i*} satisfies

$$
\sum_{k=0}^{\infty} Q_{t+k|t}\theta_i^k\left[P_t^{i*}-\frac{\varepsilon^i}{\varepsilon^i-1}M_t^i\right]X_{t+k}^i\left(\frac{P_t^{i*}}{P_{t+k}^i}\right)^{-\varepsilon^i}=0 \tag{B.7}
$$

The sectoral price index P_t^i evolves according to

$$
P_t^i=\left[\theta_i(P_{t-1}^i)^{1-\varepsilon^i}+(1-\theta_i)(P_t^{i*})^{1-\varepsilon^i}\right]^{\frac{1}{1-\varepsilon^i}} \tag{B.8}
$$

B.2 Solving the log-linearized model

We log-linearize the model around an arbitrary zero-inflation steady state, assuming no shocks and no changes in exogenous variables except for the carbon tax. We log-linearize all variables except the carbon tax, which we linearize; this allows for the case in which the steady state carbon tax $\mathcal{T}=0$. Importantly, we do not need to fully solve for steady state in order to linearize the model. We only need to know price flexibility, input shares and emissions intensity by sector in steady state.

Solving for key variables Log-linearizing (B.5) and (B.6) yields

$$w_t^* = (1 - \beta\theta_w) \sum_{k=0}^{\infty} (\beta\theta_w)^k (p_{t+k} + c_{t+k})$$
$$w_t = \theta_w w_{t-1} + (1 - \theta_w) w_t^*$$

Combining and defining $\pi_t^w = w_t - w_{t-1}$, $\omega_t = w_t - p_t$, we have the nominal wage Phillips curve

$$\pi_t^w = \kappa_w (c_t - \omega_t) + \beta \pi_{t+1}^w \tag{B.9}$$

where $\kappa_w := \dfrac{(1 - \beta\theta_w)(1 - \theta_w)}{\theta_w}$. (Again, note that with flexible wages we have $\kappa_w = \infty$ and $\omega_t = c_t$.) Real wages evolve according to

$$\omega_t = \omega_{t-1} + \pi_t^w - \pi_t^c \tag{B.10}$$

Similarly, log-linearizing (B.7) around a steady state with $\Pi^i = 1$, we have

$$p_t^{i*} = (1 - \beta\theta_i) \sum_{k=0}^{\infty} (\beta\theta_i)^k m_{t+k}^i$$

where lower case variables denote log-deviations. Log-linearizing (B.8), we have

$$p_t^i = \theta_i p_{t-1}^i + (1 - \theta_i) p_t^{i*}$$

Combining and defining $\pi_t^i = p_t^i - p_{t-1}^i$, we have the standard sectoral Phillips curve

$$\pi_t^i = \kappa_i (m_t^i - p_t^i) + \beta \pi_{t+1}^i \tag{B.11}$$

where $\kappa_i := \dfrac{(1 - \beta\theta_i)(1 - \theta_i)}{\theta_i}$.

Constant returns to scale imply that

$$M_t^i X_t^i = W_t L_t^i + \sum_{j=1}^{n} P_t^j X_t^{ij} + \mathcal{T}_t e_i X_t^i$$

Log-linearizing around steady state, since inputs are chosen to minimize cost, Shephard's lemma implies that

$$M^i X^i m_t^i = W L^i w_t + \sum_j P^j X^{ij} p_t^j + e_i X^i \widehat{\mathcal{T}}_t$$

where we linearize $\mathcal{T}_t$ (since we are linearizing around a steady state in which it is zero) and log-linearize all other variables. In real terms, we have

$$m_t^i - p_t = m_t^i - p_t^i + s_t^i = \frac{W L^i}{M^i X^i} \omega_t + \sum_j \frac{P^j X^{ij}}{M^i X^i} s_t^j + \frac{e_i P X^i}{M^i X^i} \widehat{\tau}_t \tag{B.12}$$

where $\widehat{\tau}_t = P\widehat{\mathcal{T}}_t$, and we define (the log-deviation of) real sectoral prices, deflated by CPI, to be $s_t^i := p_t^i - p_t$.

Combining (B.11) and (B.12), we have sectoral Phillips curves in terms of value added, relative prices and taxes:

$$\pi_t^i = \kappa_i \left[\frac{WL^i}{M^i X^i}\omega_t + \sum_j \frac{P^j X^{ij}}{M^i X^i} s_t^j + \frac{e_i P X^i}{M^i X^i}\widehat{\tau}_t - s_t^i \right] + \beta \pi_{t+1}^i, i = 1, ..., n \tag{B.13}$$

Stacking these n equations into a vector, we have

$$\boldsymbol{\pi_t} = K(\boldsymbol{\alpha}\omega_t - (I - \Omega)\boldsymbol{s_t} + \boldsymbol{\epsilon}\tau_t) + \beta\boldsymbol{\pi_{t+1}} \tag{B.14}$$

where K is a diagonal matrix with ith diagonal element κ_i; $\boldsymbol{\alpha}$ is a $n \times 1$ vector with ith element $\frac{WL^i}{M^i X^i}$, the labor share of total costs; Ω is a $n \times n$ matrix with ijth element $\frac{P^j X^{ij}}{M^i X^i}$, the share of expenditure on input j in sector i's total costs; and $\boldsymbol{\epsilon}$ is a $n \times 1$ vector with ith element $\frac{e_i P X^i}{M^i X^i}$. Note that to calibrate these equations, we need data on $\boldsymbol{\alpha}, \Omega, \boldsymbol{\epsilon}$, and sectoral price adjustment frequencies $1 - \theta_i$ (which can be used to calculate κ_i); we do not need the full set of structural parameters. When wages are flexible ($\theta_w = 1$), $\omega_t = y_t$ and (B.14) reduces to (B.19) in the main text.

The dynamics of relative prices must also satisfy

$$\Delta s_t^i = \pi_t^i - \pi_t^c,\ i = 1, ..., n \tag{B.15}$$

CPI inflation is defined by

$$\pi_t^c = \sum_{i=1}^{n} \widetilde{\gamma}_i \pi_t^i \tag{B.16}$$

where $\widetilde{\gamma}_i := \frac{P^i C^i}{PC}$ denotes steady state consumption expenditure shares, which may differ from γ_i. Representing these equations in vector firm yields equations (B.20) and (9) in the main text.

Given a path for $\hat{\tau}_t$, (B.13), (B.15), (B.16), (B.9) and (B.10) constitute a system of $2n + 3$ equations in $2n + 4$ endogenous variables $(\{s_t^i, \pi_t^i\}_{i=1}^n, c_t, \pi_t^c, \omega_t, \pi_t^w)$. To close the system, we need to specify a monetary policy rule. The linearized system can then be used to study the impulse response to a shock to carbon taxes.

Solving for other variables Having solved for $\{s_t^i, \pi_t^i\}_{i=1}^n, c_t, \pi_t^c, \omega_t, \pi_t^w$, we can solve for other variables of interest – sectoral quantities and aggregate emissions. Log-linearizing sectoral final consumption demand (B.1), we have

$$c_t^i = c_t - \zeta s_t^i \tag{B.17}$$

Log-linearizing goods market clearing (5) (and multiplying and dividing by steady state prices in order to relate the coefficients to observable values), we have

$$x_t^j = \sum_{j=1}^{n} \frac{P^i X^{ji}}{P^i X^i} x_t^{ji} + \frac{P^i C^i}{P^i X^i} c_t^i \tag{B.18}$$

It is convenient to denote the set of energy and non-energy goods by $\mathcal{E}$ and $\mathcal{N}$ respectively. Log-linearizing the equations characterizing demand for intermediate goods, we have

$$\begin{aligned}
x_t^{ij} &= e_t^i - \xi(p_t^j - p_t^{E,i}) \text{ if } i \in \mathcal{E} \\
x_t^{ij} &= n_t^i - \xi(p_t^j - p_t^{N,i}) \text{ if } i \in \mathcal{N} \\
e_t^i &= i_t^i - \nu(p_t^{E,i} - p_t^{I,i}) \\
n_t^i &= i_t^i - \nu(p_t^{N,i} - p_t^{I,i}) \\
i_t^i &= x_t^i - \eta(p_t^{I,i} - \widetilde{m}_t^i) \\
p_t^{I,i} &= \widetilde{\varsigma}_i p_t^{E,i} + (1 - \widetilde{\varsigma}_i) p_t^{N,i} \\
p_t^{E,i} &= \sum_j \widetilde{\omega}_{ij}^E p_t^j \\
p_t^{N,i} &= \sum_j \widetilde{\omega}_{ij}^N p_t^j
\end{aligned}$$

where $\widetilde{m}_t^i$ is the log-deviation of $\widetilde{M}_t^i$, nominal marginal cost excluding the carbon tax; $\widetilde{\varsigma}_i := \frac{P^{E,i}E^i}{P^{I,i}I^i} = \varsigma_i \left(\frac{P^{E,i}}{P^{I,i}}\right)^{1-\nu}$ is the share of energy inputs in sector i's overall intermediates expenditure; $\widetilde{\omega}_{ij}^E := \mathbf{1}\{j \in \mathcal{E}\} \frac{P_j X_{ij}}{P^{E,i}E^i} = \omega_{ij}^E \left(\frac{P^j}{P^{E,i}}\right)^{1-\xi}$ is the share of input j in sector i's expenditure on energy (and equals zero if j is not an energy input); and $\widetilde{\omega}_{ij}^N := \mathbf{1}\{j \in \mathcal{N}\} \frac{P_j X_{ij}}{P^{N,i}N^i} = \omega_{ij}^N \left(\frac{P^j}{P^{N,i}}\right)^{1-\xi}$ is the share of input j in sector i's expenditure on non-energy inputs (and equals zero if j is an energy input). In general, reduced-form parameters with tildes denote revenue shares, which generally differ from the corresponding structural parameters without shares except in the Cobb-Douglas case. For example, the share of energy inputs in sector i's overall intermediates expenditure $\widetilde{\varsigma}_i$ depends on relative prices and thus may differ from the structural parameter ς_i.

