Is the Green Transition Inflationary?*

Marco Del Negro, NY Fed and CEPR

Julian di Giovanni, NY Fed and CEPR

Keshav Dogra, NY Fed and CEPR

January 27, 2025 (First draft: February 3, 2023)

Abstract

We develop a multi-sector New Keynesian model to analyze the inflationary effects of climate policies. Climate policies need not be inflationary, but can generate an inflation-output tradeoff whose size depends on the relative flexibility of "dirty sectors prices vis-à-vis the rest of the economy. A version of the model calibrated to U.S. input-output data and sectoral heterogeneity in emissions and price stickiness matches the empirical responses to an energy shock of various CPI indexes well. It suggests that carbon taxes would have sizable inflationary implications if accommodated, while containing their impact on inflation would lead to a prolonged contraction.

JEL Classifications: E12, E31, E52, Q54

Keywords: Green transition, inflation, central bank's tradeoffs, input-output linkages

*We thank Neil Kapoor and Neel Lahiri for outstanding research assistance. We are very grateful to Diego Känzig for providing the codes in his paper and patiently addressing all our questions, as well as to Gianluigi Ferrucci, Stephie Fried, Conny Olovsson, and participants at various conferences, workshops, and seminars for their valuable feedback. The views expressed herein are those of the authors and not necessarily those of the Federal Reserve Banks of New York or any other person affiliated with the Federal Reserve System.

E-mail (URL): marco.delnegro@ny.frb.org (https://www.newyorkfed.org/research/economists/delnegro), julian.digiovanni@gmail.com (http://julian.digiovanni.ca), Keshav.Dogra@ny.frb.org (https://www.newyorkfed.org/research/economists/dogra).

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 may 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.

The goal of this paper is to study these tradeoffs using both analytics and a rich quantitative input-output (henceforth I/O) model. Specifically, we ask how the *green transition* – policies such as carbon taxes that reduce greenhouse gas emissions in order to limit global warming – affects monetary policymakers' ability to pursue price stability. We focus on the inflationary effects of climate *policy* because the green transition is an immediate concern for central bankers as policies aimed at discouraging high emission activities and/or promoting clean energy have been already put in place in many advanced economies, and more are likely to come.[1] We find that the green transition does not force monetary policymakers to tolerate higher inflation, but can potentially generate a tradeoff for policymakers. Two factors drive this tradeoff. First, the relative *stickiness* of prices in the "dirty" and the "other" sector (the rest of the economy) is a key determinant as to whether monetary policy is able to keep inflation at its target while also stabilizing output at its natural level. Second, the input-output network plays an important role in the propagation of the effects if the carbon tax. In the two-sector models used so far in the literature 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 (dirty) energy as an input for the economy is relatively small. Hence policymakers should ignore it. We show that accounting for the network reverses this conclusions, as many sticky price sectors are *indirectly* affected by the carbon tax.

We begin by documenting empirically the relationship between the "dirtiness" of a sector, as measured by emissions per value added, and price stickiness. We find that prices in "dirty" sectors tend to be more flexible than in the rest of the economy (section 2).

[1] We do not study the impact of the physical effects of climate change itself on inflation, partly because the implications of climate change for the economy, even if potentially large, are also very uncertain and hence more difficult to discuss. Our quantitative analysis so far focuses on carbon taxes, as opposed to subsidies to green energy, for two reasons. One is that according to the literature carbon taxes are both "necessary and sufficient" to address climate change, to use the words of Per Krusell (Golosov et al., 2014). The other reason is that we would need to make assumptions on the extent to which green energy sources interact with the IO network, given that the current IO structure features very little green energy. But if one is willing to make such assumptions, the model can be used to study the effects of subsidies to the green sector.

Next, we employ a simple framework to develop some analytical intuition about the forces at play (section 3). We begin by studying the effects of a tax on the dirty sector, and use a two-sector New Keynesian model where the dirty sector represents high-emission activities and the other sector stands in for the rest of the economy, initially abstracting from the green sector. Each sector is monopolistically competitive and features nominal rigidities; importantly, the degree of price stickiness can vary across sectors. The key lessons from the simple model are as follows. First, with fully flexible prices climate policies would not pose any problem for an inflation targeting central bank—hence any tradeoff is necessarily related to the presence of nominal rigidities. This is because the adjustment in relative prices can take place under any level of overall inflation. Second, in the empirically realistic case where prices are more flexible in carbon-intensive sectors, the transition creates a tradeoff between keeping inflation low and closing the output gap. Intuitively, the tradeoff arises because the central bank needs to nudge inflation in the sticky sector down so that the needed adjustment in relative prices occurs with an overall inflation level that is in line with its target. But this nudge involves cooling down the economy. If the central bank is not willing to do that, it may have to accept temporarily high inflation.[2]

To investigate the quantitative importance of our results, we calibrate a 73-sector version of the model using input-output 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 et al. (2018) (section 4). This multi-sector version of the model, which we solve non-linearly, is key for our quantitative analysis for several reasons. First, the notion that dirty sector prices are flexible while clean sectors' prices are sticky, which is embedded in some two-sector models in the literature, is an oversimplification (as shown in section 2). There are several sectors that are quite dirty in terms of emissions—in that they use a lot of fossil fuels as inputs—whose prices are quite sticky. Our granular multisector IO model lets us assign to each sector the correct level of stickiness and emissions, via the input-output matrix, without having to make oversimplifying assumptions. Second, the literature studying monetary policy in network economies (e.g., Ghassibe, 2021; La'O and Tahbaz-Salehi, 2022; Rubbo, 2023; Afrouzi and Bhattarai, 2023) has emphasized the importance of networks in the transmission of relative price shocks, such as those we study here. In particular, as discussed above, a quantitative analysis needs to take into account the fact that the effects of the carbon tax on marginal costs propagate through the network.

We find that in this input-output 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$—a magnitude based on the literature, e.g. Barron et al. (2018)—

[2] We also show that if instead climate policy primarily takes the form of subsidizing a green sector with relatively flexible prices, rather than taxing a dirty sector, our conclusions are reversed: the green transition is deflationary unless monetary policy engineers a positive output gap.

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 (henceforth, pp) or more above target for more than 6 years; 12 month core CPI is 50 basis points (henceforth, bps) or more above target for about 10 years (and 80 bps 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 bps 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 bps on average—is associated with an average contraction of 0.6 percent of output relative to natural over the entire period.

Related Literature. Schnabel (2022) argues that physical and transition risks arising from climate change may be inflationary. Schnabel classifies three sources of climate-driven inflation. First, "climateflation," where climate change increases the probability of natural disasters and severe weather events, which lead to droughts, supply chain problems and other production disruptions that may put upward pressure on prices. This climateflation captures possible physical risks of climate change, which we do not study here for the reasons discussed above. Second, "fossilflation," where the use of policies such as carbon taxes to discourage the use of fossil fuels and reduce emissions may place upward pressure on prices. This fossilflation is at the heart of the climate policy in our proposed analytical framework.[3]

Most recent studies on the impact of transition policies have focused on their effects on output (eg, Metcalf and Stock, 2023), but a growing number also studied 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.[4] 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. Importantly, the policy rate essentially does not change. All in all, these responses are consistent with the simple model outlined below, where energy prices are more flexible than core prices, and policy lets nominal energy prices do all the adjustment in relative prices. 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.[5] However, they also find that for a subset of European

[3] Schnabel (2022) also considers "greenflation," which arises from price increases in scarce commodities (e.g., lithium for batteries) as a result of the increased demand from the green energy sector.

[4] 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.

[5] 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.

countries where monetary policies are constrained, the effect on inflation is positive and significant, in line with Känzig (2022).

Some authors, like us, have used New Keynesian frameworks to study the inflationary impact of transition policies. The upshot of much of this literature, which mostly uses two-sector models, 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 particular, in contemporaneous work Olovsson and Vestin (2023) find that the Aoki (2001) result applies to the green transition: since the effects of the carbon tax on core inflation is muted given that energys share of income is small, monetary policy should see through it.[6] A number of works perform normative analysis. Nakov and Thomas (2023) investigate the question of whether central banks should fight climate change by restraining economic activity. 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. 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 taxes on the dirty sector, although their exercise is arguably less quantitative than ours. Finally, our work relates to the literature on heterogeneity in price stickiness across sectors (Carvalho, 2006; Nakamura and Steinsson, 2010) and to the aforementioned recent literature on networks and monetary policy (Ghassibe, 2021; La'O and Tahbaz-Salehi, 2022; Rubbo, 2023; Afrouzi and Bhattarai, 2023), as well as to the literature on relative price adjustments under sticky prices (Guerrieri et al., 2021, 2023).

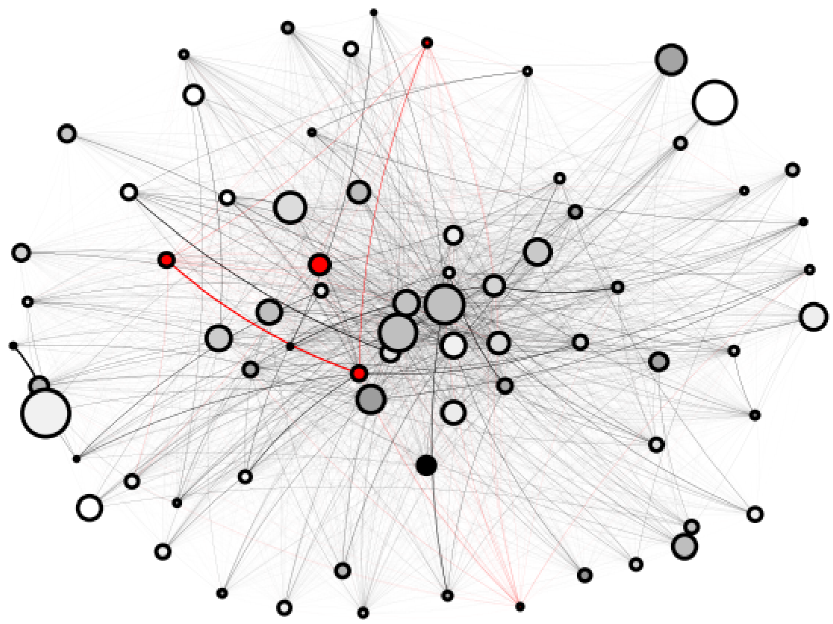
2 Energy Use and Price Rigidities in the Input-Output Network

In this section we document empirically i) the centrality of high CO_2 emission energy sectors in the U.S. input-output network, and ii) the the relationship between the "dirtiness" of a sector, as measured by emissions per value added, and price stickiness. Figure 1 makes the first point. The 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, and the edges represents the bilateral input usage of a sector pair deflated by the customer sector's gross output. One can readily see that energy sectors (red nodes) occupy a very central position in the network. The darkness of other nodes is proportional to their price flexibility, that is, sticky price sectors are lighter.[7] Not surprisingly, the non-energy part of the

[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 source information on price rigidity from Cotton and Garga (2022) that calculates 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

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).

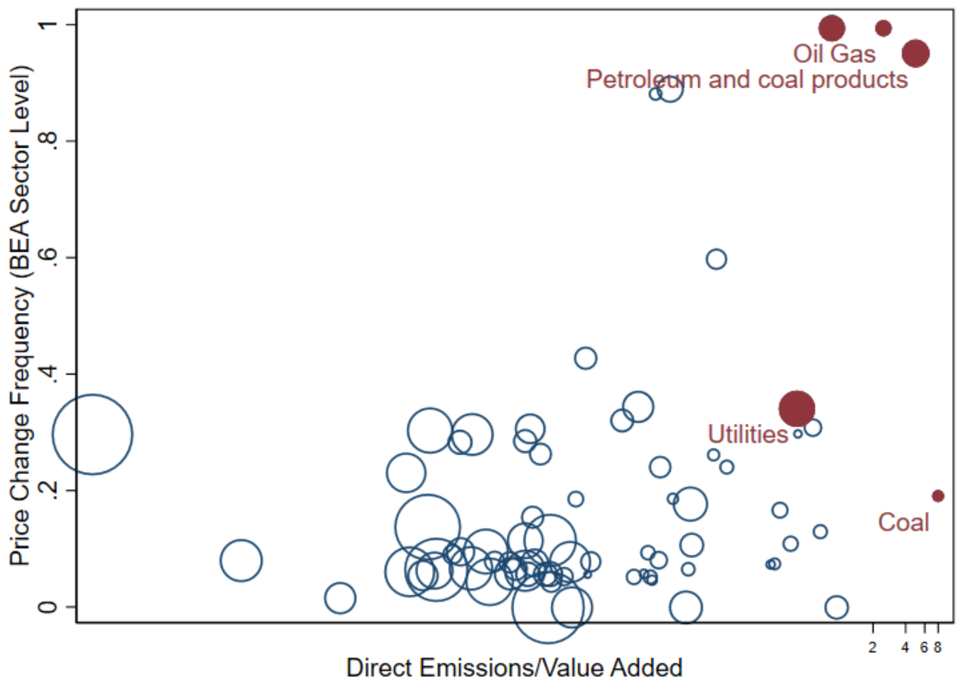
economy—which in two-sector models is a monolithic sector—is composed of a multitude of sectors with varying stickiness that interact with one another and with energy.