Since emissions per unit of gross output are fixed, the same argument based on Shephard's lemma as made above establishes that

$$\widetilde{m}_t^i = \frac{WL^i}{\widetilde{M}^i X^i} w_t + \frac{P^{I,i}I^i}{\widetilde{M}^i X^i} p_t^{I,i}$$

So, if $j \in \mathcal{E}$ we have

$$\begin{aligned}
x_t^{ij} &= x_t^i - \eta\left(p_t^{I,i} - \frac{WL^i}{\widetilde{M}^i X^i} w_t - \frac{P^{I,i} I^i}{\widetilde{M}^i X^i} p_t^{I,i}\right) - \nu(p_t^{E,i} - p_t^{I,i}) - \xi(p_t^j - p_t^{E,i}) \\
&= x_t^i - \eta\left(s_t^{I,i} - \frac{WL^i}{\widetilde{M}^i X^i}(w_t - p_t) - \frac{P^{I,i} I^i}{\widetilde{M}^i X^i} s_t^{I,i}\right) - \nu(s_t^{E,i} - s_t^{I,i}) - \xi(s_t^j - s_t^{E,i}) \\
&= x_t^i - \left[\eta\left(1 - \frac{P^{I,i} I^i}{\widetilde{M}^i X^i}\right) - \nu\right] s_t^{I,i} + \eta \frac{WL^i}{\widetilde{M}^i X^i}\omega_t - (\nu - \xi) s_t^{E,i} - \xi s_t^j \\
&= x_t^i - \Theta^{ij_t}
\end{aligned}$$

where $\Theta_t^{ij} := \left[\eta\left(1 - \frac{P^{I,i} I^i}{\widetilde{M}^i X^i}\right) - \nu\right] s_t^{I,i} - \eta \frac{WL^i}{\widetilde{M}^i X^i}\omega_t + (\nu - \xi) s_t^{E,i} + \xi s_t^j$, and we define

$$\begin{aligned}
s_t^{I,i} &= \widetilde{\varsigma}_i s_t^{E,i} + (1 - \widetilde{\varsigma}_i) s_t^{N,i} \\
s_t^{E,i} &= \sum_j \widetilde{\omega}_{ij}^E s_t^j \\
s_t^{N,i} &= \sum_j \widetilde{\omega}_{ij}^N s_t^j
\end{aligned}$$

For non-energy inputs ($j \in \mathcal{N}$) we instead have

$$\Theta_t^{ij} := \left[\eta\left(1 - \frac{P^{I,i} I^i}{\widetilde{M}^i X^i}\right) - \nu\right] s_t^{I,i} - \eta \frac{WL^i}{\widetilde{M}^i X^i}\omega_t + (\nu - \xi) s_t^{N,i} + \xi s_t^j$$

Since Θ_t^{ij} is a known function of relative prices and real wages, we can substitute $x_t^i - \Theta^{ij_t}$ back into the market clearing condition (B.18):

$$x_t^i = \sum_{j=1}^n \frac{P^i X^{ji}}{P^i X^i}(x_t^j - \Theta_t^{ji}) + \frac{P^i C^i}{P^i X^i} c_t^i$$

and invert this equation to solve for sectoral gross output x_t^i. Finally, aggregate emissions can be defined as $E_t = \sum_{i=1}^n e_i X_t^i$. Log-linearizing,

$$e_t = \sum_{i=1}^n \frac{e_i X^i}{E} x_t^i$$

where $e^i X^i$ is steady state direct emissions of sector i (which we calibrate). Note that in principle, the log-deviation of emissions can be written solely as a function of aggregate consumption c_t and relative prices $\{s^i\}_{i=1}^n$.

B.3 Effects of a permanent tax increase in the nonlinear model

Next, we describe how to compute the new steady state following a permanent increase in carbon taxes. Recall that we have

$$\widetilde{M}_t^i = \frac{1}{A_t^i}\left[\alpha_i \left(W_t\right)^{-(\eta-1)} + (1-\alpha_i)\left(P_t^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}}$$

$$P_t^{I,i} = \left[\varsigma_i \left(P_t^{E,i}\right)^{-(\nu-1)} + (1-\varsigma_i)\left(P_t^{N,i}\right)^{-(\nu-1)}\right]^{-\frac{1}{\nu-1}}$$

$$P_t^{E,i} = \left[\sum_j \omega_{ij}^E \left(P_t^j\right)^{-(\xi-1)}\right]^{-\frac{1}{\xi-1}}$$

$$P_t^{N,i} = \left[\sum_j \omega_{ij}^N \left(P_t^j\right)^{-(\xi-1)}\right]^{-\frac{1}{\xi-1}}$$

In zero-inflation steady state, we have $P^i = \mu^i M^i = \mu_i(\widetilde{M}^i + \mathcal{T} e_i)$ for every sector, i.e. (dividing by the CPI P to get relative prices and using $W/P = bC$):

$$\begin{aligned}\frac{S^i}{\mu^i} &= \frac{1}{A^i}\left[\alpha_i \left(bC\right)^{-(\eta-1)} + (1-\alpha_i)\left(S^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau e_i \\ &= \frac{1}{A^i}\left[\alpha_i \left(bC\right)^{-(\eta-1)} + (1-\alpha_i)\left\{\varsigma_i\left(\sum_j \omega_{ij}^E \left(S^j\right)^{-(\xi-1)}\right)^{\frac{\nu-1}{\xi-1}} + (1-\varsigma_i)\left(\sum_j \omega_{ij}^N \left(S^j\right)^{-(\xi-1)}\right)^{\frac{\nu-1}{\xi-1}}\right\}^{\frac{\eta-1}{\nu-1}}\right]^{-\frac{1}{\eta-1}} \\ &\quad + \tau e_i\end{aligned}$$

The definition of the CPI implies that

$$1 = \left[\sum_{i=1}^n \gamma_i (S^i)^{-(\zeta-1)}\right]^{-\frac{1}{\zeta-1}}$$

Given parameters, this is a system of $n+1$ equations in $n+1$ unknowns. In what follows, we use hats to denote gross percentage changes relative to some initial steady state: $S^i = \overline{S}^i \hat{S}^i$, etc. We can now rewrite the system of equations in terms of the $n+1$ variables $\hat{C}, \{\hat{S}_i\}$: we can solve for these percentage changes without having to calibrate variables such as productivity, relative prices, etc. in the initial steady state. To simplify notation, we will also work with the variables

$\{\hat{S}^{E,i}, \hat{S}^{N,i}, \hat{S}^{I,i}\}$, which are known functions of $\hat{S}_i$. First, we have

$$
\begin{aligned}
\frac{\overline{S}^i \widehat{S}^i}{\mu^i} &= \frac{1}{A^i}\left[\alpha_i \left(b\overline{C}\widehat{C}\right)^{-(\eta-1)} + (1-\alpha_i)\left(\overline{S}^{I,i}\widehat{S}^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau e_i \\
\widehat{S}^i &= \left[\alpha_i \left(\frac{b\overline{C}}{A^i(\overline{M}^i/\overline{P})}\right)^{-(\eta-1)} \left(\widehat{C}\right)^{-(\eta-1)} + (1-\alpha_i)\left(\frac{\overline{S}^{I,i}}{A^i(\overline{M}^i/\overline{P})}\right)^{-(\eta-1)} \left(\widehat{S}^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau\frac{e_i\mu^i}{\overline{S}^i} \\
&= \frac{\widetilde{\overline{M}}^i}{\overline{M}^i}\left[\alpha_i \left(\frac{b\overline{C}}{A^i(\widetilde{\overline{M}}^i/\overline{P})}\right)^{-(\eta-1)} \left(\widehat{C}\right)^{-(\eta-1)} + (1-\alpha_i)\left(\frac{\overline{S}^{I,i}}{A^i(\widetilde{\overline{M}}^i/\overline{P})}\right)^{-(\eta-1)} \left(\widehat{S}^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau\frac{e_i\mu^i}{\overline{S}^i} \\
&= (1-\widetilde{e}^i\overline{\tau})\left[\widetilde{\alpha}_i\left(\widehat{C}\right)^{-(\eta-1)} + (1-\widetilde{\alpha}_i)\left(\widehat{S}^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau\widetilde{e}_i
\end{aligned}
$$

Next,

$$
\begin{aligned}
\widehat{S}^{I,i} &= \left[\varsigma_i\left(\frac{\overline{S}^{E,i}}{\overline{S}^{I,i}}\right)^{-(\nu-1)}\left(\widehat{S}^{E,i}\right)^{-(\nu-1)} + (1-\varsigma_i)\left(\frac{\overline{S}^{N,i}}{\overline{S}^{I,i}}\right)^{-(\nu-1)}\left(\widehat{S}^{N,i}\right)^{-(\nu-1)}\right]^{-\frac{1}{\nu-1}} \\
&= \left[\widetilde{\varsigma}_i\left(\widehat{S}^{E,i}\right)^{-(\nu-1)} + (1-\widetilde{\varsigma}_i)\left(\widehat{S}^{N,i}\right)^{-(\nu-1)}\right]^{-\frac{1}{\nu-1}}
\end{aligned}
$$

Finally, we have

$$
\begin{aligned}
\widehat{S}^{E,i} &= \left[\sum_j \widetilde{\omega}^E_{ij}\left(\widehat{S}^j\right)^{-(\xi-1)}\right]^{-\frac{1}{\xi-1}} \\
\widehat{S}^{N,i} &= \left[\sum_j \widetilde{\omega}^N_{ij}\left(\widehat{S}^j\right)^{-(\xi-1)}\right]^{-\frac{1}{\xi-1}}
\end{aligned}
$$

Thus, we can write the first n equations as

$$
\begin{aligned}
\frac{\widehat{S}^i}{1-\widetilde{e}^i\overline{\tau}} = &\left[\widetilde{\alpha}_i\left(\widehat{C}\right)^{-(\eta-1)} + (1-\widetilde{\alpha}_i)\left\{\widetilde{\varsigma}_i\left(\sum_j \widetilde{\omega}^E_{ij}\left(\widehat{S}^j\right)^{1-\xi}\right)^{\frac{\nu-1}{\xi-1}} + (1-\widetilde{\varsigma}_i)\left(\sum_j \widetilde{\omega}^N_{ij}\left(\widehat{S}^j\right)^{1-\xi}\right)^{\frac{\nu-1}{\xi-1}}\right\}^{\frac{\eta-1}{\nu-1}}\right]^{\frac{1}{1-\eta}} \\
&+ \frac{\tau\widetilde{e}_i}{1-\widetilde{e}^i\overline{\tau}}
\end{aligned}
$$

where $\widetilde{\alpha}_i := \dfrac{\overline{WL}^i}{\widetilde{\overline{M}}^i\overline{X}^i} = \alpha_i\left(\dfrac{\overline{w}}{A^i\widetilde{\overline{M}}^i/\overline{P}}\right)^{-(\eta-1)}$ is the labor share of pretax marginal cost for sector i in the initial steady state; $1-\widetilde{\alpha}_i := \dfrac{\overline{P^{I,i}}\overline{I}^i}{\overline{M}^i\overline{X}^i} = \left(\dfrac{\overline{S}^{I,i}}{A^i\widetilde{\overline{M}}^i/\overline{P}}\right)^{-(\eta-1)}(1-\alpha_i)$ is the share of intermediate inputs in pretax marginal costs (note that the two shares sum to 1); $\widetilde{e}_i = \dfrac{e_i}{\overline{M^i}/\overline{P}}$ is sector i's direct emissions, relative to total marginal costs; and the other reduced-form parameters with tildes are defined as above. Similarly, the the $(n+1)$th equation becomes:

$$1 = \left[\sum_{i=1}^{n} \widetilde{\gamma}^i (\hat{S}^i)^{-(\zeta-1)}\right]^{-\frac{1}{\zeta-1}}$$

where $\widetilde{\gamma}_i = \gamma_i(\overline{S}^i)^{-(\zeta-1)}$ is the consumption share of sector i in the initial steady state. So, in order to solve this system of $n+1$ equations in $n+1$ unknowns (the percentage change in each relative price and aggregate consumption), we need the same information that we already used to solve the linearized model. Given τ and the initial shares, the percentage changes $\{\widehat{S}^i\}, \widehat{C}$ can be solved for without needing to solve for all variables or impose normalizations.