Figure 2 shows that energy sectors, and in general sectors that make most use of energy, tend to be more flexible on average than less energy-intensive sectors. The picture plots a bin scatter of the sector-level price rigidity measure against the CO_2/VA ratio for 396 U.S. sectors based on *direct* emissions' creation in production, where direct emissions are a measure of "dirty" energy usage.[8] 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 emissions (relative to value added) tend to have a higher average frequency of price change, although there

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.

[8]We follow the methodology of Shapiro et al. (2018) to construct sector-level emission measures based each sectors use of fossil fuels (oil, gas, and coal) in production along with fossil fuel emissions data from the EPA and EIA. As in Shapiro et al. (2018), a sector's emissions can be calculated based on its *direct* use of the fossil fuel sectors in production. A sector-level emissions intensity is defined as the ratio of CO2 emissions to value added using 2012 BEA IO data (kilotons of CO_2 emitted per millions of US$ value added). Appendix A describes all details of our data construction.

Figure 2. Mean price change frequency of a good in a given sector vs CO_2 emissions/value added across 73 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 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. Regressions of level on level or log-level on log-level yield a positive and significant coefficient. [Three comments: (1) go to 73 sectors to be same as Fig 1? (2) Highlighting utilities might confuse the reader as this is now a sector that gets directly taxed. (3) Similar comment for petroleum and coal products as these must use oil and coal as inputs. If we highlight (2) and (3), I would suggest doing this in another color [maybe red empty circle?]]

are some very sticky price sectors that are quite energy intensive. The granular multisector IO model we present in section 4 lets us assign the correct level of stickiness and emissions to each sector, via the input-output matrix, without having to make oversimplifying assumptions.

3 Analytical Results from a Two-Sector Model

The goal of this section is to deliver qualitative insights using the simplest possible model. We therefore start with a two-sector model, where the sectors are a dirty high-emissions sector that the government wants to tax, and the rest of the economy. Our two-sector model is a relatively standard New Keynesian economy except that household consumption is an aggregate of dirty goods, which may be taxed, and other goods. The economy consists of a representative household, monopolistically competitive firms, a fiscal authority, and a central bank.

Households. The representative household solves

$$\max_{\{C_t, C_t^o, C_t^d, C_t^o(\cdot), C_t^d(\cdot), L_t\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \{\ln C_t - bL_t\}$$

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

$$C_t = (C_t^o/\gamma)^\gamma (C_t^d/(1-\gamma))^{1-\gamma}$$

$$C_t^i = \left(\int_0^1 C_t^i(j)^{\frac{\varepsilon_t^i - 1}{\varepsilon_t^i}} dj \right)^{\frac{\varepsilon_t^i}{\varepsilon_t^i - 1}}, \ i = o, d,$$

where W_t denotes the nominal wage rate and T_t denotes net transfers from the government and monopolistically competitive firms. Consumption C_t is a Cobb-Douglas aggregate of consumption of other goods C_t^o and dirty goods C_t^d, each of which is in turn a CES aggregate of the varieties $C_t^o(j), C_t^d(j)$ produced by monopolistically competitive producers, with elasticities of substitution ε_t^o and ε_t^d respectively. Since the baseline model does not feature an input-output structure, dirty goods should be thought of as a stand-in for goods and services with relatively high greenhouse gas emissions, both direct and indirect, while other goods represent all other consumption.

The household's optimality conditions imply the standard relationships

$$C_t^o = \gamma C_t (P_t / P_t^o) = \gamma C_t S_t^{1-\gamma},$$

$$C_t^d = (1-\gamma) C_t (P_t / P_t^d) = (1-\gamma) C_t S_t^{-\gamma},$$

$$C_t^i(j) = \left(\frac{P_t^i(j)}{P_t^i} \right)^{-\varepsilon_t^i} C_t^i, \ i = o, d, \ j \in [0,1],$$

$$\frac{W_t}{P_t} = bC_t,$$

$$1 = \beta \mathbb{E}_t \left[(1+i_t) \frac{C_t}{C_{t+1}} \frac{P_t}{P_{t+1}} \right],$$

where $P_t = (P_t^o)^\gamma (P_t^d)^{1-\gamma}$ is the aggregate price level, and $S_t = \frac{P_t^d}{P_t^o}$ denotes the price of dirty goods relative to other goods.

Firms. The monopolistically competitive producer of variety $j \in [0,1]$ in sector $i = o, d$ faces a tax $\mathcal{T}_t^i$ (which may be negative, i.e. a subsidy) per unit of output produced. We will assume $\mathcal{T}_t^o \leq 0$ and $\mathcal{T}_t^d \geq 0$, i.e. other goods may be subsidized, while dirty goods may be taxed (a proxy for carbon taxes and regulations). Firms produce using a linear technology $Y_t^i(j) = A_t^i L_t^i(j)$ with labor as the only input and face quadratic costs of adjusting prices.[9] We assume these adjustment costs as "psychic" (or, equivalently, they are transfers to households) i.e. they will not appear

[9]Section 3.2.3 discusses the effect of incorporating input-output linkages, but we relegate the derivation of these results to Appendix B.2.

in aggregate resource constraints. Thus, the nominal marginal cost for a firm in sector i equals $M_t^i = \frac{W_t}{A_t^i} + \mathcal{T}_t^i$.

A natural interpretation of the tax is that greenhouse gas emissions are proportional to production of dirty goods, and the government taxes these emissions. However, we do not explicitly model the emissions generated by the dirty sector, the effect of emissions on climate, or the effect of climate on welfare and economic outcomes (eg, see Golosov et al., 2014; Känzig, 2022). Our focus is on the effect of climate policy on inflation over the medium term; while a change in climate policy will affect emissions and hence climate change, the effect of policy on inflation via this channel is likely to be small over the horizon we are interested in.

The firm solves

$$\max \ E_0 \sum_{t=0}^{\infty} Q_{t|0} \left\{ (P_t^i(j) - M_t^i) Y_t^i \left(\frac{P_t^i(j)}{P_t^i} \right)^{-\varepsilon_t^i} - \frac{\Psi^i}{2} \left(\frac{P_t^i(j)}{P_{t-1}^i(j)} - 1 \right)^2 P_t^i Y_t^i \right\},$$

where $Q_{s|t} = \beta^{s-t} \frac{P_t C_t}{P_s C_s}$ denotes the representative household's nominal stochastic discount factor (SDF). Taking the first-order conditions, assuming a symmetric equilibrium and using market clearing to simplify the SDF terms yields the sectoral Phillips curves

$$\Pi_t^i(\Pi_t^i - 1) = \frac{\varepsilon_t^i}{\Psi^i} \left(\frac{M_t^i}{P_t^i} - \frac{1}{\mu_t^i} \right) + \mathbb{E}_t \left\{ \beta \Pi_{t+1}^i (\Pi_{t+1}^i - 1) \right\}, \ i = o, d,$$

where $\Pi_t^i = \frac{P_t^i}{P_{t-1}^i}$ denotes inflation in sector i, and we define $\mu_t^i = \frac{\varepsilon_t^i}{\varepsilon_t^i - 1}$ to be the desired (gross) markup in sector $i = o, d$. The cost of price adjustment Ψ^i may differ between sectors. In particular, prices in the dirty sector may be more flexible ($\Psi^d < \Psi^o$), or even fully flexible ($\Psi^d = 0$).

The relative price S_t evolves according to

$$S_t = \frac{\Pi_t^d}{\Pi_t^o} S_{t-1}. \tag{1}$$

CPI inflation is defined as $\Pi_t = (\Pi_t^o)^\gamma (\Pi_t^d)^{1-\gamma}$.

Monetary and fiscal policy. The monetary authority sets the nominal interest rate i_t; the fiscal authority sets taxes $\mathcal{T}_t^o, \mathcal{T}_t^d$ and adjusts the lump sum transfer to households as necessary to maintain a balanced budget. We assume government debt is in zero net supply ($B_t = 0, \forall t$) which is without loss of generality since the economy features Ricardian equivalence. Rather than specify a particular monetary policy rule, we will study outcomes under various different rules.

Market clearing. In equilibrium markets clear for goods in each sector and for labor:

$$C_t^i = Y_t^i = A_t^i L_t^i, \ i = o, d,$$
$$L_t^o + L_t^d = L_t,$$

Model solution. To solve the model, note that real marginal costs (deflated by prices in each sector) can be written as

$$\frac{M_t^i}{P_t^i} = \frac{W_t}{P_t^i A_t^i} + \frac{\mathcal{T}_t^i}{P_t^i} = \frac{W_t}{P_t A_t^i}\frac{P_t}{P_t^i} + \frac{\mathcal{T}_t^i}{P_t^i} = \frac{bY_t}{A_t^i}\frac{P_t}{P_t^i} + \frac{\mathcal{T}_t^i}{P_t^i},$$

where $\frac{P_t}{P_t^o} = S_t^{1-\gamma}$ and $\frac{P_t}{P_t^d} = S_t^{-\gamma}$. Thus, we can substitute out for marginal costs to obtain

$$\Pi_t^o(\Pi_t^o - 1) = \frac{\varepsilon_t^o}{\Psi^o}\left(bY_t\frac{S_t^{1-\gamma}}{A_t^o} + \frac{\mathcal{T}_t^o}{P_t^o} - \frac{1}{\mu_t^o}\right) + \mathbb{E}_t\left\{\beta\Pi_{t+1}^o(\Pi_{t+1}^o - 1)\right\}, \quad (2)$$

$$\Pi_t^d(\Pi_t^d - 1) = \frac{\varepsilon_t^d}{\Psi^d}\left(bY_t\frac{S_t^{-\gamma}}{A_t^d} + \frac{\mathcal{T}_t^d}{P_t^d} - \frac{1}{\mu_t^d}\right) + \mathbb{E}_t\left\{\beta\Pi_{t+1}^d(\Pi_{t+1}^d - 1)\right\}. \quad (3)$$

Taxes $\frac{\mathcal{T}_t^d}{P_t^d} > 0$ are isomorphic to a positive cost-push shock or increase in dirty firms' desired markups: they tend to increase inflation. Taking $\frac{\mathcal{T}_t^o}{P_t^o}$ and $\frac{\mathcal{T}_t^d}{P_t^d}$ as given, (2) and (3) together with (1) gives us three equations in four unknowns, $\Pi_t^o, \Pi_t^d, S_t, Y_t$. Given a specification of the monetary policy rule and the path of taxes, these equations fully characterize equilibrium.

Taxes. We wish to study the macroeconomic effects of climate policy, modeled as the effect of an increase in taxes on the dirty sector $\mathcal{T}_t^d$. Rather than working with taxes directly, however, it is convenient to define the 'virtual markup' $\widetilde{\mu}_t^i$ such that

$$\frac{1}{\widetilde{\mu}_t^i} = \frac{1}{\mu_t^i} - \frac{\mathcal{T}_t^i}{P_t^i}, \ \ i = o, d.$$

An increase in real taxes on dirty goods $\frac{\mathcal{T}_t^d}{P_t^d}$ is isomorphic to an increase in dirty goods producers' desired markup μ_t^d: both imply an increase in that sector's virtual markup $\widetilde{\mu}_t^d$, inducing producers to prefer lower output and higher prices.

In the experiments described below, we assume productivity is constant in each sector, and model climate policy as follows. The economy is initially in a steady state with zero CPI inflation ($\Pi_t = 1$) and real taxes (or subsidies) consistent with $\widetilde{\mu}_{-1}^o = 1$, $\widetilde{\mu}_{-1}^d = 1$. At date 0, it becomes common knowledge that the tax on dirty goods will increase such that μ_t^d converges to a higher long-run level $\widetilde{\mu}_\infty^d > \widetilde{\mu}_0^d$:

$$\ln\widetilde{\mu}_t^d - \ln\widetilde{\mu}_\infty^d = \rho^{t+1}(\ln\widetilde{\mu}_{-1}^d - \ln\widetilde{\mu}_\infty^d),$$

where ρ governs the speed with which convergence to the long-run level occurs.

3.1 The Long Run and the Flexible-Price Benchmark

In this section we briefly describe the steady state after the taxes on the dirty sector have been implemented and the effect of nominal rigidities has vanished. We also discuss the effect that the whole dynamic path of taxes would have in a counterfactual economy where prices were *always* perfectly flexible.

Flexible-price equilibrium. While we are ultimately interested in the effect of the green transition on inflation, which is only a meaningful topic in an economy with nominal rigidities, the flexible-price equilibrium provides a useful benchmark. In the flexible price limit ($\Psi^i = 0, i = o, d$), firms are free to set prices in each sector equal to their desired markup over marginal cost, and the Phillips curves (2) and (3) become

$$bY_t \frac{S_t^{1-\gamma}}{A_t^o} = \frac{1}{\widetilde{\mu}_t^o}, \tag{4}$$

$$bY_t \frac{S_t^{-\gamma}}{A_t^d} = \frac{1}{\widetilde{\mu}_t^d}. \tag{5}$$

Relative prices, output, and hours worked in the flexible price equilibrium are given by

$$\begin{aligned}
S_t &= \frac{\widetilde{\mu}_t^d}{\widetilde{\mu}_t^o} \frac{A_t^o}{A_t^d}, \\
Y_t &= \frac{1}{b} \left(\frac{A_t^o}{\widetilde{\mu}_t^o} \right)^{\gamma} \left(\frac{A_t^d}{\widetilde{\mu}_t^d} \right)^{1-\gamma} := Y_t^*, \\
Y_t^i &= \frac{1}{b} \frac{A_t^i}{\widetilde{\mu}_t^i}, \ i = o, d, \\
L_t &= \frac{1}{b} \left[\frac{\gamma}{\widetilde{\mu}_t^o} + \frac{1-\gamma}{\widetilde{\mu}_t^d} \right], \\
&= \left[\gamma \left(\frac{\widetilde{\mu}_t^d}{\widetilde{\mu}_t^o} \right)^{1-\gamma} + (1-\gamma) \left(\frac{\widetilde{\mu}_t^d}{\widetilde{\mu}_t^o} \right)^{-\gamma} \right] \frac{Y_t}{(A_t^o)^{\gamma} (A_t^d)^{1-\gamma}}.
\end{aligned}$$

We refer to the flexible price level of output Y_t^* as *potential output*.

Here we note that throughout, whenever we discuss efficiency, we ignore externalities associated with higher output of dirty goods, which are not modeled here. Implicitly, these externalities are the reason that the government would want to reduce the output of the dirty sector. What we call the 'efficient' level of output features higher dirty-sector output than would be socially desirable.

Even when prices are fully flexible, the equilibrium may not be efficient owing to the distortions arising from taxes and/or monopolistic competition. In the efficient flexible price equilibrium (which maximizes the utility of the representative household), these distortions are absent and $\widetilde{\mu}_t^o = \widetilde{\mu}_t^d = 1$. As is standard in New Keynesian models, this requires subsidizing output to offset monopolistic distortions, $\frac{\mathcal{T}_t^i}{P_t^i} = -\frac{1}{\widetilde{\mu}_t^i}$. Relative prices are then purely driven by relative costs of production, $S_t = A_t^o / A_t^d$, aggregate output is $Y_t = \frac{1}{b}(A_t^o)^{\gamma}(A_t^d)^{1-\gamma}$, sectoral output is $Y_t^i = \frac{1}{b} A_t^i$, $i = o, d$, and labor supply is $L_t = \frac{1}{b}$. As mentioned above, we assume the economy starts out in the efficient steady state, $\widetilde{\mu}_{-1}^o = \widetilde{\mu}_{-1}^d = 1$.

New steady state under a higher carbon tax. We will study the effect of an increase in taxes on the dirty sector, which raises $\widetilde{\mu}_t^d > 1$. Under flexible prices, this increases the relative price of dirty goods to $S_t = \mu_t^d A_t^o / A_t^d > A_t^o / A_t^d$, and reduces dirty sector output to $\frac{1}{b} \frac{A_t^d}{\widetilde{\mu}_t^d} < \frac{1}{b} A_t^d$. Given our assumptions on household preferences, this tax neither increases nor decreases output in the other sector, and therefore it reduces aggregate potential output. Note that the proportional reduction in the output of the dirty sector, relative to the efficient level of production, equals $\frac{1}{\widetilde{\mu}_t^d}$. Thus, the policy we study can also be interpreted as a *quantity target* which reduces dirty sector output by some percentage amount relative to its efficient level.

When productivity and $\widetilde{\mu}_t^i$ are both constant, the flexible-price equilibrium is also a zero-inflation steady state of the sticky-price economy, featuring $\Pi_t^o = \Pi_t^d = \Pi_t = 1$. Given our assumptions on taxes, the economy transitions from the efficient steady state to a new steady state with higher relative prices $S_t = \widetilde{\mu}_\infty^d S_{-1}$ and lower aggregate output $Y_\infty = (\widetilde{\mu}_\infty^d)^{-(1-\gamma)} Y_{-1}$.

In this new steady state the relative price of the dirty good – relative to the price for the rest of the economy's output – is going to be higher, because taxes increase the marginal cost of producing dirty output. For this same reason, dirty output is going to be scarcer, which is the point of taxes in the first place. In the main experiment we consider, taxes on the dirty sector will not affect the flexible-price level of output in the other sector, and so the overall level of output will also be lower than before. Since we consider a gradual increase in taxes, this decline in the flexible-price level of output, Y_t^*. takes place gradually over time. More generally, whether taxes on the dirty sector affect production in the other sector would depend on whether these taxes are used to subsidize the rest of the economy or not, as well as on the degree of substitutability in consumption between dirty and non-dirty output (our baseline model assumes a unit elasticity of substitution, i.e. Cobb-Douglas preferences). Regardless, the central feature of the green transition is that it features a decline in both the absolute size and the share of the dirty sector.

To achieve such an outcome, dirty output needs to eventually become more expensive in relative terms. Is the green transition then inflationary? Not necessarily. A change in relative prices can be achieved in many ways – by increasing the nominal price of dirty goods or lowering the price of rest-of-the-economy output. Either combination works, and the ultimate result in terms of inflation depends entirely on monetary policy. If prices are flexible, monetary policy only determines nominal variables and not real allocations. Since the choice of the central bank has no consequence for real activity, there is no reason why it would choose an inflation rate different from its objective.[10] In sum, when prices are flexible, the green transition *per se* is neither inflationary nor deflationary. Any inflationary effects of the green transition therefore must have to do with nominal rigidities.

[10] As shown in Woodford (2003) in a flexible price economy the central bank pins down expected (and hence average) inflation by its choice of the nominal interest rate, via the Fisher equation, given that the real interest rate in such economy always equals r^*, that is, it is independent from monetary policy.

3.2 The Role of Nominal Rigidities

If nominal rigidities are present, taxes on the dirty sector may present the central bank with a tradeoff between efficiently facilitating the green transition and maintaining low inflation. The nature of this tradeoff, however, depends crucially on the relative degree of nominal rigidities in the dirty sector and the rest of the economy, as discussed below.[11]

3.2.1 Relative prices and Sectoral Phillips Curves

We now study the behavior of inflation during the transition to a new steady state with higher taxes on dirty goods. We loglinearize the system around the 'new' zero-inflation steady state consistent with $\widetilde{\mu}^d_\infty$. Without yet specifying a monetary policy rule, this yields four equations which can be used to understand the macroeconomic tradeoffs introduced by the green transition:

$$\pi^o_t = \kappa^o(y_t - y^*_t + (1-\gamma)(s_t - s^*_t)) + \beta\mathbb{E}_t\pi^o_{t+1}, \tag{6}$$

$$\pi^d_t = \kappa^d(y_t - y^*_t - \gamma(s_t - s^*_t)) + \beta\mathbb{E}_t\pi^d_{t+1}, \tag{7}$$

$$s_t = s_{t-1} + \pi^d_t - \pi^o_t, \tag{8}$$

$$\pi_t = \gamma\pi^o_t + (1-\gamma)\pi^d_t. \tag{9}$$

Here lower case variables denote log-deviations from the new, high-tax steady state: y_t denotes (the log-deviation of) aggregate output and $s_t := p^d_t - p^o_t$ denotes the price of dirty goods relative to other goods. $y^*_t := -(1-\gamma)\mu^d_t$ and $s^*_t := \mu^d_t$ denote the log-deviations of the flexible price values of y_t and s_t, and their evolution is given by

$$\mu^d_t = \rho^{t+1}\mu^d_{-1}, \quad \mu^d_{-1} \le 0, \quad s_{-1} = \mu^d_{-1} < 0.$$

(where with some abuse of notation μ^d_t denotes the log-deviation of $\widetilde{\mu}^d_t$ from steady state). Note that $\mu^d_0 < 0$ means that μ^d_t is initally below its new steady state value.

Equations (6) and (7) are Phillips curves for the other and dirty sectors. These equations relate inflation in the two sectors (π^o_t and π^d_t respectively) to the deviation of aggregate output y_t and relative prices s_t from their flexible price levels, y^*_t and s^*_t. These starred variables do not depend on monetary policy, but *do* depend on climate policy: as described above, the gradual introduction of a tax on dirty goods will gradually increase s^*_t, and reduce potential output y^*_t, towards their new steady state levels. The sectoral Phillips curve slopes κ^o and κ^d measure the degree of price flexibility in the other and dirty sectors respectively.[12] Equation (8) is an accounting identity stating that the change in relative prices equals the difference in sectoral inflation rates. Finally,

[11] Indeed, the literature has often argued that shocks to the relative price of energy are inflationary precisely because prices in this sector are relatively flexible (Gordon, 1975; Aoki, 2001; Rubbo, 2023). Since the energy sector also accounts for the majority of greenhouse gas emissions, one might suspect that prices are more flexible in dirty sectors of the economy.

[12] The data suggest that the empirically relevant case is $\kappa^d > \kappa^o$. [Take estimates from old table?]

equation (9) defines overall CPI inflation (where γ and $1-\gamma$ denote the expenditure shares of the other and dirty sectors respectively).

Why do relative prices enter the sectoral Phillips curves (6) and (7)? As in a 1-sector New Keynesian model, inflation in each sector depends on the marginal cost in that sector. This in turn depends on that sector's *product wage*, i.e. nominal wages deflated by the price of that sector's output. For any given *real wage* (i.e. nominal wages deflated by the CPI), an increase in the relative price of dirty goods s_t increases the product wage in the other sector, adding to inflationary pressure there, and reduces the product wage in the dirty sector. Mathematically (abstracting from changes in productivity and taxes):

$$\underbrace{mc_t^i}_{\substack{\text{marginal cost}\\ \text{in sector } i}} = \underbrace{w_t - p_t^i}_{\text{product wage}} = \underbrace{w_t - p_t}_{\substack{\text{real wage}\\ = y_t}} - \underbrace{(p_t^i - p_t)}_{\substack{\text{relative price}\\ \text{of sector } i}} = \begin{cases} y_t + (1-\gamma)s_t & \text{for } i = o, \\ y_t - \gamma s_t & \text{for } i = d. \end{cases}$$

3.2.2 The Role of Relative Price Stickiness

To understand what happens in our model economy when nominal prices are slow to adjust, it is instructive to first consider a few special cases.

Case 1: Other prices fixed, dirty prices flexible. Start with the extreme case where dirty prices are fully flexible ($\kappa^d = \infty$), while they are completely sticky in nominal terms – that is, fixed – for the remainder of the economy ($\kappa^o = 0$). In this case, our system reduces to

$$s_t = s_t^* + \frac{1}{\gamma}(y_t - y_t^*), \tag{10}$$

$$\pi_t = (1-\gamma)\pi_t^d = (1-\gamma)\Delta s_t. \tag{11}$$

Equation (10) states that the relative price of dirty goods can rise above its flexible price level when the output gap is positive (which raises wages and costs in the dirty sector); equation (11) states that inflation is driven by dirty sector prices since other prices are fixed. In such a situation it is obvious that the green transition would be inflationary: the only way to reduce the share of the dirty sector, and increase the *relative* price of dirty goods, is for the dirty prices to move up (from (8), if $\pi_t^o = 0$, implementing $\Delta s_t > 0$ requires $\pi_t^d > 0$). Since all other prices are fixed, overall inflation needs to move up as well (from the definition of CPI inflation (7), if $\pi_t^d > 0$ and $\pi_t^o = 0$, $\pi_t > 0$). Changes in relative prices are necessarily associated with aggregate inflation.[13]

Case 2: Other prices sticky, dirty prices flexible. Now maintain the assumption that dirty prices are fully flexible ($\kappa^d = \infty$), but suppose that prices for the rest of the economy are

[13] Olovsson and Vestin (2023) show that if monetary authorities only care about inflation in the other sector π_t^o, which is fixed, then the flexible price equilibrium is implemented. This is apparent from equations (10) and (11): if π_t^d fully adjusts so that relative prices are the same as in the flexible price equilibrium, then $y_t = y_t^*$.

sticky, but not completely rigid ($0 < \kappa^o < \infty$). In this case, our system becomes

$$
\begin{aligned}
s_t &= s_t^* + \frac{1}{\gamma}(y_t - y_t^*), && (12)\\
\pi_t^o &= \frac{\kappa^o}{\gamma}(y_t - y_t^*) + \beta\mathbb{E}_t\pi_{t+1}^o, && (13)\\
\pi_t &= \pi_t^o + (1-\gamma)\Delta s_t. && (14)
\end{aligned}
$$

Here the central bank has a choice: as (14) shows, the central bank can engineer whatever level of overall inflation π_t it wants, while still allowing relative prices s_t to increase, by picking inflation in the non-dirty sector π_t^o. However, since π_t^o is determined by the Phillips curve (13), the only way to achieve this objective amounts to picking the level of output gap $y_t - y_t^*$ for the economy. In turn, this gives rise to the tradeoff mentioned at the beginning of this section.

For concreteness, suppose the central bank has a zero inflation target. In order to implement such a target, and at the same time to achieve the required adjustment in relative prices, if dirty output prices are rising there needs to be deflation in the rest of the economy. Such deflation can only be accomplished by having a negative output gap, that is, a recession. Hence it is still true that the green transition is *per se* neither inflationary nor deflationary. But in order to achieve the desired level of inflation the central bank needs to exert some influence on aggregate economic activity, so as to affect marginal costs in the sticky sector. Intuitively, in the presence of stickiness the required nominal adjustment in the sticky sector needs a push from the central bank. This push is not costless, as it hinges on the output gap and therefore generates a tradeoff.