Having solved for the new steady state, we will linearize around the new steady state to compute the transition. In order to linearize around the new steady state, we need to recompute all the share parameters (reduced form parameters with tildes). Note first that

$$\begin{aligned}
\frac{\widetilde{M}^i}{P} &= \frac{M^i}{P} - \tau e_i \\
&= \frac{\overline{M}^i}{\overline{P}}\widehat{S}^i - \tau e_i \\
\frac{\widetilde{M}^i/P}{\overline{\widetilde{M}}^i/\overline{P}} &= \frac{\overline{M}^i/\overline{P}}{\overline{\widetilde{M}}^i/\overline{P}}\widehat{S}^i - \tau\frac{e_i}{\overline{\widetilde{M}}^i/\overline{P}} \\
&= \frac{\overline{M}^i/\overline{P}}{\overline{M}^i/\overline{P} - \overline{\tau}e_i}\widehat{S}^i - \frac{\overline{M}^i/\overline{P}}{\overline{M}^i/\overline{P} - \overline{\tau}e_i}\tau\frac{e_i}{\overline{M}^i/\overline{P}} \\
&= \frac{1}{1-\widetilde{e}_i\overline{\tau}}\widehat{S}^i - \tau\frac{\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}
\end{aligned}$$

In the special case where the initial steady state features no carbon tax ($\overline{\tau}=0$), this becomes

$$\frac{\widetilde{M}^i/P}{\overline{\widetilde{M}}^i/\overline{P}} = \widehat{S}^i - \tau\widetilde{e}_i$$

Thus in the general case, we have

$$\widetilde{\alpha}_i^n = \widetilde{\alpha}_i \left(\hat{C}\right)^{-(\eta-1)} \left(\frac{1}{1-\widetilde{e}_i\overline{\tau}}\widehat{S}^i - \tau\frac{\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}\right)^{\eta-1}$$

$$1-\widetilde{\alpha}_i^n = (1-\widetilde{\alpha}_i)\left(\sum_j \widetilde{\omega}_{ij}(\hat{S}^j)^{-(\xi-1)}\right)^{\frac{\eta-1}{\xi-1}} \left(\frac{1}{1-\widetilde{e}_i\overline{\tau}}\widehat{S}^i - \tau\frac{\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}\right)^{\eta-1}$$

$$\widetilde{\varsigma}_i^n = \widetilde{\varsigma}_i \left(\frac{\widehat{S}^{E,i}}{\widehat{S}^{I,i}}\right)^{1-\nu}$$

$$1-\widetilde{\varsigma}_i^n = (1-\widetilde{\varsigma}_i)\left(\frac{\widehat{S}^{N,i}}{\widehat{S}^{I,i}}\right)^{1-\nu}$$

$$\widetilde{\omega}_{ij}^{E,n} = \widetilde{\omega}_{ij}^{E,n}\left(\frac{\widehat{S}^j}{\widehat{S}^{E,i}}\right)^{1-\xi}$$

$$\widetilde{\omega}_{ij}^{N,n} = \widetilde{\omega}_{ij}^{N,n}\left(\frac{\widehat{S}^j}{\widehat{S}^{N,i}}\right)^{1-\xi}$$

$$\widetilde{e}_i^n = \frac{e_i}{M^i/P} = \frac{\widetilde{e}_i}{\hat{S}^i}$$

It is straightforward to verify that the objects we have called $\widetilde{\alpha}_i^n$ and $1-\widetilde{\alpha}_i^n$ sum to 1. Their sum is

$$\widetilde{\alpha}_i \left(\hat{C}\right)^{-(\eta-1)} \left(\frac{1}{1-\widetilde{e}_i\overline{\tau}}\widehat{S}^i - \tau\frac{\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}\right)^{\eta-1} + (1-\widetilde{\alpha}_i)\left(\sum_j \widetilde{\omega}_{ij}(\hat{S}^j)^{-(\xi-1)}\right)^{\frac{\eta-1}{\xi-1}} \left(\frac{1}{1-\widetilde{e}_i\overline{\tau}}\widehat{S}^i - \tau\frac{\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}\right)^{\eta-1}$$

$$= \left(\frac{\widehat{S}^i - \tau\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}\right)^{-(\eta-1)} \left(\frac{1}{1-\widetilde{e}_i\overline{\tau}}\widehat{S}^i - \tau\frac{\widetilde{e}_i}{1-\widetilde{e}_i\overline{\tau}}\right)^{\eta-1} = 1$$

$$\widetilde{\gamma}_i^n = \frac{\widetilde{\gamma}_i(\widehat{S}^i)^{1-\zeta}}{\sum_j \widetilde{\gamma}_j(\widehat{S}^j)^{1-\zeta}}$$

It is also straightforward to verify that the objects we have called $\widetilde{\varsigma}_i^n$ and $1-\widetilde{\varsigma}_i^n$ sum to 1 and that $\sum_j \widetilde{\omega}_{ij}^{E,n} = \sum_j \widetilde{\omega}_{ij}^{N,n} = 1$.

When log-linearizing around the new steady state and computing dynamics, we need to specify initial conditions for endogenous state variables (relative prices and real wages), expressed as log-deviations relative to the new steady state. These is simply

$$s_{-1}^i = -\ln \hat{S}^i,\ \omega_{-1}^i = -\ln \hat{C}$$

Finally, we solve for the new steady state values of gross sectoral output and average emissions. It is convenient to treat energy and non-energy sectors separately. Sector i's intermediate demand for an energy good $j \in \mathcal{E}$ satisfies

$$\frac{S_j X^{ij}}{(\widetilde{M^i}/P)X^i} = (1-\widetilde{\alpha}_i^n)\widetilde{\varsigma}_i^n\widetilde{\omega}_{ij}^{E,n}$$

$$\frac{X^{ij}}{X^i} = (1-\widetilde{\alpha}_i^n)\widetilde{\varsigma}_i^n\widetilde{\omega}_{ij}^{E,n}\frac{(M^i/P-\tau e_i)}{S_j} = (1-\widetilde{\alpha}_i^n)\widetilde{\varsigma}_i^n\widetilde{\omega}_{ij}^{E,n}(1-\tau\widetilde{e}_i^n)\frac{\overline{M^i/P}}{\overline{S}^j}\frac{\widehat{S}^i}{\widehat{S}^j}$$

Thus, for an energy sector $i \in \mathcal{E}$, using market clearing we have

$$C^i + \sum_j X^{ji} = X^i$$

$$\overline{C}^i\widehat{C}(\widehat{S}^i)^{-\zeta} + \sum_{j=1}^n (1-\widetilde{\alpha}_j^n)\widetilde{\varsigma}_j^n\widetilde{\omega}_{ji}^{E,n}(1-\tau\widetilde{e}_j^n)\frac{\overline{M^j/P}}{\overline{S}^i}\frac{\widehat{S}^j}{\widehat{S}^i}\overline{X}^j\widehat{X}^j = \overline{X}^i\widehat{X}^i$$

$$\frac{\overline{C}^i}{\overline{X}^i}\widehat{C}(\widehat{S}^i)^{-\zeta} + \sum_{j=1}^n (1-\widetilde{\alpha}_j^n)\widetilde{\varsigma}_j^n\widetilde{\omega}_{ji}^{E,n}(1-\tau\widetilde{e}_j^n)\frac{\overline{M^j/P}}{\overline{S}^j}\frac{\overline{S}^j\overline{X}^j}{\overline{S}^i\overline{X}^i}\frac{\widehat{S}^j}{\widehat{S}^i}\widehat{X}^j = \widehat{X}^i$$

Similarly, for a non-energy sector $i \in \mathcal{N}$ we have

$$\frac{\overline{C}^i}{\overline{X}^i}\widehat{C}(\widehat{S}^i)^{-\zeta} + \sum_{j=1}^n (1-\widetilde{\alpha}_j^n)(1-\widetilde{\varsigma}_j^n)\widetilde{\omega}_{ji}^{N,n}(1-\tau\widetilde{e}_j^n)\frac{\overline{M^j/P}}{\overline{S}^j}\frac{\overline{S}^j\overline{X}^j}{\overline{S}^i\overline{X}^i}\frac{\widehat{S}^j}{\widehat{S}^i}\widehat{X}^j = \widehat{X}^i$$

This a linear system in $\{\hat{X}^i\}$, which we can invert to solve for $\{\hat{X}^i\}$. The change in emissions is then

$$\hat{E} = \sum_i \frac{e_i\overline{X}^i}{\overline{E}}\hat{X}^i$$

i.e. we just need to weight the proportional change in each sector's gross output by that sector's initial share of total emissions.

B.4 Transition dynamics in the nonlinear model

In principle, solving a multisector Calvo model nonlinearly requires keeping track of two additional forward-looking auxiliary variables for each sector. Given that the nonlinearities of the Calvo Phillips curve are not our focus, to reduce the dimensionality of our system, we instead assume that the linearized relation between inflation and (log) marginal cost (B.11) continues to hold: that is, we have

$$\pi_t^i = \kappa_i\left(\ln(M_t^i/P_t) + \ln\mu_i - \ln S_t^i\right) + \beta\pi_{t+1}^i$$

We treat the wage Phillips curve in the same way, implying that

$$\pi_t^w = \kappa_w(\ln\hat{C}_t - \ln\hat{w}_t) + \beta\pi_{t+1}^w$$

where $\widehat{w}_t$ denotes the gross percentage deviation of real wages W_t/P_t from its steady state value.