If prices are sticky also in the dirty sector, $\kappa^d < \infty$, as will be the case in the numerical examples discussed in the next section, the conclusions do not change. As long as prices are stick*ier* in the rest of the economy, the central bank can only achieve zero overall inflation by generating a contraction in economic activity. Conversely, if prices were stickier in the dirty sector, implementing zero inflation would require a boom in economic activity.

Case 3: Prices equally sticky in both sectors. However, in the knife-edge case where stickiness is the same in both sectors ($\kappa^o = \kappa^d \equiv \kappa$), no output gap is needed to achieve the required adjustment in relative prices. Nominal prices in both sectors are just as sluggish, and will gradually adjust in opposite directions without affecting overall inflation. Mathematically, our system becomes

$$
\begin{aligned}
\pi_t &= \kappa(y_t - y_t^*) + \beta\mathbb{E}_t\pi_{t+1}, && (15)\\
\Delta s_t &= -\kappa(s_t - s_t^*) + \beta\mathbb{E}\Delta s_{t+1}. && (16)
\end{aligned}
$$

That is, we can write a standard aggregate Phillips curve for CPI inflation in terms of an output gap which does not depend directly on relative prices. Similarly, relative prices are governed by a second order difference equation which depends on their flexible price level s_t^*, but not directly on output.[14] In this special case (but *only* in this case!), aggregate inflation is fully determined by the aggregate output gap, while the evolution of relative prices depends on fundamental factors and is unaffected by monetary policy. Despite the green transition, the monetary authority can close the output gap while implementing zero inflation.

To understand this result, recall that changes in relative prices have opposite-signed effects on marginal costs in the two sectors: an increase in the relative price of dirty goods s_t raises marginal cost for the clean sector, and reduces it for the dirty sector. These effects must cancel out for (expenditure-weighted) average marginal cost for the economy as a whole:

$$\overline{mc}_t := \gamma mc_t^o + (1-\gamma)mc_t^d = w_t - p_t - \underbrace{\left[\gamma(p_t^o - p_t) + (1-\gamma)(p_t^d - p_t)\right]}_{=0 \text{ by definition of } p_t}.$$

In general, *average* marginal costs are not what determines aggregate inflation. Instead, marginal costs in the more flexible price sector have an outsized effect on aggregate inflation. But in the special case where $\kappa^o = \kappa^d = \kappa$, it is average marginal costs that matter: we can simply aggregate the sectoral Phillips curves to get the same aggregate Phillips curve as in a one-sector model, equation (15).

There are two things to note about this special case. First, a zero output gap $(y_t - y_t^*)$ still implies that the *level* of output is declining in line with potential y_t^*. But in itself, this does not necessarily indicate an adverse tradeoff. Presumably when setting the tax on the dirty sector, the fiscal authority traded off the cost of lower output against the (unmodeled) benefit from lower carbon emissions. The monetary authority would not want to completely offset the effect of the tax and prevent dirty output from declining, even if it was feasible to do so.

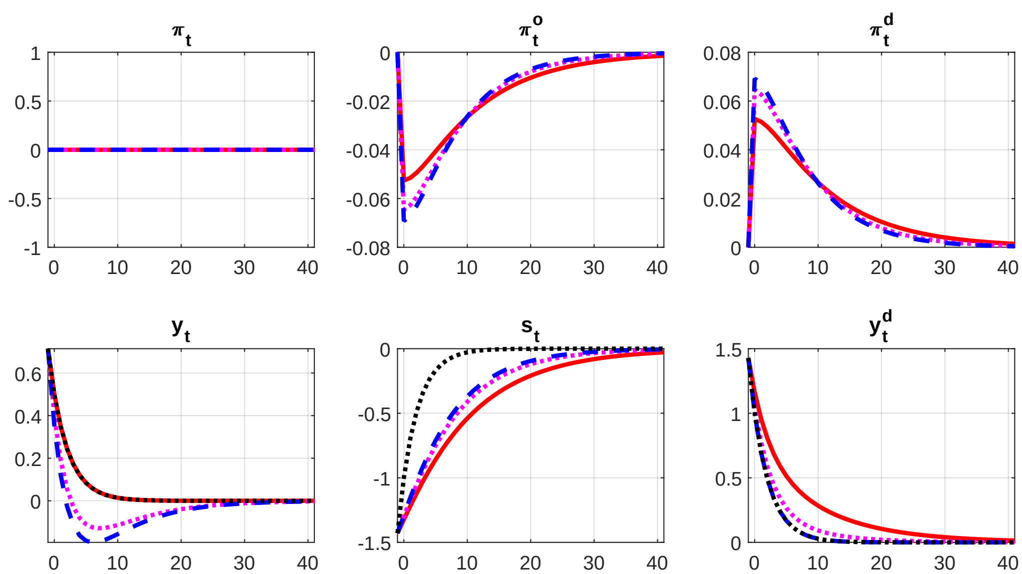
Second, while in this case the central bank can keep *aggregate* output equal to its flexible price level while maintaining zero inflation, it does not follow that relative prices and sectoral output are equal to their flexible-price levels. Nominal rigidities slow down the adjustment of relative prices (this is easiest to see in the limiting case where $\kappa \to 0$; clearly if prices are fixed in *both* sectors, (8) implies that relative prices and sectoral output shares can *never* adjust). In fact, in this case monetary policy cannot do anything to speed up the transition. Not only do relative prices not affect aggregate inflation; by the same token, the aggregate level of economic activity does not affect relative prices.

The general case: Some numerical examples. When moving beyond the special cases just described, one way to illustrate the monetary policy tradeoffs associated with the green transition

[14] Solving this equation yields $s_t = \lambda s_{t-1} + \psi s_t^*$, where $\lambda = \frac{1+\beta+\kappa-\sqrt{(1+\beta+\kappa)^2-4\beta}}{2\beta} \in (0,1)$, $\psi = \frac{\kappa}{1+\kappa+\beta(1-\rho-\lambda)} > 0$. In the limit as prices in both sectors become fully rigid ($\kappa \to 0$), $\lambda \to 1$, and $\psi \to 0$, i.e. relative prices are fixed ($s_t = s_{t-1}$) and do not move towards their flexible price level; in the limit as both sectors become fully flexible ($\kappa \to \infty$), $\lambda \to 0$, $\psi \to 1$, i.e. relative prices jump instantly to their flexible price level ($s_t = s_t^*$).

is to compare outcomes under two extreme policies: strict inflation targeting, which sets $\pi_t = 0$, and strict output gap targeting, which sets $y_t - y_t^* = 0$. The figures below present a numerical example (this is not intended to be quantitative, and the parameterization and results are only illustrative). The calibration is described in detail in Appendix B.1. The red lines show a calibration with $\kappa^d = \kappa^o = 0.01$; blue-dashed lines illustrate the case with flexible prices in the dirty sector ($\kappa^d = \infty$); magenta-dotted lines illustrate an intermediate case where the slope of the Phillips curve is 5 times larger in the dirty sector, $\kappa^d = 0.05$. Black dotted lines show the flexible-price levels of s_t, y_t, and dirty sector output y_t^d. Dirty output (shown in the bottom-right panel) is given by $y_t^d = y_t - \gamma s_t$; this variable can also be interpreted as the level of emissions, and so the difference between the colored lines and black dotted lines in the bottom right panel illustrates how nominal rigidities slow down the green transition, relative to the flexible price benchmark. Figure 3 plots dynamics under strict inflation targeting $\pi_t = 0$. Figure 4 plots dynamics under strict output gap targeting, $y_t = y_t^*$. All variables are plotted as log-deviations relative to the new steady state featuring lower output and a higher relative price s_t.

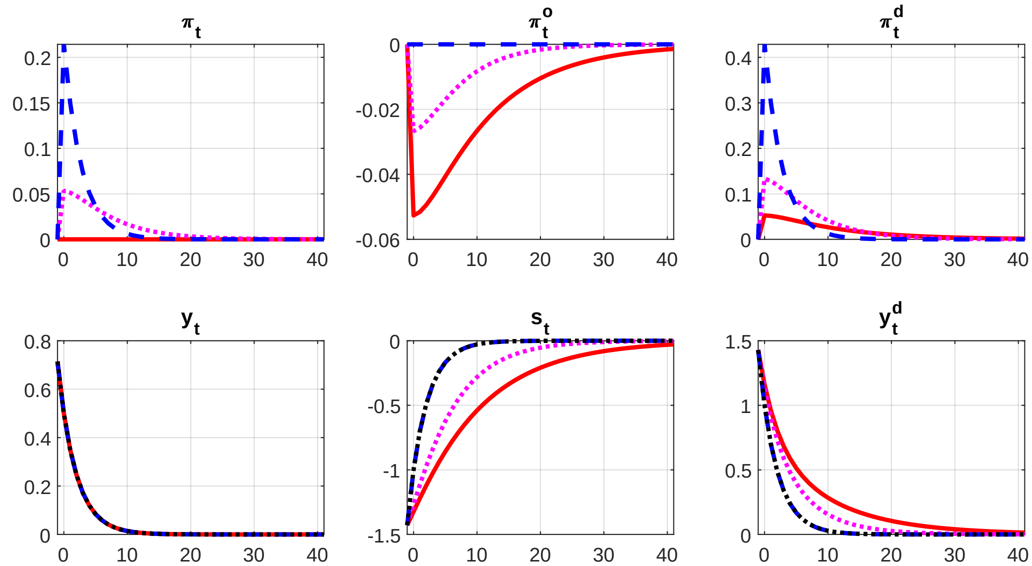
Figure 3. Dynamics under strict inflation targeting



Notes: Red lines denote calibration with $\kappa^o = \kappa^d$, dashed blue lines denote calibration with $\kappa^d = \infty$, magenta dotted lines denote calibration with $\kappa^d = 5\kappa^o$, and dotted black lines denote flexible price allocations.

As described above, when $\kappa^o = \kappa^d$, inflation targeting is equivalent to output gap targeting and so the red lines are identical across the two figures. Output remains equal to potential and declines towards its new lower steady state level. The relative price of dirty goods increases, but more slowly than in a flexible price economy since prices take time to adjust. Inflation in the dirty goods sector is balanced by deflation in the clean goods sector.

Figure 4. Dynamics under strict output gap targeting



Notes: Red lines denote calibration with $\kappa^o = \kappa^d$, dashed blue lines denote calibration with $\kappa^d = \infty$, magenta dotted lines denote calibration with $\kappa^d = 5\kappa^o$, and dotted black lines denote flexible price allocations.

When prices are more flexible in the dirty goods sector, the equivalence between inflation targeting and output gap targeting breaks down. Maintaining an unchanged inflation target ($\pi_t = 0$) requires implementing a larger decline in output, i.e. a negative output gap: output undershoots its longer-run level. Conversely, keeping output equal to potential requires tolerating an initial increase in overall inflation. A higher degree of price flexibility in the dirty sector makes this tradeoff between output gap and overall inflation stabilization more pronounced. Under output gap targeting, marginal costs increase in the dirty sector and fall in the clean sector (owing to lower economic activity), but the increase in costs in the dirty sector has a larger impact on sectoral inflation since prices in this sector are more flexible (compare the dotted-magenta and dashed-blue lines in the top-middle and top-right panels of Figure 4). Thus, overall inflation increases (top-left panel). Offsetting this and stabilizing overall inflation would require reducing economic activity even more to bring down marginal costs and prevent π_t^d from spiking.

3.2.3 Input-Output Linkages

We now briefly discuss how our conclusions would change if we allow the rest of the economy to use dirty output as an input in production (this extension is described in detail in Appendix B.2). Some of the intuition obtained from this very stylized IO model will be useful in interpreting the results from the full-fledged multi-sector model discussed in section 4.

Consider first the flexible-price economy, and suppose the policymaker introduces a tax on dirty output in order to engineer the same proportional reduction in the gross output of the dirty sector as in our baseline model. Holding the consumption share of dirty goods $(1-\gamma)$ fixed, the same reduction in dirty output now implies a larger reduction in aggregate *potential* output y^*, since it also curtails production in the rest of the economy which uses dirty goods as an input. However, a given reduction in dirty sector output can now be achieved with a smaller change in relative prices s^*, because dirty goods are used as an input to produce other goods, and so a tax on dirty goods raises costs for the other sector.

With nominal rigidities, input-output linkages also quantitatively affect the tradeoff monetary authorities face between stabilizing inflation and closing the output gap, although our qualitative results remain largely unchanged. The Phillips curve for the dirty sector (7) remains the same, since dirty goods producers still only use labor as an input. The Phillips curve for the other sector becomes

$$\pi_t^o = \kappa^o \left[(1-\omega_{od})(y_t - y_t^*) + (1-\gamma+\gamma\omega_{od})(s_t - s_t^*)\right] + \beta \mathbb{E}_t \pi_{t+1}^o \tag{17}$$

where $\omega_{od} > 0$ denotes the cost share of dirty goods in the production of other goods (and $1-\omega_{od}$ the labor share). Higher usage of dirty output by the other sector $\omega_{od} > 0$ makes the other sector's Phillips curve less sensitive to aggregate economic activity, but more sensitive to the relative price of dirty goods. Intuitively, an increase in dirty sector prices now increases marginal costs directly via the price of inputs, as well as indirectly by increasing the product wage for a given real wage.

Suppose prices are perfectly flexible in the dirty sector ($\kappa^d = \infty$) but somewhat sticky in the other sector ($0 < \kappa^o < \infty$). As in our baseline model, since the relative price of dirty goods s_t is increasing, a central bank committed to stabilizing CPI inflation π_t must engineer deflation in the other sector, which requires a negative output gap; however, this tradeoff is less severe than in our baseline model. The relationship between inflation in the other sector π_t^o and the output gap is the same as in our baseline. This is because the lower slope of the dirty sector Phillips curve with respect to the output gap ($\kappa^o(1-\omega_{od})$) is exactly compensated by the higher sentitivity to $s_t - s_t^*$. Since the output gap also has an effect on the relative price s_t (dirty goods producers set prices equal to marginal costs, which depend on wages and hence on the output gap) the overall effect is identical. Thus as in our baseline, stabilizing the output gap implies zero inflation in the other sector, and so positive CPI inflation. However, since the required increase in relative prices is less dramatic than in our baseline, the gap between dirty and other sector inflation is smaller, and so overall CPI inflation is lower, though still positive.[15]

Again, the presence of a tradeoff depends on the assumption that prices are more flexible in the dirty sector. Recall that when prices are equally sticky in both sectors ($\kappa^o = \kappa^d$), there is no tradeoff between stabilizing CPI inflation and closing the output gap in our baseline economy. With input-output linkages, since firms produce not only for consumers but for other firms, CPI inflation

[15] Mathematically, $\pi_t = \pi_t^o + (1-\gamma)\Delta s_t$; given π_t^o, a smaller Δs_t implies smaller π_t.

is not the relevant benchmark: instead, there is no tradeoff between stabilizing *PPI* inflation and closing the output gap.[16] PPI is higher than CPI inflation in the scenarios we consider, since it puts a higher weight on dirty goods prices which are increasing during the transition. Thus, while IO linkages may not change the tradeoff faced by a PPI-targeting central bank, they do make the tradeoff less severe for a CPI-targeting central bank. In fact, when $\kappa^d = \kappa^o$, the sign of the tradeoff reverses: stabilizing CPI inflation requires running a *positive* output gap, i.e. preventing output from falling as much as potential.

In sum, in the empirically realistic case where dirty sector prices are significantly more flexible, the standard tradeoff remains, but IO linkages generally make it less severe. This is a somewhat surprising result, as one might have thought that IO linkages would put the central bank in a more difficult spot. Again though, while the tradeoff between stabilizing CPI inflation and the output *gap* $y_t - y_t^*$ is less severe, IO linkages also increase the decline in y_t^*, so closing the output gap implies a steeper decline in the *level* of output y_t.

4 Multisector model

We now extend our analysis to consider a quantitative multisector model with production networks.

4.1 Model Environment

There are n sectors, $i = 1, ..., n$.

Households The representative household solves

$$\max_{\{C_t,\{C_t^i,C_t^i(\cdot)\}_{i=1}^n\}_{t=0}^\infty} \mathbb{E}_0 \sum_{t=0}^\infty \beta^t \left\{ \ln C_t - \widetilde{b} \int_0^1 L_t(\iota) d\iota \right\} \tag{18}$$

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

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

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

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

[16] Since CPI equals PPI in our baseline economy without intermediate inputs, this implies that IO linkages do not change the tradeoff between stabilizing PPI and closing the output gap.

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 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

$$\max_{W_t^*} \sum_{k=0}^{\infty} (\theta_w \beta)^k \left[\frac{W_t^*}{P_{t+k} C_{t+k}} - \widetilde{b}\right] L_{t+k} \left(\frac{W_t^*}{W_{t+k}}\right)^{-\varepsilon^w} \tag{19}$$

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

$$M^i X^i = \min_{L_t^i, I_t^i, E_t^i, N_t^i \{X_t^{ij}\}_{j=1}^n} W_t L_t^i + \sum_j P_t^j X_t^{ij} + \mathcal{T}_t e_i X_t^i \tag{20}$$

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

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

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

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

Here $\mathcal{T}_t$ is the nominal carbon tax per unit of emissions, and e_i is the emissions intensity of sector i, i.e. the volume of emissions produced by producing one unit of gross output of good i. e_i is assumed to be fixed. We also define M_t^i to be the firm's marginal cost inclusive of the carbon tax.

We will calibrate e_i to raw emissions (which are nonzero only for oil and gas extraction and coal mining). 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 refinery, 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, 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, whether or not the fuel is actually used to produce emissions (for example, in our model if a plastics manufacturer uses crude oil without producing emissions, it still pays the same price as an oil refinery).

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

$$\max \sum_{k=0}^{\infty} Q_{t+k|t} \theta_i^k [P_t^{i*} - M_t^i] X_{t+k}^i \left(\frac{P_t^{i*}}{P_{t+k}^i} \right)^{-\varepsilon^i} \tag{21}$$

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 t and $t+k$.[17]

Monetary policy We will consider outcomes under the same two monetary policy rules as in our simple two-sector model: (i) strict inflation targeting:

$$\Pi_t := \frac{P_t}{P_{t-1}} = 1$$

and (ii) strict output gap targeting, in which the central bank keeps aggregate consumption (and hence value added) equal to its level C_t^* in a counterfactual flexible-price economy where $\theta_i = 0$ for all i:

$$C_t = C_t^*$$

As in the two-sector model, we consider experiments in which a carbon tax is announced at date 0 and gradually transitions to some long-run level:

$$\tau_{t+1} - \tau^* = \rho(\tau_t - \tau^*), \tau_0 = 0, \text{ where } \tau_t := \frac{\mathcal{T}_t}{P_t}$$

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

$$C_t^i + \sum_{j=1}^{n} X_t^{ji} = X_t^i, i = 1, ..., n \tag{22}$$

$$\sum_{i=1}^{n} L_t^i = L_t \tag{23}$$

4.2 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 facilitate rapid solution of the nonlinear model, we work at the summary level, except that we break out oil extraction, gas extraction, and coal mining as distinct sectors, giving

[17] 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.

us 73 sectors.[18] 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.[19] We manually classify some of our 69 sectors as 'food' or 'energy'.

While the model is *prima facie* heavily parameterized, the vast majority of the parameters are pinned down by the input-output tables and by sector-level micro estimates of price rigidities. For each industry i, the 2012 BEA input-output 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.[20] Consumption expenditure shares $\widetilde{\gamma}_i$ are simply calculcated as $\frac{P^i C^i}{\sum_j P^j C^j}$. Appendix C shows that the full nonlinear dynamics 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 input-output matrix, for each remaining sector, we subtract from its gross output the usage of its output by omitted sectors. That is, we set

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

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

[18] 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.

[19] See Appendix A for more details.

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

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).

Finally, 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.

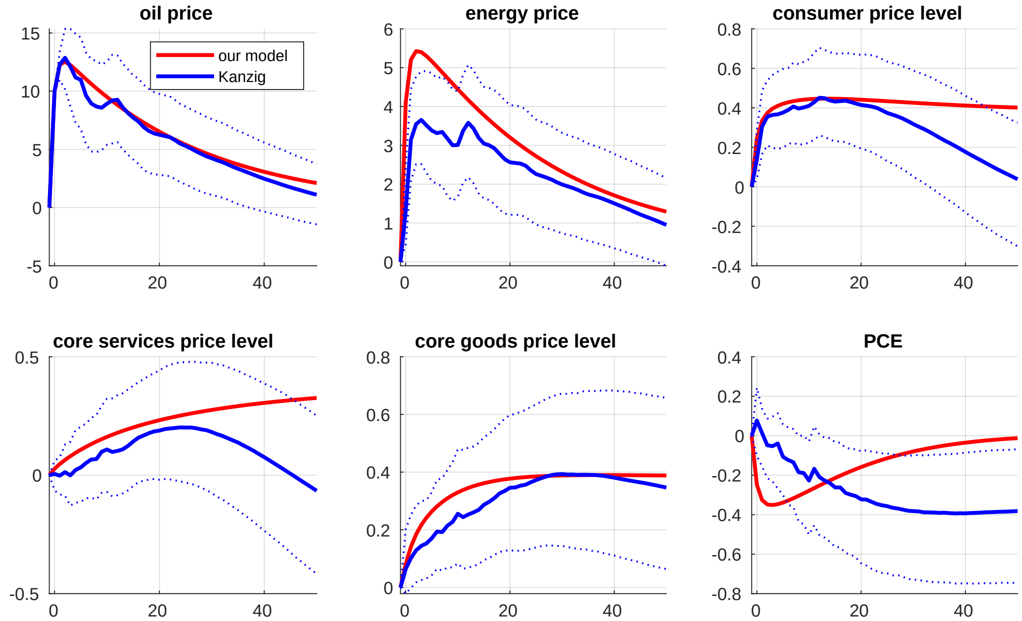
4.3 Model Validation: The Propagation of Oil Shocks Through the Input-Output Network

In this section we compare the impulse response to oil price shocks from 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 5 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 5 are close by construction.[21] In spite of the fact that no other

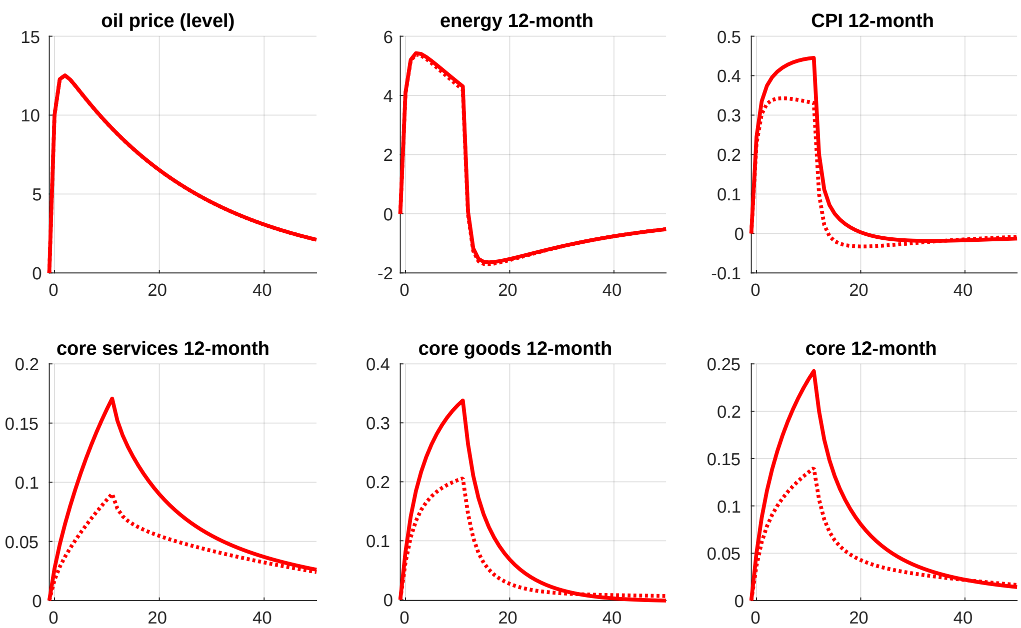
[21] In order to compute these responses we use a 396-sector version of the model, calibrated in the way described in the previous section. We found the non linear solution methods to be infeasible for such a large model, hence we aggregated it to 73 sector. Reassuringly the responses for this more aggregated version are virtually the same as for the 396-sector version.

Figure 5. 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 6. Känzig's WTI oil shocks responses: the role of propagation through the IO network



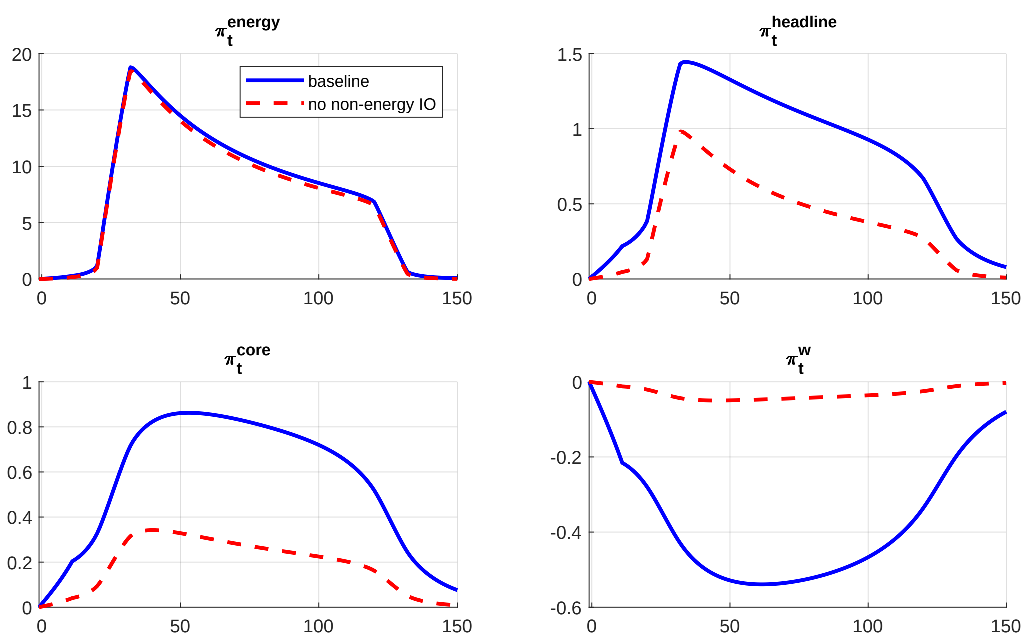
Notes: Solid red: same IRFs as Figure 5 but in terms of 12-month inflation (except for oil). Dotted red: counterfactual without IO network *except* for energy.