However, we allow the relation between real marginal costs, wages, relative prices and taxes to be fully nonlinear:

$$\frac{M_t^i}{P_t} = \frac{1}{A^i}\left[\alpha_i\left(\frac{W_t}{P_t}\right)^{-(\eta-1)} + (1-\alpha_i)\left[\sum_j \omega_{ij}\left(S_t^j\right)^{-(\xi-1)}\right]^{\frac{\eta-1}{\xi-1}}\right]^{-\frac{1}{\eta-1}} + \tau_t e_i$$

Using the same procedure as above, we can rewrite this system of equations in terms of gross percentage changes relative to the initial steady state with zero taxes:

$$(M_t^i/P_t) = \frac{\overline{S}^i}{\mu^i}\left[\widetilde{\alpha}_i\left(\widehat{w}_t\right)^{-(\eta-1)} + (1-\widetilde{\alpha}_i)\left\{\widetilde{\varsigma}_i\left(\sum_j \widetilde{\omega}_{ij}^E\left(\widehat{S}_t^j\right)^{1-\xi}\right)^{\frac{\nu-1}{\xi-1}} + (1-\widetilde{\varsigma}_i)\left(\sum_j \widetilde{\omega}_{ij}^N\left(\widehat{S}_t^j\right)^{1-\xi}\right)^{\frac{\nu-1}{\xi-1}}\right\}^{\frac{\eta-1}{\nu-1}}\right]^{\frac{1}{1-\eta}}$$
$$+ \frac{\overline{S}^i}{\mu^i}\tau\widetilde{e}_i$$

where $\widehat{S}_t^i$ is defined as before. In addition, note that $\pi_t^i = \pi_t^c + \Delta \ln S_t^i$. Thus, we can write our Phillips curves as

$$\ln S_t^i + \kappa_i^{-1}\left(\pi_t^c + \Delta \ln S_t^i - \beta(\pi_{t+1}^c + \Delta \ln S_{t+1}^i)\right)$$
$$= \ln\left(\left[\widetilde{\alpha}_i\left(\widehat{w}_t\right)^{-(\eta-1)} + (1-\widetilde{\alpha}_i)\left\{\widetilde{\varsigma}_i\left(\sum_j \widetilde{\omega}_{ij}^E\left(\widehat{S}_t^j\right)^{1-\xi}\right)^{\frac{\nu-1}{\xi-1}} + (1-\widetilde{\varsigma}_i)\left(\sum_j \widetilde{\omega}_{ij}^N\left(\widehat{S}_t^j\right)^{1-\xi}\right)^{\frac{\nu-1}{\xi-1}}\right\}^{\frac{\eta-1}{\nu-1}}\right]^{\frac{1}{1-\eta}} + \tau\widetilde{e}_i\right)$$

As before, we also have

$$1 = \left[\sum_{i=1}^n \widetilde{\gamma}^i(\hat{S}_t^i)^{-(\zeta-1)}\right]^{-\frac{1}{\zeta-1}}$$

Real wages and wage and price inflation are related by

$$\hat{w}_t = \hat{w}_{t-1}e^{\pi_t^w - \pi_t^c}$$

We specify monetary policy as

$$\ln \hat{C}_t - \ln \hat{C}_t^* + \psi\pi_t^c = 0$$

Given a path of taxes, in order to solve the model it only remains to solve for $\hat{C}_t^*$, the level of aggregate consumption in the notional flexible-price, flexible-wage economy (again expressed as a fraction of consumption in the initial steady state). This variable, and relative prices in the flexible-price, flexible wage economy $\hat{S}_t^{i*}$, are implicitly defined by

$$S_t^{i*} = \left[\widetilde{\alpha}_i \left(\widehat{C}_t^* \right)^{-(\eta-1)} + (1-\widetilde{\alpha}_i) \left\{ \widetilde{\varsigma}_i \left(\sum_j \widetilde{\omega}_{ij}^E \left(\widehat{S}_t^{j*} \right)^{1-\xi} \right)^{\frac{\nu-1}{\xi-1}} + (1-\widetilde{\varsigma}_i) \left(\sum_j \widetilde{\omega}_{ij}^N \left(\widehat{S}_t^{j*} \right)^{1-\xi} \right)^{\frac{\nu-1}{\xi-1}} \right\}^{\frac{\eta-1}{\nu-1}} \right]^{\frac{1}{1-\eta}} + \tau \widetilde{e}_i$$

$$1 = \left[\sum_{i=1}^n \widetilde{\gamma}^i (\hat{S}_t^{i*})^{-(\zeta-1)} \right]^{-\frac{1}{\zeta-1}}$$

This gives us a system of $2n+5$ nonlinear difference equations in $2n+5$ endogenous variables. We solve this system using the 'perfect foresight solver' in Dynare.

In the counterfactual experiment, for each nonenergy sector $i \in \mathcal{N}$, we set $\tilde{\alpha}_i^{cf} = \tilde{\alpha}_i + (1 - \tilde{\alpha}_i)(1-\tilde{\varsigma}_i)$ and $\tilde{\varsigma}_i^{cf} = 1$. That is, in the counterfactual economy, nonenergy sectors only use energy goods as inputs, and the cost share of these inputs in the initial steady state is the same as in our baseline calibration, while the cost share of nonenergy inputs is set to zero. We reassign these inputs' share of cost to labor, $\tilde{\alpha}_i^{cf}$.

B.5 Model validation details

When comparing the impulse response functions from our linearized model to those obtained empirically by Känzig (2021), we assume that monetary policy in our model is described by an inertial Taylor rule. In log-linearized form:

$$i_t = \rho_i i_{t-1} + (1-\rho_i)\phi_\pi \pi_t^c$$

Since our model is monthly, we set $\rho_i = (0.85)^{1/3}$; we also set $\phi_\pi = 1.01$.

Since for this exercise we specify monetary policy in terms of an interest rate rule, to close the model, we also need to use the standard Euler equation implied by our log-linearized model:

$$c_t = \mathbb{E}_t c_{t+1} - (i_t - \mathbb{E}\pi_{t+1})$$

We implement the oil price shock as an AR(2) markup shock to the oil extraction sector. That is, this sector's Phillips curve becomes

$$\pi_t^{oil} = \kappa^{oil}(\alpha^{oil} + \sum_i \Omega_{oil,i} s_t^i - s_t^{oil} + \mu_t^{oil}) + \beta \mathbb{E}_t \pi_{t+1}^{oil}$$

where

$$\mu_t^{oil} = \rho_{oil,1}\mu_{t-1}^{oil} + \rho_{oil,2}\mu_{t-2}^{oil} + \varepsilon_t^{oil}$$

and ε_t^{oil} is i.i.d. with mean zero. We choose $\rho_{oil,1}, \rho_{oil,2}$ and the size of the shock to minimize the sum of squared differences between the cumulative change in the real price of oil s_t^{oil} in our model and in Känzig (2021)'s empirical IRF (where it is measured as the WTI spot price, deflated by the US CPI).

B.6 Proof of Proposition 1

Given our assumptions on carbon taxes and monetary policy, we have the system

$$\boldsymbol{\pi_t} = K(\boldsymbol{\alpha} y_t + (\Omega - I)\boldsymbol{s_t} + \boldsymbol{\epsilon}\tau_t) + \beta\boldsymbol{\pi_{t+1}} \tag{B.19}$$

$$\boldsymbol{s_t} = \boldsymbol{s_{t-1}} + \boldsymbol{\pi_t} - \mathbf{1}\boldsymbol{\gamma}'\boldsymbol{\pi_t} \tag{B.20}$$

$$\tau_t = \tau_{t-1} + g \tag{B.21}$$

$$y_t = y_t^*, \tag{B.22}$$

where the flexible price levels of output y_t^* and relative prices $\boldsymbol{s}_t^*$ are defined by the system

$$\boldsymbol{\alpha} y_t^* - (I - \Omega)\boldsymbol{s}_t^* + \boldsymbol{\epsilon}\tau_t = 0 \tag{B.23}$$

$$\boldsymbol{\gamma}'\boldsymbol{s}_t^* = 0 \tag{B.24}$$

To define y_t^* explicitly, premultiply (B.23) by the row vector of Domar weights $\boldsymbol{\lambda}' = \boldsymbol{\gamma}'(I - \Omega)^{-1}$ and use (B.24), together with the fact that $\boldsymbol{\lambda}'\boldsymbol{\alpha} = 1$, to get

$$\underbrace{\boldsymbol{\lambda}'\boldsymbol{\alpha}}_{=1} y_t^* - \underbrace{\boldsymbol{\gamma}'(I - \Omega)^{-1}(I - \Omega)\boldsymbol{s}_t^*}_{=0} + \boldsymbol{\lambda}'\boldsymbol{\epsilon}\tau_t = 0$$

$$y_t^* + \boldsymbol{\lambda}'\boldsymbol{\epsilon}\tau_t = 0$$

implying that $y_t^* = -(\boldsymbol{\lambda}'\boldsymbol{\epsilon})\tau_t = -\boldsymbol{\gamma}'(I - \Omega)^{-1}\boldsymbol{\epsilon}\tau_t$. Substituting back into (B.23), we have

$$\boldsymbol{s}_t^* = \left(I - \mathbf{1}\boldsymbol{\gamma}'\right)(1 - \Omega)^{-1}\boldsymbol{\epsilon}\tau_t \tag{B.25}$$

Note that since $\boldsymbol{\gamma}'\mathbf{1} = 1$, given an initial condition $\boldsymbol{s}_{-1}$ satisfying $\boldsymbol{\gamma}'\boldsymbol{s}_{-1}$, (B.20) implies that $\boldsymbol{\gamma}'\boldsymbol{s}_t = 0$ for all $t \geq 0$. We assume that given our specification of monetary policy, the system is stable in the sense that, absent any shocks ($\tau_t = 0$ for all t), the economy returns to steady state following any initial distribution of relative prices $\boldsymbol{s_{-1}}$ satisfying $\boldsymbol{\gamma}'\boldsymbol{s_{-1}} = 0$.