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 enery, overall CPI, core goods, and core services relatively well, at least up to two years out.[22] 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 6 display the same impulse responses as Figure 5, 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 about 10 bps after one year, but for core CPI and core services inflation the network accounts for about half of the responses to oil shocks.

4.4 Results: Schnabel Was Right After All

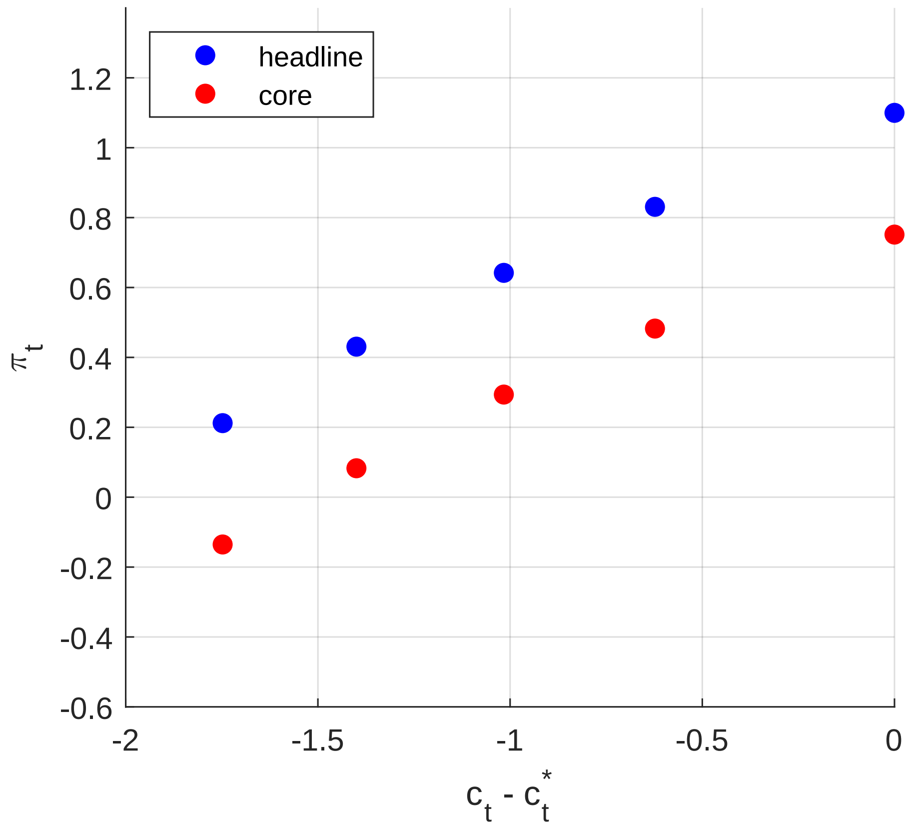
Figure 7. The inflationary consequences of the carbon tax: dynamics under *output gap* targeting



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

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

Figure 8. Tradeoffs in the quantitative IO model

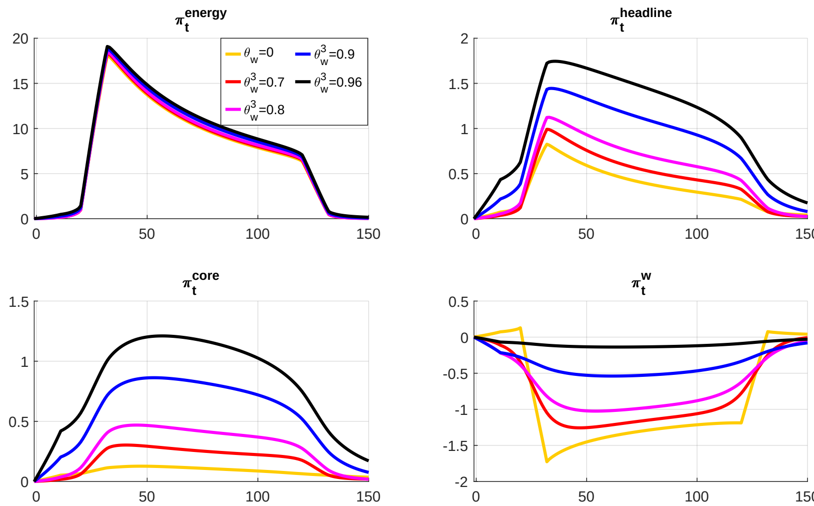


Notes: The dots compute average inflation and output gap over 100 months after the announcement of the tax increase for different policy rules.

The experiment we consider is a linear increase in the carbon tax from 0 to 100 $ over 100 months—a magnitude based on the literature, e.g. Barron et al. (2018)—anticipated 20 months in advance (Figure A1 in the Appendix shows the path for the carbon tax). As mentioned, we solve the 73 sector version of model non-linearly. The blue lines in Figure 7 show the effect of the carbon tax on inflation—energy, headline CPI, core CPOI, and wage inflation— for the case when monetary policy closes the output gap. We find that, broadly speaking, Isabel Schnabel was correct in that the carbon tax has sizable inflationary implications: 12 month headline CPI is one pps or more above target for more than 6 years; 12 month core CPI is 50 bps or more above target for about 10 years (and 80 bps or more above target for about 3).

In order to highlight the role played by the network for these results, the dashed red lines in Figure 7 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 (ths is the same counterfactual experiment performed in Figure 6 of section 4.3). Figure 7 shows that the impact of the network is substantial: for headline inflation the network accounts for between one third

Figure 9. 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)

and half of the responses, while for core inflation the network is about two thirds of the impact. In sum, because of the network the Aoki (2001) view of the world is incorrect when it comes to assessing the inflationary effects of climate policy: the tax on dirty energy has first order effects on core inflation.

The results in Figure 7 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 8 addresses this question, as it shows *average* inflation and *average* output gap over 100 months after the announcement of the tax increase under alternative reaction functions that place also weight on the inflation gap.[23] It shows that these tradeoffs are non-negligible: controlling headline inflation—e.g., keeping inflation to less than 60 bps 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 bps 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 pps of higher unemployment on average during this 100 month period.

Finally, Figure 9 speaks to the importance of wage stickiness for the quantitative results. Recall that 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 9), nominal wages fall substantially as soon as the carbon tax is introduced, and continue falling for much of the period

[23]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 7 the parameter ψ was set to 0.

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.

4.5 Robustness to the elasticity of substitution

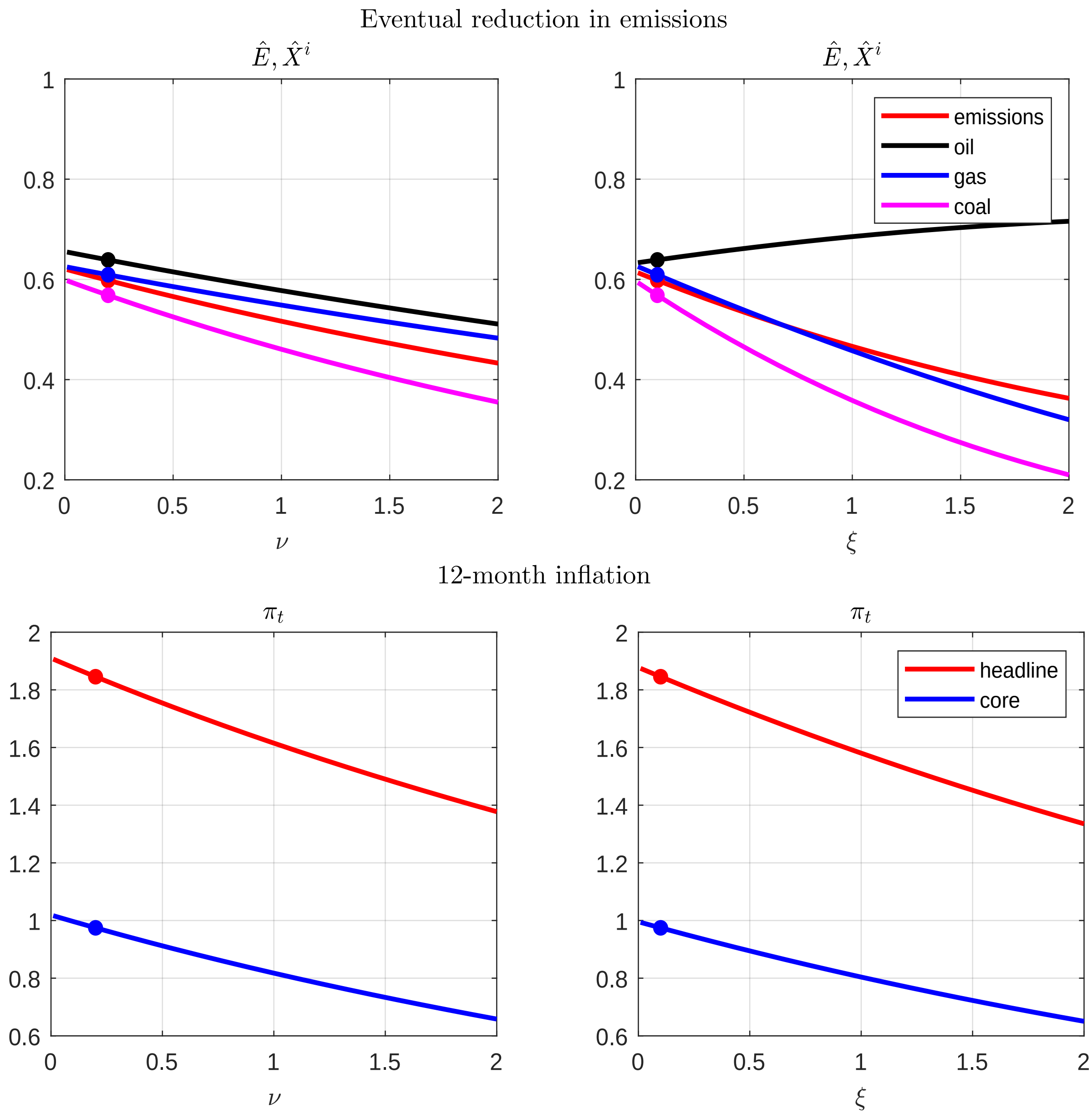
Of course, one may rightly wonder to what extent these conclusions are robust to our modeling choices and to our calibration. We can at least address the latter question. The impact of a carbon tax on emissions depends on how easy it it for producers and consumers to substitute away from fossil-fuel intensive goods and inputs. In our model, this is primarily governed by the elasticity of substitution between different inputs of a given type ξ, and the elasticity between energy and non-energy inputs ν. The top two panels of figure 10 are somewhat reassuring, as they show that our baseline choice of elasticities is quite low (circles indicate our baseline calibration), and that lowering them further would increase the reduction in eventual emissions induced by the 20 dollar carbon tax, but not by much.[24]

The bottom two panels of figure 10 show the extent to which the inflationary dynamics shown in Figure 3 are robust to changing the elasticity of substitution parameters. Specifically, the panels plot average annualized headline and core inflation after 12 months as a function of ν and ξ. The larger the elasticities ν and ξ, the lower the inflationary impact of the carbon tax as upstream sectors are able to substitute energy with other inputs. The reason why this is the case for ν, the elasticity of substitution between energy and non-energy inputs, is readily understood. However, ξ, the elasticity of substitution between different non-energy inputs, and between different types of energy input, also matters, for two reasons. First, some non-energy sectors are more affected by the increase in energy prices than other, as they use more energy, and being able to substitute away from these sectors lowers the inflationary impact. Second, a higher ξ makes it easier to substitute from dirty to clean energy, mitigating the effect of the carbon tax on the overall price of energy.[25] The figure shows however that the lines are rather flat: one would have to increase the elasticities by an order of magnitude relative to our baseline calibration for the inflation response to be significantly different.

[24] Figure 10 plots the long-run level level of emissions after the tax is fully implemented, as a fraction of emissions prior to the introduction of the tax. The entire path of emissions is shown in figure A2 in the appendix.

[25] In our model, clean energy is included in the "Electric power generation, transmission, and distribution" sector. The 2012 BEA input-output tables, on which our calibration is based, do not distinguish between renewable and dirty fuel sources within electric power generation.

Figure 10. Robustness to the elasticity of substitution



Notes: Top row: 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. Bottom row: lines show year-over-year headline (red line) and core (blue line) inflation over the 12 months following the announcement of the tax shock (i.e. the sum of $100\times$ the log-deviation of π_t from zero over the first 12 months), as a function of the same elasticities.

5 Conclusion

It has been argued that the green transition will be inflationary. In this paper we investigated whether this is the case using both a simple two-sector model, in order to gain intuition, and a quantitative input-output model with almost 400 sectors calibrated to data on input-output linkages and sectoral heterogeneity in emissions and price stickiness. We show that whether the green transition is inflationary crucially depends on (1) price stickiness, (2) central bank policy, (3) whether the green transition consists of taxes or subsidies. If prices were flexible there would be no reason for the green transition to be inflationary or deflationary, regardless of (3). If prices of non-dirty goods and services in the economy are stickier than prices in the dirty sectors – a realistic situation – then policies aimed at reducing production in the dirty sector impose a tradeoff on the central bank between stabilizing inflation and closing the output gap. These conclusions are reversed if the green transition consists of subsidies to a clean energy sector, as for example in the recent Inflation Reduction Act, as long as prices in this sector are more flexible than in the rest of the economy. Our quantitative model suggests that an increase in carbon taxes from 0 to 20 (2012) dollars would generate a sizable tradeoff: containing the impact on headline or core inflation would lead to a deep recession. But while sizeable, the tradeoff is relatively short-lived as it wanes after one year.

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.

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.

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.

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.

Gordon, Robert J, "Alternative responses of policy to external supply shocks," *Brookings Papers on Economic Activity*, 1975, *1975* (1), 183–206.

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.

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.

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

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

Woodford, Michael, *Interest and prices*, Princeton Univ. Press, 2003.

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. 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 et al. (2018) 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 expand the number of sectors in order to disentangle oil and gas usage across the US production network. We use the BEA's industry-by-commodity "make" table M and commodity-by-industry "use" table U: 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 split industry 211000 (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 consumption of oil and gas per the EIA.[26] We then update the "use" table by splitting the commodity usage of the old 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 406×405 and 405×406 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

[26] 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).

$\overline{U}$ 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. 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 usage 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 4.) 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 and the 2017 six-digit NAICS sectors in which terms Cotton and Garga (2022) present their price change frequencies. The BEA's sectors are closely related to the 2012 NAICS sectors, and a concordance is provided in the IO 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.

Appendix B Model Details

B.1 Calibration for Figures in Two-sector Model

When plotting the figures for our two-sector model, we set $\beta = 0.99$, $\gamma = 0.5$, and $\kappa^o = 0.01$. In terms of the path of climate policy, we set $\mu_0^d = -1$, implying a long-run reduction in the size of the dirty sector of $\frac{e^{\mu_0^d} - e^0}{e^{\mu_0^d}} \approx 63\%$. We set $\rho = 0.7$, implying that taxes on the dirty sector increase relatively rapidly towards their new higher steady state level.

B.2 Input-Output Linkages

We now allow for the two sectors to use each other's products as intermediate inputs. Firms in sector $i = o, d$ have the constant returns to scale production function

$$X_t^i = A_t^i (X_t^{io})^{\omega_{io}} (X_t^{id})^{\omega_{id}} (L_t^i)^{\omega_{il}},$$

where $\omega_{io} + \omega_{id} + \omega_{il} = 1$ (in our baseline model, $\omega_{io} = \omega_{id} = 0, \omega_{il} = 1$). Here X_t^{od} (for example) denotes the quantity of dirty goods used by firms in the "other" sector. In particular, if $\omega_{od} > 0$, production of other goods requires dirty goods as input. 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. Thus, the demand for the variety produced by firm j

in sector i still has the form

$$X_t^i(j) = X_t^i \left(\frac{P_t^i(j)}{P_t^i} \right)^{-\varepsilon_t^i}.$$

Now, however, X_t^i denotes *gross* output of sector i, which in general will differ from value added or net output (which we still refer to as Y_t^i or Y_t for sectoral and aggregate net output respectively). The market clearing conditions for each sector are

$$C_t^i + X_t^{oi} + X_t^{di} = X_t^i = A_t^i (X_t^{io})^{\omega_{io}} (X_t^{id})^{\omega_{id}} (L_t^i)^{\omega_{il}}, \ i = o, d.$$

Nominal marginal cost for a firm in sector i now equals

$$M_t^i = \frac{1}{A_t^i} \left(\frac{P_t^o}{\omega_{io}} \right)^{\omega_{io}} \left(\frac{P_t^d}{\omega_{id}} \right)^{\omega_{id}} \left(\frac{W_t}{\omega_{il}} \right)^{\omega_{il}} + \mathcal{T}_t^i.$$

Deflating by product prices in each sector, real marginal costs are given by

$$\begin{aligned} \frac{M_t^o}{P_t^o} &= \frac{1}{\omega_o A_t^o} (bY_t)^{\omega_{ol}} S_t^{\omega_{od} + \omega_{ol}(1-\gamma)} + \frac{\mathcal{T}_t^o}{P_t^o}, \\ \frac{M_t^d}{P_t^d} &= \frac{1}{\omega_d A_t^d} (bY_t)^{\omega_{dl}} S_t^{-\omega_{do} - \omega_{dl}\gamma} + \frac{\mathcal{T}_t^d}{P_t^d}, \end{aligned}$$

where we define $\omega_i = (\omega_{io})^{\omega_{io}} (\omega_{id})^{\omega_{id}} (\omega_{ld})^{\omega_{ld}}$, $i = o, d$. Cost minimization implies that the quantities of intermediate inputs and labor used by sector i are given by

$$\begin{aligned} X_t^{io} &= \frac{X_t^i}{A_t^i} \left(\frac{P_t^o}{\omega_{io}} \right)^{\omega_{io}-1} \left(\frac{P_t^d}{\omega_{id}} \right)^{\omega_{id}} \left(\frac{W_t}{\omega_{il}} \right)^{\omega_{il}}, \\ X_t^{id} &= \frac{X_t^i}{A_t^i} \left(\frac{P_t^o}{\omega_{io}} \right)^{\omega_{io}} \left(\frac{P_t^d}{\omega_{id}} \right)^{\omega_{id}-1} \left(\frac{W_t}{\omega_{il}} \right)^{\omega_{il}}, \\ L_t^i &= \frac{X_t^i}{A_t^i} \left(\frac{P_t^o}{\omega_{io}} \right)^{\omega_{io}} \left(\frac{P_t^d}{\omega_{id}} \right)^{\omega_{id}} \left(\frac{W_t}{\omega_{il}} \right)^{\omega_{il}-1}. \end{aligned}$$

Flexible-price benchmark. In the flexible price equilibrium, we have

$$\begin{aligned} \frac{1}{\widetilde{\mu}_t^o} &= \frac{1}{\omega_o A_t^o} (bY_t)^{\omega_{ol}} S_t^{\omega_{od} + \omega_{ol}(1-\gamma)}, \\ \frac{1}{\widetilde{\mu}_t^d} &= \frac{1}{\omega_d A_t^d} (bY_t)^{\omega_{dl}} S_t^{-\omega_{do} - \omega_{dl}\gamma}, \end{aligned}$$

which implicitly define equilibrium net output Y_t and relative prices S_t. The quantities of inputs used by sector i satisfy

$$X_t^{io} = \frac{\omega_{io}}{P_t^o} P_t^i X_t^i \frac{1}{\widetilde{\mu}_t^i}, \qquad X_t^{id} = \frac{\omega_{id}}{P_t^d} P_t^i X_t^i \frac{1}{\widetilde{\mu}_t^i}, \qquad L_t^i = \frac{\omega_{il}}{W_t} P_t^i X_t^i \frac{1}{\widetilde{\mu}_t^i}.$$

Substituting these into the resource constraints, we obtain a relation between the value of net and gross output:

$$\begin{aligned} P_t^o X_t^o &= \gamma P_t Y_t + \frac{\omega_{oo}}{\widetilde{\mu}_t^o} P_t^o X_t^o + \frac{\omega_{do}}{\widetilde{\mu}_t^d} P_t^d X_t^d, \\ P_t^d X_t^d &= (1-\gamma) P_t Y_t + \frac{\omega_{od}}{\widetilde{\mu}_t^o} P_t^o X_t^o + \frac{\omega_{dd}}{\widetilde{\mu}_t^d} P_t^d X_t^d. \end{aligned}$$

Dividing through by P_t, we can represent this in matrix form as

$$\boldsymbol{s} \circ \boldsymbol{x} = \boldsymbol{\gamma} Y_t + \boldsymbol{\Omega}' \widetilde{\boldsymbol{\mu}}^{-1} (\boldsymbol{s} \circ \boldsymbol{x}),$$

where $\circ$ denotes the element-wise product, $\boldsymbol{s} = (P_t^o/P_t, P_t^d/P_t)'$, $\boldsymbol{x} = (X_t^o, X_t^d)'$, $\boldsymbol{\gamma} = (\gamma, 1-\gamma)'$, $\widetilde{\boldsymbol{\mu}}$ denotes the diagonal matrix with $\widetilde{\mu}_t^i$ on the diagonal, and $\boldsymbol{\Omega}$ denotes the 2×2 matrix of intermediate input shares ω_{ij}, $i = o, d$, $j = o, d$. Rearranging, we have

$$\begin{aligned} \boldsymbol{s} \circ \boldsymbol{x} &= (I - \boldsymbol{\Omega}' \widetilde{\boldsymbol{\mu}}^{-1})^{-1} \boldsymbol{\gamma} Y_t, \\ \boldsymbol{x} &= Y_t \boldsymbol{s}^{-1} \circ \left[(I - \boldsymbol{\Omega}' \widetilde{\boldsymbol{\mu}}^{-1})^{-1} \boldsymbol{\gamma} \right]. \end{aligned}$$

In our baseline model without input-output linkages, $\boldsymbol{\Omega}$ is a matrix of zeros, and the vector of sectoral gross output is simply $\boldsymbol{x} = Y_t \boldsymbol{s}^{-1} \circ \boldsymbol{\gamma}$, which is the vector of sectoral net output or consumption.

To simplify the analysis, we will focus on the case where $\omega_{od} > 0$, $\omega_{oo} = \omega_{dd} = \omega_{do} = 0$, $\omega_{ol} = 1 - \omega_{od}$, $\omega_{dl} = 1$. That is, the only linkage is that dirty goods are used by the other sector as inputs. In this case, flexible-price net output and relative prices are given by

$$\begin{aligned} S_t &= \left(\frac{\omega_o A_t^o}{\widetilde{\mu}_t^o} \right) \left(\frac{\omega_d A_t^d}{\widetilde{\mu}_t^d} \right)^{-(1-\omega_{od})}, \\ Y_t &= \frac{1}{b} \left(\frac{\omega_o A_t^o}{\widetilde{\mu}_t^o} \right)^{\gamma} \left(\frac{\omega_d A_t^d}{\widetilde{\mu}_t^d} \right)^{1-\gamma+\gamma\omega_{od}}, \\ Y_t^d &= (1-\gamma) Y_t S_t^{-\gamma} = \frac{1-\gamma}{b} \left(\frac{\omega_d A_t^d}{\widetilde{\mu}_t^d} \right). \end{aligned}$$

Turning from net to gross output, in this special case we have

$$(I - \boldsymbol{\Omega}' \widetilde{\boldsymbol{\mu}}^{-1})^{-1} = \begin{pmatrix} 1 & 0 \\ -\omega_{od} (\widetilde{\mu}_t^o)^{-1} & 1 \end{pmatrix}^{-1} = \begin{pmatrix} 1 & 0 \\ \omega_{od} (\widetilde{\mu}_t^o)^{-1} & 1 \end{pmatrix},$$

and the formula above implies

$$X_t^o = \gamma Y_t S_t^{1-\gamma}, \qquad X_t^d = Y_t S_t^{-\gamma} [\gamma \omega_{od} (\widetilde{\mu}_t^o)^{-1} + 1 - \gamma] = \frac{\gamma \omega_{od} (\widetilde{\mu}_t^o)^{-1} + 1 - \gamma}{b} \left(\frac{\omega_d A_t^d}{\widetilde{\mu}_t^d} \right).$$

The use of dirty output as an intermediate input ($\omega_{od} > 0$) increases this sector's gross output, all else equal. In particular, the share of expenditures on dirty goods as a fraction of gross output is $\dfrac{\gamma \omega_{od} (\widetilde{\mu}_t^o)^{-1} + 1 - \gamma}{\gamma \omega_{od} (\widetilde{\mu}_t^o)^{-1} + 1} > 1 - \gamma$. Nonetheless, as in our baseline, $\widetilde{\mu}_t^d$ can still be interpreted as the *proportional* reduction in dirty sector output under flexible prices.