Given these preliminaries, the proof has three steps. First, we rewrite our system of equations in terms of gaps between variables and their flexible price levels. Subtracting (B.23) from (B.19), using $y_t = y_t^*$ and defining the relative price gap $\boldsymbol{s_t^g} = \boldsymbol{s_t} - \boldsymbol{s_t^*}$, we have

$$\boldsymbol{\pi_t} = -K(I - \Omega)\boldsymbol{s_t^g} + \beta\boldsymbol{\pi_{t+1}} \tag{B.26}$$

Combining (B.20), (B.25) and the definition of $\boldsymbol{s}_t^g$,

$$\boldsymbol{s_t^g} = \boldsymbol{s_{t-1}^g} + \boldsymbol{\pi_t} - \mathbf{1}\boldsymbol{\gamma}'\boldsymbol{\pi_t} - (I - \Omega)^{-1}\left[\boldsymbol{\epsilon} - \left(\frac{\boldsymbol{\lambda}'\boldsymbol{\epsilon}}{\boldsymbol{\lambda}'\boldsymbol{\alpha}}\right)\boldsymbol{\alpha}\right] g \tag{B.27}$$

By assumption, if $g = 0$, the system (B.26)-(B.27) converges to $\boldsymbol{\pi_t} = \boldsymbol{s_t^g} = \mathbf{0}$.

Next, suppose $g \neq 0$. The steady state of the system (B.26)-(B.27) is defined by

$$(1-\beta)\boldsymbol{\pi} = -K(I-\Omega)\boldsymbol{s^g} \tag{B.28}$$

$$\mathbf{0} = \boldsymbol{\pi} - \mathbf{1}\boldsymbol{\gamma}'\boldsymbol{\pi} - (I-\Omega)^{-1}\left[\boldsymbol{\epsilon} - \left(\frac{\boldsymbol{\lambda}'\boldsymbol{\epsilon}}{\boldsymbol{\lambda}'\boldsymbol{\alpha}}\right)\boldsymbol{\alpha}\right] g \tag{B.29}$$

$$\boldsymbol{\gamma}'\boldsymbol{s^g} = 0 \tag{B.30}$$

(B.28) and (B.30) imply $\boldsymbol{\lambda}'K^{-1}\boldsymbol{\pi} = 0$. Thus, from (B.29) we have

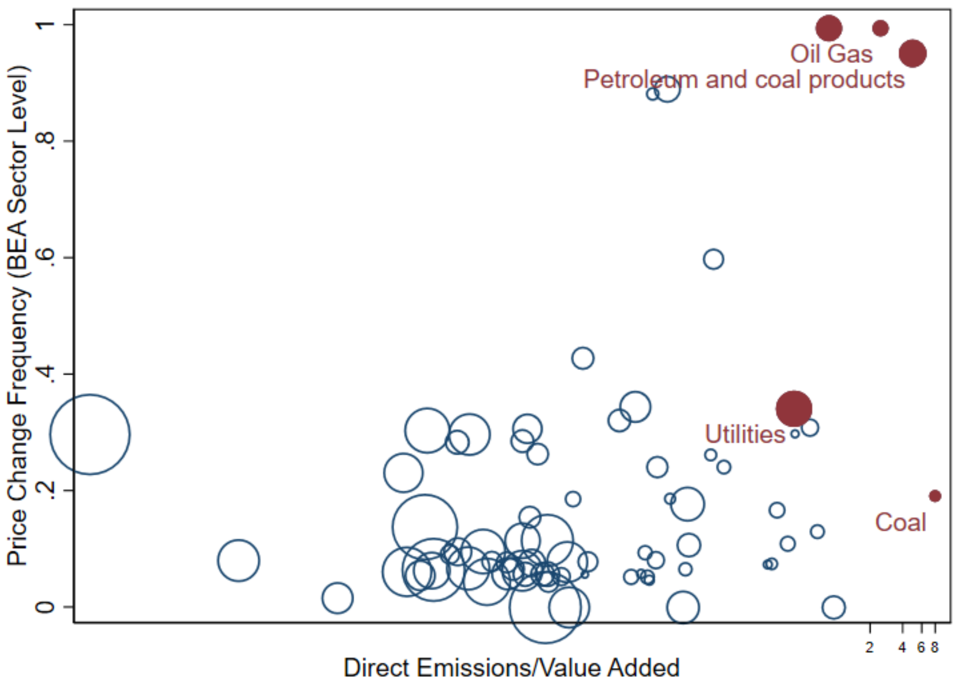
$$\begin{aligned}
\boldsymbol{\gamma}'\boldsymbol{\pi} &= -(\boldsymbol{\lambda}'K^{-1}\mathbf{1})^{-1}\boldsymbol{\lambda}'K^{-1}(I-\Omega)^{-1}\left[\boldsymbol{\epsilon} - \left(\frac{\boldsymbol{\lambda}'\boldsymbol{\epsilon}}{\boldsymbol{\lambda}'\boldsymbol{\alpha}}\right)\boldsymbol{\alpha}\right] g \\
\boldsymbol{\pi} &= \left[I - \frac{\mathbf{1}\boldsymbol{\lambda}'K^{-1}}{\boldsymbol{\lambda}'K^{-1}\mathbf{1}}\right](I-\Omega)^{-1}\left[\boldsymbol{\epsilon} + \left(\frac{\boldsymbol{\lambda}'\boldsymbol{\epsilon}}{\boldsymbol{\lambda}'\boldsymbol{\alpha}}\right)\boldsymbol{\alpha}\right] g \\
\boldsymbol{s^g} &= -(1-\beta)(I-\Omega)^{-1}K^{-1}\left[I - \frac{\mathbf{1}\boldsymbol{\lambda}'K^{-1}}{\boldsymbol{\lambda}'K^{-1}\mathbf{1}}\right](I-\Omega)^{-1}\left[\boldsymbol{\epsilon} + \left(\frac{\boldsymbol{\lambda}'\boldsymbol{\epsilon}}{\boldsymbol{\lambda}'\boldsymbol{\alpha}}\right)\boldsymbol{\alpha}\right] g
\end{aligned}$$

Finally, subtracting (B.28)-(B.29) from (B.26)-(B.27) and defining $\widehat{\boldsymbol{\pi_t}} = \boldsymbol{\pi_t} - \boldsymbol{\pi}$, $\widehat{\boldsymbol{s^g_t}} = \boldsymbol{s^g_t} - \boldsymbol{s^g}$, we have

$$\begin{aligned}
\widehat{\boldsymbol{\pi_t}} &= -K(I-\Omega)\widehat{\boldsymbol{s^g_t}} + \beta\widehat{\boldsymbol{\pi_{t+1}}} \\
\widehat{\boldsymbol{s^g_t}} &= \widehat{\boldsymbol{s^g_{t-1}}} + \widehat{\boldsymbol{\pi_t}} - \mathbf{1}\boldsymbol{\gamma}'\widehat{\boldsymbol{\pi_t}}
\end{aligned}$$

Clearly this system is mathematically identical to the system (B.28)-(B.29) with $g = 0$. Thus, if the latter system converges to $\boldsymbol{\pi_t} = \boldsymbol{s^g_t} = \mathbf{0}$, this system converges to $\widehat{\boldsymbol{\pi_t}} = \widehat{\boldsymbol{s^g_t}} = \mathbf{0}$. In other words, $\boldsymbol{\pi}_t \to \boldsymbol{\pi}$ and $\boldsymbol{s^g_t} \to \boldsymbol{s^g}$. So we are done.

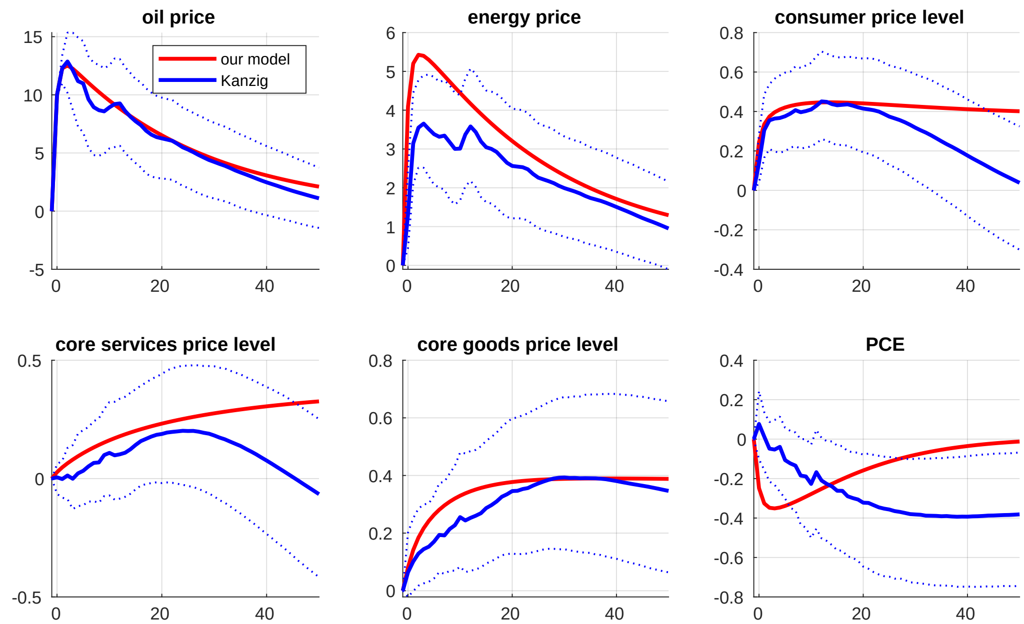
Figure A1. Mean price change frequency of a good in a given sector vs CO_2 emissions/value added across 69 sectors in the United States



Notes: This figure plots a bin scatter of the sector-level mean price change frequency against the sector-level CO_2 direct emissions to value added. The emissions ratio is expressed in terms of kilotons of CO_2 emitted per millions of US$ value added produced and is based on the direct usage of fossil fuels (oil, gas, or coal) in production, and is plotted on a log scale. Circle sizes are based on the toal sector-level value added within a bin.

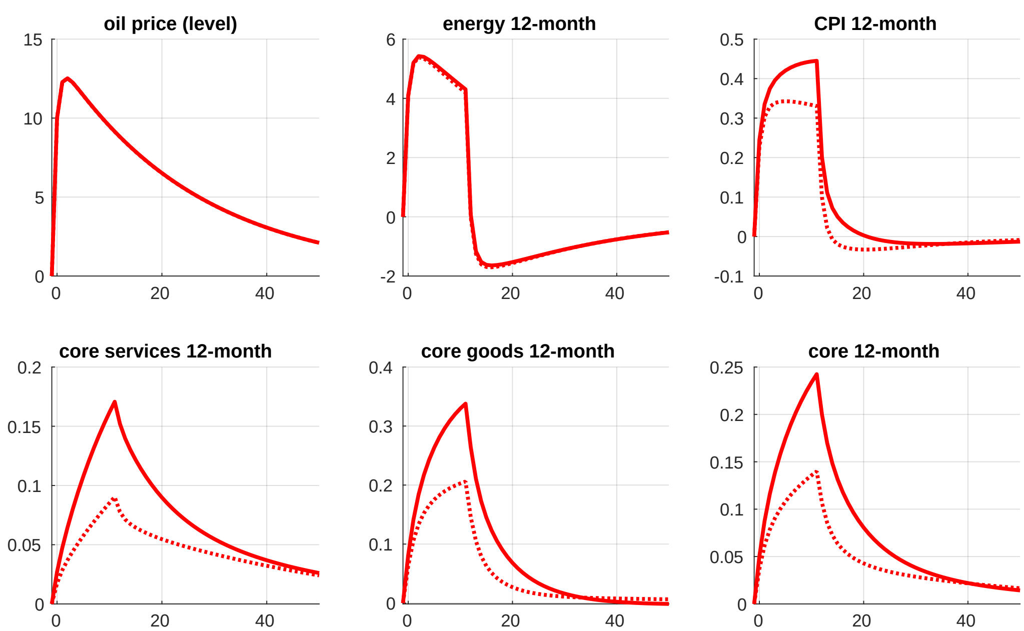
Appendix C Appendix Tables and Figures

Figure A2. Känzig's WTI oil shocks responses: model vs SVAR—396-sector version



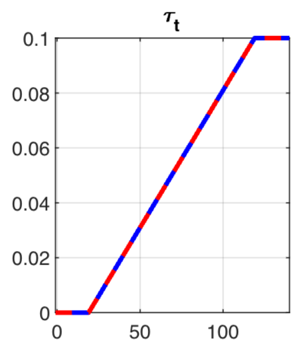
Notes: Solid/dotted blue lines: Känzig (2021)'s WTI oil shocks responses of various price indexes with 90 percent coverage intervals (log levels). Solid red lines: 400 sector model responses.

Figure A3. Känzig's WTI oil shocks responses: the role of propagation through the IO network—396-sector version



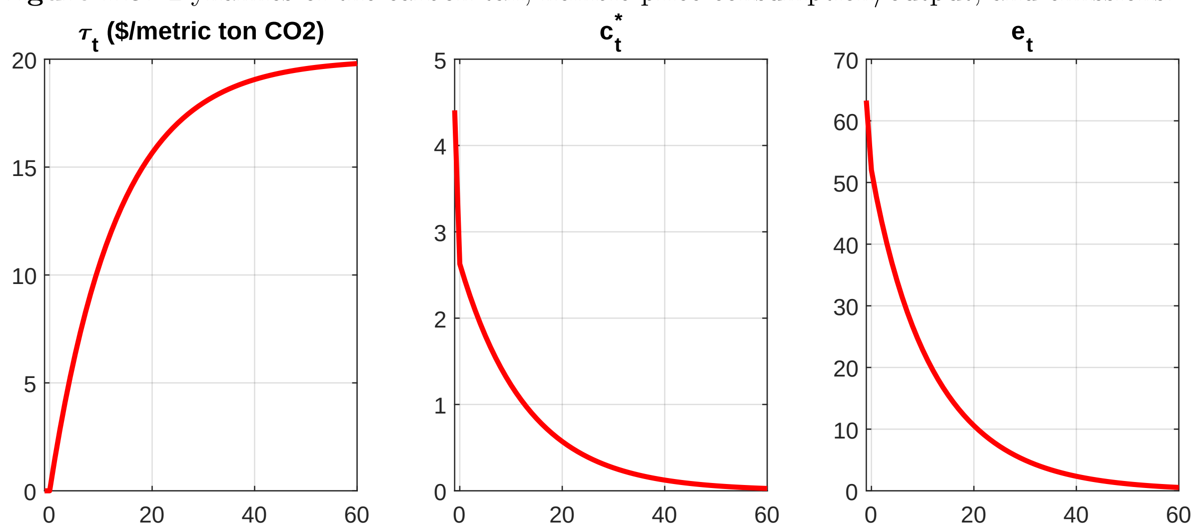
Notes: Solid red: same IRFs as Figure 3 but in terms of 12-month inflation (except for oil). Dotted red: counterfactual without IO network *except* for energy.

Figure A4. Path for the carbon tax



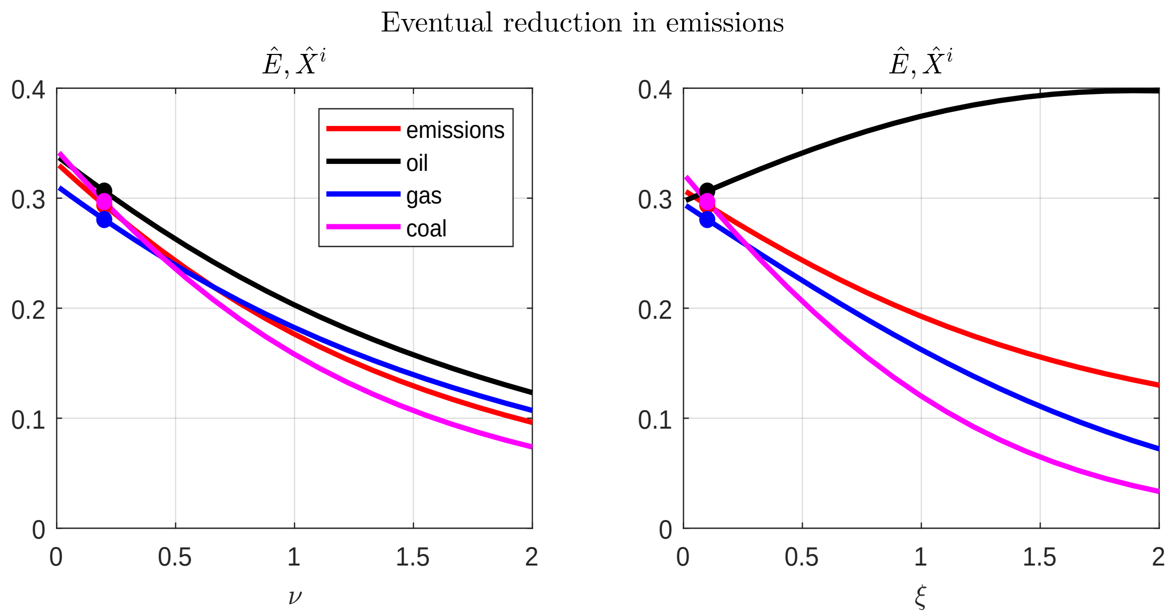
Notes: The figure shows the path of the the carbon tax for the experiment described in section 5.3.

Figure A5. Dynamics of the carbon tax, flexible price consumption/output, and emissions.



Notes: Left panel shows τ_t, the level of the carbon tax in dollars per metric ton of CO2 emissions; middle and right panels show flexible-price consumption and emissions, respectively, as 100×log-deviations from the new steady state.

Figure A6. Emissions as a function of the elasticity of substitution



Notes: The lines show emissions and gross output in each of the polluting sectors in the new steady state as a fraction of their values in the old steady state, as a function of the elasticity of substitution between energy and non-energy inputs ν (left panel) and the elasticity of substitution between intermediate input varieties ξ (right panel), fixing all other parameters at their baseline calibration. Circles indicate our baseline calibration.

Table A1. Mean price change frequency of a good in a given sector and CO_2 emissions/value added across 396 sectors in USA in 2012

Sector	Code	CO_2/VA	Price Δ Frequency
Cement manufacturing	327310	44.180	0.184
Lime and gypsum product manufacturing	327400	36.810	0.649
Secondary smelting and alloying of aluminum	331314	32.718	0.658
Pulp mills	322110	20.248	0.484
Other petroleum and coal products manufacturing	324190	18.580	0.439
Alumina refining and primary aluminum production	331313	14.633	0.942
Ground or treated mineral and earth manufacturing	327992	13.230	0.143
Mineral wool manufacturing	327993	9.107	0.341
Wet corn milling	311221	8.566	0.392
Poultry and egg production	112300	8.292	0.749
Asphalt paving mixture and block manufacturing	324121	8.079	0.547
Coal mining	212100	7.901	0.191
Clay product and refractory manufacturing	327100	7.137	0.070
Miscellaneous nonmetallic mineral products	327999	5.951	0.057
Petroleum refineries	324110	5.739	0.982
Industrial gas manufacturing	325120	5.135	0.223
Natural gas distribution	221200	4.472	0.610
Textile and fabric finishing and fabric coating mills	313300	4.106	0.128
Paperboard mills	322130	4.063	0.238
Iron and steel mills and ferroalloy manufacturing	331110	3.373	0.271
Seafood product preparation and packaging	311700	3.319	0.386
Concrete pipe, brick, and block manufacturing	327330	3.256	0.070
All other converted paper product manufacturing	322299	3.125	0.073
Asphalt shingle and coating materials manufacturing	324122	3.044	0.413
Glass and glass product manufacturing	327200	2.830	0.057
Gas extraction	211000	2.477	0.994
Cut stone and stone product manufacturing	327991	2.317	0.032
Printing ink manufacturing	325910	1.942	0.088
Nonferrous metal foundries	331520	1.859	0.092
Petrochemical manufacturing	325110	1.854	0.223
Other concrete product manufacturing	327390	1.801	0.072
Electric lamp bulb and part manufacturing	335110	1.742	0.126
Ready-mix concrete manufacturing	327320	1.735	0.113
Other nonmetallic mineral mining and quarrying	2123A0	1.681	0.049
Other household nonupholstered furniture	33712N	1.508	0.049
Synthetic dye and pigment manufacturing	325130	1.482	0.223
Paper mills	322120	1.464	0.282
Abrasive product manufacturing	327910	1.446	0.031

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Aluminum product manufacturing from purchased aluminum	33131B	1.365	0.374
Polystyrene foam product manufacturing	326140	1.328	0.051
Other Basic Inorganic Chemical Manufacturing	325180	1.299	0.139
Fats and oils refining and blending	311225	1.256	0.533
Fabric mills	313200	1.228	0.076
Soybean and other oilseed processing	311224	1.058	0.787
Urethane and other foam product (except polystyrene) manufacturing	326150	1.032	0.032
Copper, nickel, lead, and zinc mining	212230	1.011	0.096
Laminated plastics plate, sheet (except packaging), and shape manufacturing	326130	1.000	0.053
Fiber, yarn, and thread mills	313100	0.980	0.065
Dry, condensed, and evaporated dairy product manufacturing	311514	0.958	0.417
Breakfast cereal manufacturing	311230	0.923	0.495
Sugar and confectionery product manufacturing	311300	0.888	0.177
Ferrous metal foundries	331510	0.884	0.057
Flour milling and malt manufacturing	311210	0.877	0.269
Ice cream and frozen dessert manufacturing	311520	0.859	0.149
Nonferrous Metal (except Aluminum) Smelting and Refining	331410	0.836	0.655
Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	331490	0.831	0.485
Oil extraction	211000	0.826	0.994
Copper rolling, drawing, extruding and alloying	331420	0.813	0.348
Coffee and tea manufacturing	311920	0.755	0.087
Rubber and plastics hoses and belting manufacturing	326220	0.716	0.032
Iron, gold, silver, and other metal ore mining	2122A0	0.702	0.096
Stone mining and quarrying	212310	0.690	0.049
Other basic organic chemical manufacturing	325190	0.640	0.307
Synthetic rubber and artificial and synthetic fibers and filaments manufacturing	3252A0	0.594	0.126
Carbon and graphite product manufacturing	335991	0.583	0.055
Fruit and vegetable canning, pickling, and drying	311420	0.583	0.064
Dog and cat food manufacturing	311111	0.581	0.699
Paper Bag and Coated and Treated Paper Manufacturing	322220	0.566	0.066
All other food manufacturing	311990	0.561	0.326
Frozen food manufacturing	311410	0.501	0.194
Adhesive manufacturing	325520	0.486	0.098
Other animal food manufacturing	311119	0.477	0.524
Cheese manufacturing	311513	0.457	0.474
Steel product manufacturing from purchased steel	331200	0.443	0.075
Water transportation	483000	0.432	0.298
Electric power generation, transmission, and distribution	221100	0.410	0.291
Snack food manufacturing	311910	0.408	0.127

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Nonupholstered wood household furniture manufacturing	337122	0.402	0.065
Sanitary paper product manufacturing	322291	0.399	0.073
Flavoring syrup and concentrate manufacturing	311930	0.381	0.057
Carpet and rug mills	314110	0.377	0.064
Cookie, cracker, pasta, and tortilla manufacturing	3118A0	0.371	0.209
Stationery product manufacturing	322230	0.346	0.073
Breweries	312120	0.338	0.066
Tire manufacturing	326210	0.337	0.069
Fluid milk and butter manufacturing	31151A	0.330	0.785
Other commercial and service industry machinery manufacturing	333318	0.312	0.039
Seasoning and dressing manufacturing	311940	0.276	0.039
Other rubber product manufacturing	326290	0.276	0.032
All other chemical product and preparation manufacturing	3259A0	0.265	0.088
Power, distribution, and specialty transformer manufacturing	335311	0.251	0.047
Fishing, hunting and trapping	114000	0.244	0.882
Paperboard container manufacturing	322210	0.235	0.073
Wineries	312130	0.232	0.066
Distilleries	312140	0.223	0.066
Optical instrument and lens manufacturing	333314	0.209	0.037
Fertilizer manufacturing	325310	0.208	0.416
Pesticide and other agricultural chemical manufacturing	325320	0.195	0.042
Soft drink and ice manufacturing	312110	0.195	0.263
Industrial and commercial fan and blower and air purification equipment manufacturing	333413	0.190	0.041
Plastics pipe, pipe fitting, and unlaminated profile shape manufacturing	326120	0.190	0.161
Showcase, partition, shelving, and locker manufacturing	337215	0.175	0.038
Other textile product mills	314900	0.161	0.062
Propulsion units and parts for space vehicles and guided missiles	33641A	0.158	0.060
Greenhouse, nursery, and floriculture production	111400	0.156	0.887
Veneer, plywood, and engineered wood product manufacturing	321200	0.152	0.251
Plastics material and resin manufacturing	325211	0.150	0.317
Bread and bakery product manufacturing	311810	0.149	0.041
Storage battery manufacturing	335911	0.144	0.055
Poultry processing	311615	0.142	0.497
All other miscellaneous electrical equipment and component manufacturing	335999	0.122	0.031
Other crop farming	111900	0.120	0.965
Medicinal and botanical manufacturing	325411	0.119	0.037
Plastics bottle manufacturing	326160	0.118	0.087
Plastics packaging materials and unlaminated film and sheet manufacturing	326110	0.114	0.184
Machine tool manufacturing	333517	0.111	0.029

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Dairy cattle and milk production	112120	0.103	0.948
Travel trailer and camper manufacturing	336214	0.099	0.086
Vegetable and melon farming	111200	0.099	0.875
Rail transportation	482000	0.094	0.241
Forestry and logging	113000	0.094	0.882
Photographic and photocopying equipment manufacturing	333316	0.092	0.038
Fabricated pipe and pipe fitting manufacturing	332996	0.090	0.066
Couriers and messengers	492000	0.090	0.208
Animal (except poultry) slaughtering, rendering, and processing	31161A	0.088	0.516
Sawmills and wood preservation	321100	0.082	0.324
All other wood product manufacturing	3219A0	0.081	0.109
Water, sewage and other systems	221300	0.079	0.107
Motor vehicle body manufacturing	336211	0.076	0.057
Air transportation	481000	0.076	0.598
Pipeline transportation	486000	0.067	0.262
Air and gas compressor manufacturing	333912	0.066	0.050
Institutional furniture manufacturing	337127	0.066	0.046
Paint and coating manufacturing	325510	0.063	0.098
Wood kitchen cabinet and countertop manufacturing	337110	0.062	0.052
Grain farming	1111B0	0.058	0.858
Fluid power process machinery	33399B	0.057	0.043
All other forging, stamping, and sintering	33211A	0.057	0.074
In-vitro diagnostic substance manufacturing	325413	0.056	0.055
Lighting fixture manufacturing	335120	0.056	0.025
Dry-cleaning and laundry services	812300	0.053	0.033
Office supplies (except paper) manufacturing	339940	0.050	0.017
Motor vehicle steering, suspension component (except spring), and brake systems manufacturing	3363A0	0.050	0.109
Switchgear and switchboard apparatus manufacturing	335313	0.050	0.038
Spring and wire product manufacturing	332600	0.047	0.038
Truck transportation	484000	0.045	0.107
Railroad rolling stock manufacturing	336500	0.044	0.074
Transit and ground passenger transportation	485000	0.042	0.066
Soap and cleaning compound manufacturing	325610	0.041	0.066
Coating, engraving, heat treating and allied activities	332800	0.040	0.054
Support activities for printing	323120	0.037	0.003
Office furniture and custom architectural woodwork and millwork manufacturing	33721A	0.036	0.038
Oilseed farming	1111A0	0.036	0.946
Religious organizations	813100	0.035	0.079
Museums, historical sites, zoos, and parks	712000	0.034	0.079

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Other industrial machinery manufacturing	33329A	0.033	0.039
Millwork	321910	0.031	0.043
Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	1121A0	0.031	0.969
Motor home manufacturing	336213	0.030	0.068
Wiring device manufacturing	335930	0.030	0.050
Motor vehicle electrical and electronic equipment manufacturing	336320	0.029	0.109
Heating equipment (except warm air furnaces) manufacturing	333414	0.029	0.055
Motor vehicle gasoline engine and engine parts manufacturing	336310	0.029	0.109
Custom roll forming	332114	0.028	0.056
Drilling oil and gas wells	213111	0.028	0.321
Postal service	491000	0.028	0.165
Other plastics product manufacturing	326190	0.028	0.043
Tobacco product manufacturing	312200	0.028	0.100
Fruit and tree nut farming	111300	0.027	0.792
Automotive equipment rental and leasing	532100	0.027	0.494
Speed changer, industrial high-speed drive, and gear manufacturing	333612	0.026	0.055
Ship building and repairing	336611	0.026	0.075
Leather and allied product manufacturing	316000	0.026	0.117
Doll, toy, and game manufacturing	339930	0.025	0.027
Other nonresidential structures	2332D0	0.025	0.115
Motor vehicle metal stamping	336370	0.025	0.109
Amusement parks and arcades	713100	0.025	0.079
Scenic and sightseeing transportation and support activities for transportation	48A000	0.025	0.262
Mining and oil and gas field machinery manufacturing	333130	0.024	0.038
Turbine and turbine generator set units manufacturing	333611	0.024	0.141
Curtain and linen mills	314120	0.023	0.021
Industrial process furnace and oven manufacturing	333994	0.022	0.034
Residential maintenance and repair	230302	0.022	0.115
Motor vehicle transmission and power train parts manufacturing	336350	0.021	0.109
Hardware manufacturing	332500	0.021	0.067
Elementary and secondary schools	611100	0.021	0.054
Other amusement and recreation industries	713900	0.020	0.079
Mechanical power transmission equipment manufacturing	333613	0.020	0.084
Printing	323110	0.020	0.054
Sporting and athletic goods manufacturing	339920	0.019	0.047
Transportation structures and highways and streets	2332C0	0.019	0.115
Facilities support services	561200	0.019	0.068
Manufacturing and reproducing magnetic and optical media	334610	0.019	0.039
Manufacturing structures	233230	0.018	0.115

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Toilet preparation manufacturing	325620	0.018	0.028
Health care structures	233210	0.017	0.115
Nonresidential maintenance and repair	230301	0.017	0.115
Other general purpose machinery manufacturing	33399A	0.017	0.036
Waste management and remediation services	562000	0.017	0.094
Small electrical appliance manufacturing	335210	0.017	0.042
Plumbing fixture fitting and trim manufacturing	332913	0.017	0.052
Funds, trusts, and other financial vehicles	525000	0.016	0.058
Packaging machinery manufacturing	333993	0.016	0.040
Household cooking appliance manufacturing	335221	0.016	0.094
Metal tank (heavy gauge) manufacturing	332420	0.016	0.034
Boat building	336612	0.016	0.110
Industrial mold manufacturing	333511	0.016	0.032
Power-driven handtool manufacturing	333991	0.016	0.074
Other fabricated metal manufacturing	332999	0.015	0.095
Dental laboratories	339116	0.015	0.064
Dental equipment and supplies manufacturing	339114	0.015	0.084
News syndicates, libraries, archives and all other information services	5191A0	0.014	0.022
Other aircraft parts and auxiliary equipment manufacturing	336413	0.014	0.046
Cutlery and handtool manufacturing	332200	0.013	0.036
Civic, social, professional, and similar organizations	813B00	0.013	0.079
Computer terminals and other computer peripheral equipment manufacturing	334118	0.013	0.034
Other Motor Vehicle Parts Manufacturing	336390	0.013	0.109
Sign manufacturing	339950	0.013	0.030
Cutting and machine tool accessory, rolling mill, and other metalworking machinery manufacturing	33351B	0.012	0.035
Office and commercial structures	2332A0	0.012	0.115
Truck trailer manufacturing	336212	0.012	0.061
Biological product (except diagnostic) manufacturing	325414	0.012	0.072
Ball and roller bearing manufacturing	332991	0.012	0.038
Other support activities for mining	21311A	0.012	0.321
Other ambulatory health care services	621900	0.012	0.080
Power boiler and heat exchanger manufacturing	332410	0.011	0.039
Turned product and screw, nut, and bolt manufacturing	332720	0.011	0.020
Metal crown, closure, and other metal stamping (except automotive)	332119	0.011	0.038
Other educational services	611B00	0.011	0.092
Metal can, box, and other metal container (light gauge) manufacturing	332430	0.011	0.081
Other furniture related product manufacturing	337900	0.011	0.054
Material handling equipment manufacturing	333920	0.010	0.039
Community food, housing, and other relief services, including rehabilitation services	624A00	0.010	0.048

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Multifamily residential structures	233412	0.010	0.115
Power and communication structures	233240	0.010	0.115
Other residential structures	2334A0	0.010	0.115
General and consumer goods rental	532A00	0.010	0.100
Valve and fittings other than plumbing	33291A	0.010	0.038
Lawn and garden equipment manufacturing	333112	0.010	0.068
Construction machinery manufacturing	333120	0.010	0.084
Ornamental and architectural metal products manufacturing	332320	0.009	0.076
Commercial and industrial machinery and equipment rental and leasing	532400	0.009	0.297
Full-service restaurants	722110	0.009	0.051
Animal production, except cattle and poultry and eggs	112A00	0.009	0.833
Ammunition, arms, ordnance, and accessories manufacturing	33299A	0.009	0.064
Other major household appliance manufacturing	335228	0.009	0.094
Educational and vocational structures	233262	0.009	0.115
Limited-service restaurants	722211	0.008	0.119
Plate work and fabricated structural product manufacturing	332310	0.008	0.077
Special tool, die, jig, and fixture manufacturing	333514	0.008	0.033
Automobile manufacturing	336111	0.008	0.273
All other food and drinking places	722A00	0.008	0.045
Machine shops	332710	0.008	0.051
Military armored vehicle, tank, and tank component manufacturing	336992	0.007	0.060
Support activities for agriculture and forestry	115000	0.007	0.882
Upholstered household furniture manufacturing	337121	0.007	0.046
Residential mental health, substance abuse, and other residential care facilities	623B00	0.007	0.057
All other transportation equipment manufacturing	336999	0.007	0.060
Ophthalmic goods manufacturing	339115	0.006	0.036
Primary battery manufacturing	335912	0.006	0.055
Services to buildings and dwellings	561700	0.006	0.061
Gambling industries (except casino hotels)	713200	0.006	0.079
Communication and energy wire and cable manufacturing	335920	0.005	0.048
Other computer related services, including facilities management	54151A	0.005	0.063
Motor and generator manufacturing	335312	0.005	0.056
Semiconductor machinery manufacturing	333242	0.005	0.039
Single-family residential structures	233411	0.005	0.115
All other miscellaneous manufacturing	339990	0.005	0.040
Other electronic component manufacturing	33441A	0.004	0.047
Motor vehicle seating and interior trim manufacturing	336360	0.004	0.109
Photographic services	541920	0.004	0.095
Directory, mailing list, and other publishers	5111A0	0.004	0.079

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Satellite, telecommunications resellers, and all other telecommunications	517A00	0.004	0.260
Motor vehicle and motor vehicle parts and supplies	423100	0.004	0.038
Farm machinery and equipment manufacturing	333111	0.004	0.068
Pharmaceutical preparation manufacturing	325412	0.004	0.055
Accommodation	721000	0.004	0.428
Child day care services	624400	0.004	0.069
Individual and family services	624100	0.004	0.028
Relay and industrial control manufacturing	335314	0.004	0.047
Spectator sports	711200	0.004	0.066
Other communications equipment manufacturing	334290	0.004	0.047
Grocery and related product wholesalers	424400	0.004	0.251
Pump and pumping equipment manufacturing	33391A	0.004	0.050
Other support services	561900	0.004	0.068
Warehousing and storage	493000	0.004	0.186
Jewelry and silverware manufacturing	339910	0.003	0.020
Motorcycle, bicycle, and parts manufacturing	336991	0.003	0.060
Performing arts companies	711100	0.003	0.079
Periodical Publishers	511120	0.003	0.079
Commercial and industrial machinery and equipment repair and maintenance	811300	0.003	0.107
Aircraft engine and engine parts manufacturing	336412	0.003	0.066
Other engine equipment manufacturing	333618	0.003	0.057
Grantmaking, giving, and social advocacy organizations	813A00	0.003	0.079
Industrial process variable instruments manufacturing	334513	0.003	0.035
Surgical appliance and supplies manufacturing	339113	0.003	0.051
Newspaper publishers	511110	0.002	0.079
Air conditioning, refrigeration, and warm air heating equipment manufacturing	333415	0.002	0.089
Guided missile and space vehicle manufacturing	336414	0.002	0.060
Data processing, hosting, and related services	518200	0.002	0.122
Other financial investment activities	523900	0.002	0.058
Semiconductor and related device manufacturing	334413	0.002	0.047
Medical and diagnostic laboratories	621500	0.002	0.080
Business support services	561400	0.002	0.068
Other durable goods merchant wholesalers	423A00	0.002	0.038
Heavy duty truck manufacturing	336120	0.002	0.273
Offices of other health practitioners	621300	0.002	0.112
Investigation and security services	561600	0.002	0.068
Automatic environmental control manufacturing	334512	0.002	0.040
Book publishers	511130	0.002	0.079
Nursing and community care facilities	623A00	0.002	0.057

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Promoters of performing arts and sports and agents for public figures	711A00	0.002	0.079
Building material and garden equipment and supplies dealers	444000	0.002	0.199
Apparel manufacturing	315000	0.002	0.024
Light truck and utility vehicle manufacturing	336112	0.002	0.167
Motor vehicle and parts dealers	441000	0.001	0.263
Computer storage device manufacturing	334112	0.001	0.106
Specialized design services	541400	0.001	0.063
Personal care services	812100	0.001	0.031
Machinery, equipment, and supplies	423800	0.001	0.038
Other nondurable goods merchant wholesalers	424A00	0.001	0.251
Nondepository credit intermediation and related activities	522A00	0.001	0.058
Sound recording industries	512200	0.001	0.091
Securities and commodity contracts intermediation and brokerage	523A00	0.001	0.058
Gasoline stations	447000	0.001	0.459
Veterinary services	541940	0.001	0.087
Wholesale electronic markets and agents and brokers	425000	0.001	0.145
Hospitals	622000	0.001	0.063
Household laundry equipment manufacturing	335224	0.001	0.094
Architectural, engineering, and related services	541300	0.001	0.063
Management of companies and enterprises	550000	0.001	0.115
Office administrative services	561100	0.001	0.068
Food and beverage stores	445000	0.001	0.286
Watch, clock, and other measuring and controlling device manufacturing	33451A	0.001	0.043
Monetary authorities and depository credit intermediation	52A000	0.001	0.035
Offices of dentists	621200	0.001	0.100
Surgical and medical instrument manufacturing	339112	0.001	0.085
Scientific research and development services	541700	0.001	0.063
Junior colleges, colleges, universities, and professional schools	611A00	0.001	0.075
Home health care services	621600	0.001	0.080
Internet publishing and broadcasting and Web search portals	519130	0.001	0.022
Aircraft manufacturing	336411	0.001	0.069
Automotive repair and maintenance	811100	0.001	0.156
Analytical laboratory instrument manufacturing	334516	0.001	0.040
Household refrigerator and home freezer manufacturing	335222	0.001	0.094
Printed circuit assembly (electronic assembly) manufacturing	334418	0.001	0.047
Irradiation apparatus manufacturing	334517	0.001	0.040
Telephone apparatus manufacturing	334210	0.001	0.047
All other miscellaneous professional, scientific, and technical services	5419A0	0.001	0.091
Personal and household goods repair and maintenance	811400	0.001	0.054

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Outpatient care centers	621400	0.001	0.080
Petroleum and petroleum products	424700	0.001	0.251
All other retail	4B0000	0.001	0.183
Other personal services	812900	0.001	0.075
Household appliances and electrical and electronic goods	423600	0.001	0.038
Travel arrangement and reservation services	561500	0.001	0.076
Computer systems design services	541512	0.001	0.063
Environmental and other technical consulting services	5416A0	0.001	0.063
Electronic and precision equipment repair and maintenance	811200	0.001	0.111
Electronic computer manufacturing	334111	0.001	0.299
Software publishers	511200	0.001	0.108
Clothing and clothing accessories stores	448000	0.001	0.327
Professional and commercial equipment and supplies	423400	0.001	0.038
Nonstore retailers	454000	0.000	0.530
Wireless telecommunications carriers (except satellite)	517210	0.000	0.269
Drugs and druggists' sundries	424200	0.000	0.251
Audio and video equipment manufacturing	334300	0.000	0.084
Other real estate	531ORE	0.000	0.297
Totalizing fluid meter and counting device manufacturing	334514	0.000	0.033
Motion picture and video industries	512100	0.000	0.091
General merchandise stores	452000	0.000	0.284
Electromedical and electrotherapeutic apparatus manufacturing	334510	0.000	0.055
Health and personal care stores	446000	0.000	0.142
Advertising, public relations, and related services	541800	0.000	0.063
Accounting, tax preparation, bookkeeping, and payroll services	541200	0.000	0.055
Radio and television broadcasting	515100	0.000	0.128
Broadcast and wireless communications equipment	334220	0.000	0.047
Lessors of nonfinancial intangible assets	533000	0.000	0.297
Electricity and signal testing instruments manufacturing	334515	0.000	0.024
Management consulting services	541610	0.000	0.063
Death care services	812200	0.000	0.089
Independent artists, writers, and performers	711500	0.000	0.091
Offices of physicians	621100	0.000	0.029
Wired telecommunications carriers	517110	0.000	0.252
Custom computer programming services	541511	0.000	0.063
Search, detection, and navigation instruments manufacturing	334511	0.000	0.051
Cable and other subscription programming	515200	0.000	0.128
Direct life insurance carriers	524113	0.000	0.080
Legal services	541100	0.000	0.016

Continued on next page

Table A1 – continued from previous page

Sector	Code	CO_2/VA	Price Δ Frequency
Insurance agencies, brokerages, and related activities	524200	0.000	0.080
Employment services	561300	0.000	0.068
Insurance carriers, except direct life	5241XX	0.000	0.080
Tenant-occupied housing	531HST	0.000	0.297
Owner-occupied housing	531HSO	0.000	0.297
Private households	814000	0.000	0.079
Customs duties	4200ID	0.000	0.145