The firm's problem has the same structure as before, except that gross output X_t^i replaces net output Y_t^i (we assume price adjustment costs are also scaled by gross output):

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} Q_{t|0} \left\{ (P_t^i(j) - M_t^i) X_t^i \left(\frac{P_t^i(j)}{P_t^i} \right)^{-\varepsilon_t^i} - \frac{\Psi^i}{2} \left(\frac{P_t^i(j)}{P_{t-1}^i(j)} - 1 \right)^2 P_t^i X_t^i \right\}.$$

Taking FOCs and assuming a symmetric equilibrium, we have:[27]

$$\Pi_t^i\left(\Pi_t^i - 1\right) = \frac{\varepsilon_t^i}{\Psi^i}\left(\frac{M_t^i}{P_t^i} - \frac{1}{\mu_t^i}\right) + \beta \frac{Y_t}{Y_{t+1}} \frac{\Pi_{t+1}^i}{\Pi_{t+1}} \frac{X_{t+1}^i}{X_t^i} \Pi_{t+1}^i \left(\Pi_{t+1}^i - 1\right).$$

Defining the 'virtual markup' $\widetilde{\mu}_t^i$ as before, and log-linearizing around a zero inflation steady state, we have the sectoral Phillips curves:

$$\begin{aligned}
\pi_t^o &= \kappa^o((1-\omega_{od})y_t + [1-\gamma+\gamma\omega_{od}]s_t) + \beta\mathbb{E}_t\pi_{t+1}^o, \\
\pi_t^d &= \kappa^d(y_t - \gamma s_t + \mu_t^d) + \beta\mathbb{E}_t\pi_{t+1}^d.
\end{aligned}$$

While the dirty sector Phillips curve is unchanged from our baseline, $\omega_{od} > 0$ makes the other sector's Phillips curve less sensitive to aggregate economic activity, but more sensitive to the relative price of dirty goods. Log-linearizing the expressions above describing the flexible-price levels of Y_t and S_t, we have $y_t^* = -(1-\gamma+\gamma\omega_{od})\mu_t^d$ and $s_t = (1-\omega_{od})\mu_t^d$, which can be used to obtain the Phillips curves in the main text. Note that the same proportional reduction in dirty output μ_t^d results in a larger reduction in aggregate output when $\omega_{od} > 0$.

With $\omega_{od} > 0$, if prices are equally flexible in both sectors ($\kappa^o = \kappa^d = \kappa$), stabilizing CPI inflation will not close the output gap. Multiplying the two Phillips curves by their consumption expenditure weights γ and $1-\gamma$, summing, and using the expressions for y_t^* and s_t^*, we obtain the CPI Phillips curve

$$\pi_t = \kappa\left[(1-\gamma\omega_{od})(y_t - y_t^*) + \gamma\omega_{od}(s_t - s_t^*)\right] + \beta\mathbb{E}_t\pi_{t+1}.$$

Since $s_t < s_t^*$ during the transition, stabilizing CPI inflation allows output to run somewhat above potential (though recall that potential output is itself declining more sharply than in our baseline model without IO linkages). If instead we weight the two Phillips curves by their *gross* expenditure shares $\frac{\gamma}{\gamma\omega_{od}+1}$ and $\frac{\gamma\omega_{od}+1-\gamma}{\gamma\omega_{od}+1}$, we obtain the PPI Phillips curve[28]

$$\pi_t^{PPI} := \frac{\gamma}{\gamma\omega_{od}+1}\pi_t^o + \frac{\gamma\omega_{od}+1-\gamma}{\gamma\omega_{od}+1}\pi_t^d = \frac{\kappa}{\gamma\omega_{od}+1}(y_t - y_t^*) + \beta\mathbb{E}_t\pi_{t+1}^{PPI}.$$

In this special case, it is stabilizing PPI inflation that is equivalent to closing the output gap. PPI puts a higher weight on dirty sector prices, which are increasing during the transition. Consequently, stabilizing PPI inflation would require a more aggressive monetary policy response than stabilizing CPI.

[27]Since net output need not equal gross output, the term $\frac{Y_t}{Y_{t+1}}\frac{\Pi_{t+1}^i}{\Pi_{t+1}}\frac{X_{t+1}^i}{X_t^i}$ is not necessarily equal to 1 as in our baseline model. This will not affect the linearized Phillips curve given that we log-linearize around a zero-inflation steady state.

[28]Here, as in the experiments in our baseline, we assume $\widetilde{\mu}_t^o = 1$, i.e. there is a constant subsidy to correct distortions from monopolistic competition in the other sector.

If prices are sticky (or even perfectly fixed) in the other sector, but perfectly flexible in the dirty sector, then as in our baseline, the dirty sector Phillips curve reduces to $s_t = \frac{1}{\gamma}(y_t + \mu_t^d)$. Substituting into the Phillips curve for the other sector, we have

$$\pi_t^o = \frac{\kappa^o}{\gamma}(y_t - y_t^*) + \beta \mathbb{E}_t \pi_{t+1}^o,$$

as in our baseline economy without IO linkages. When prices in the dirty sector are completely flexible, stabilizing inflation in the rest of the economy implements flexible price allocations; stabilizing overall CPI inflation instead requires a negative output gap.

To recap: if prices are equally flexible in both sectors ($\kappa^d/\kappa^o = 1$), stabilizing CPI inflation implies running output above potential, but if prices are infinitely more flexible in the dirty sector ($\kappa^d/\kappa^o = \infty$), stabilizing CPI implies running output below potential as in our baseline. Is there some degree of relative price flexibility at which stabilizing inflation closes the output gap, and there is no tradeoff? Yes: this will be the case when

$$\frac{\kappa^d}{\kappa^o} = 1 + \frac{\gamma \omega_{od}}{1-\gamma}.$$

Intuitively, in this knife-edge case, the difference in price flexibility exactly offsets the difference between PPI and CPI weights. To prove this, assume that $\kappa^d = \left(1 + \frac{\gamma \omega_{od}}{1-\gamma}\right)\kappa^o$ and add the expenditure-weighted Phillips curves to obtain the CPI Phillips curve:

$$\begin{aligned}\pi_t &= \gamma \kappa^o \left[(1-\omega_{od}) y_t + (1-\gamma+\gamma\omega_{od}) s_t\right] + (1-\gamma+\gamma\omega_{od})\,\kappa^o \left[(y_t - y_t^*) - \gamma(s_t - s_t^*)\right] + \beta \mathbb{E}_t \pi_{t+1} \\ &= \kappa^o (y_t - y_t^*) + \beta \mathbb{E}_t \pi_{t+1}.\end{aligned}$$

Appendix C Multisector model

C.1 Optimality conditions

The household's optimization problem (18) implies the following. First, the demand for each sector is given by

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

where the consumer price index P_t is given by

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

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

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

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

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

The solution to the union's optimization problem (19) yields the optimality condition

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

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

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

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 (20) 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

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

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

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

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

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

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

The solution to the firm's optimal pricing problem (21) implies that the price set by a resetting firm in sector i at date t, P_t^{i*} satisfies

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

The sectoral price index P_t^i evolves according to

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

C.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 (C.5) and (C.6) yields

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

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

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

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

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

Similarly, log-linearizing (C.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 (C.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

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

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

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

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

or in real terms,

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

where we define (the log-deviation of) real sectoral prices, deflated by CPI, to be $s_t^i := p_t^i - p_t$.

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

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

To calibrate these equations, we need

1. sectoral price adjustment frequencies $1 - \theta_i$ (to get κ_i)
2. labor shares $\frac{W L^i}{M^i X^i}$. (These are all shares of total costs $M^i X^i$, rather than revenues $P^i X^i$.)
3. intermediate input shares $\frac{P^j X^{ij}}{M^i X^i}$
4. emissions shares $\frac{e_i}{M^i X^i}$

The dynamics of relative prices must also satisfy

$$\Delta s_t^i = \pi_t^i - \pi_t,\ i = 1, ..., n \tag{C.14}$$

CPI inflation is defined by

$$\pi_t = \sum_{i=1}^{n} \widetilde{\gamma}_i \pi_t^i \tag{C.15}$$

where $\widetilde{\gamma}_i := \frac{P^i C^i}{PC}$ denotes steady state consumption expenditure shares, which may differ from γ_i.

Given a path for $\hat{\tau}_t$, (C.13), (C.14), (C.15), (C.9) and (C.10) constitute a system of $2n+3$ equations in $2n+4$ endogenous variables $(\{s_t^i, \pi_t^i\}_{i=1}^n, c_t, \pi_t, \omega_t, \pi_t^w)$. 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 $\{s_t^i, \pi_t^i\}_{i=1}^n, c_t, \pi_t, \omega_t, \pi_t^w$, we can solve for other variables of interest – sectoral quantities and aggregate emissions. Log-linearizing sectoral final consumption demand (C.1), we have

$$c_t^i = c_t - \zeta s_t^i \tag{C.16}$$

Log-linearizing goods market clearing (22) (and multiplying and dividing by steady state prices in order to relate the coefficients to observable values), we have

$$x_t^j = \sum_{j=1}^{n} \frac{P^i X^{ji}}{P^i X^i} x_t^{ji} + \frac{P^i C^i}{P^i X^i} c_t^i \tag{C.17}$$

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 (C.17):

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

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 $\{s^i\}_{i=1}^n$.

C.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 $W/P = bC$):

$$\frac{S^i}{\mu^i} = \frac{1}{A^i}\left[\alpha_i (bC)^{-(\eta-1)} + (1-\alpha_i)\left(S^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau e_i$$

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

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

$$\frac{\overline{S}^i \widehat{S}^i}{\mu^i} = \frac{1}{A^i}\left[\alpha_i\left(b\overline{C}\widehat{C}\right)^{-(\eta-1)} + (1-\alpha_i)\left(\overline{S}^{I,i}\widehat{S}^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau e_i$$

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

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

$$= (1-\widetilde{e}^i\overline{\tau})\left[\widetilde{\alpha}_i\left(\widehat{C}\right)^{-(\eta-1)} + (1-\widetilde{\alpha}_i)\left(\widehat{S}^{I,i}\right)^{-(\eta-1)}\right]^{-\frac{1}{\eta-1}} + \tau\widetilde{e}_i$$

Next,

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

$$= \left[\widetilde{\varsigma}_i\left(\widehat{S}^{E,i}\right)^{-(\nu-1)} + (1-\widetilde{\varsigma}_i)\left(\widehat{S}^{N,i}\right)^{-(\nu-1)}\right]^{-\frac{1}{\nu-1}}$$

Finally, we have

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

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

Thus, we can write the first n equations as

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

where $\widetilde{\alpha}_i := \frac{\overline{WL}^i}{\overline{\widetilde{M}}^i\overline{X}^i} = \alpha_i\left(\frac{\overline{w}}{A^i\overline{\widetilde{M}}^i/\overline{P}}\right)^{-(\eta-1)}$ is the labor share of pretax marginal cost for sector i in the initial steady state; $1-\widetilde{\alpha}_i := \frac{\overline{P^{I,i}}\overline{I}^i}{\overline{M}^i\overline{X}^i} = \left(\frac{\overline{S}^{I,i}}{A^i\overline{\widetilde{M}}^i/\overline{P}}\right)^{-(\eta-1)}(1-\alpha_i)$ is the share of intermediate inputs in pretax marginal costs (note that the two shares sum to 1); $\widetilde{e}_i = \frac{e_i}{\overline{M^i}/\overline{P}}$ 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

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

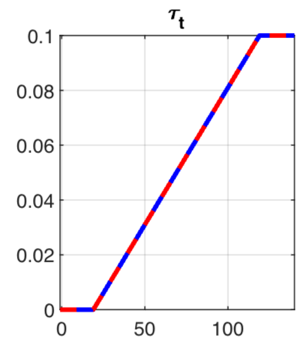
This a linear system in $\{\hat{X}^i\}$, which we can invert to solve for $\{\hat{X}^i\}$. The change in emissions is then

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

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.

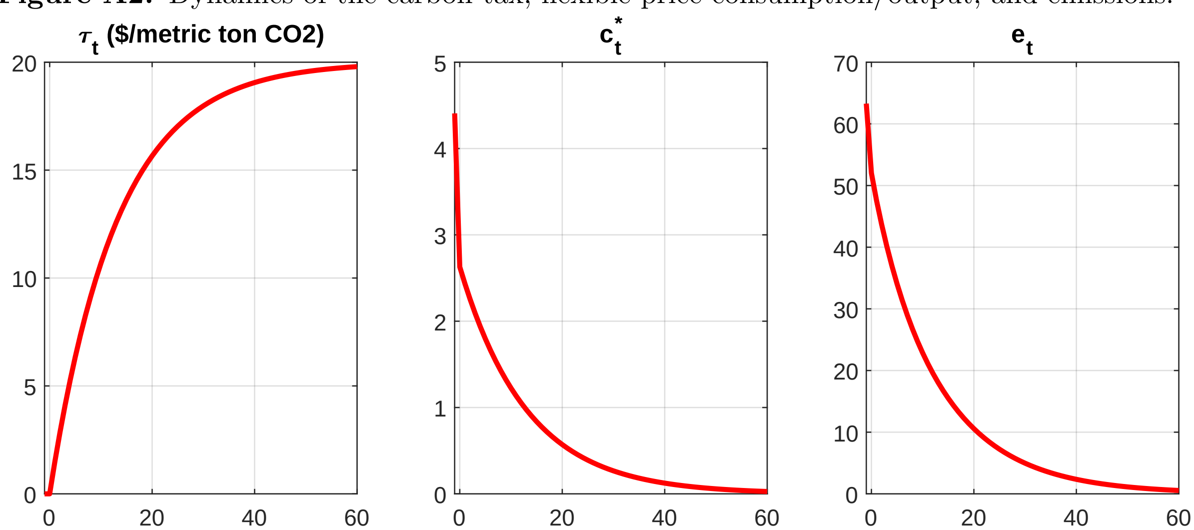
Appendix D Appendix Tables and Figures

Figure A1. Path for the carbon tax



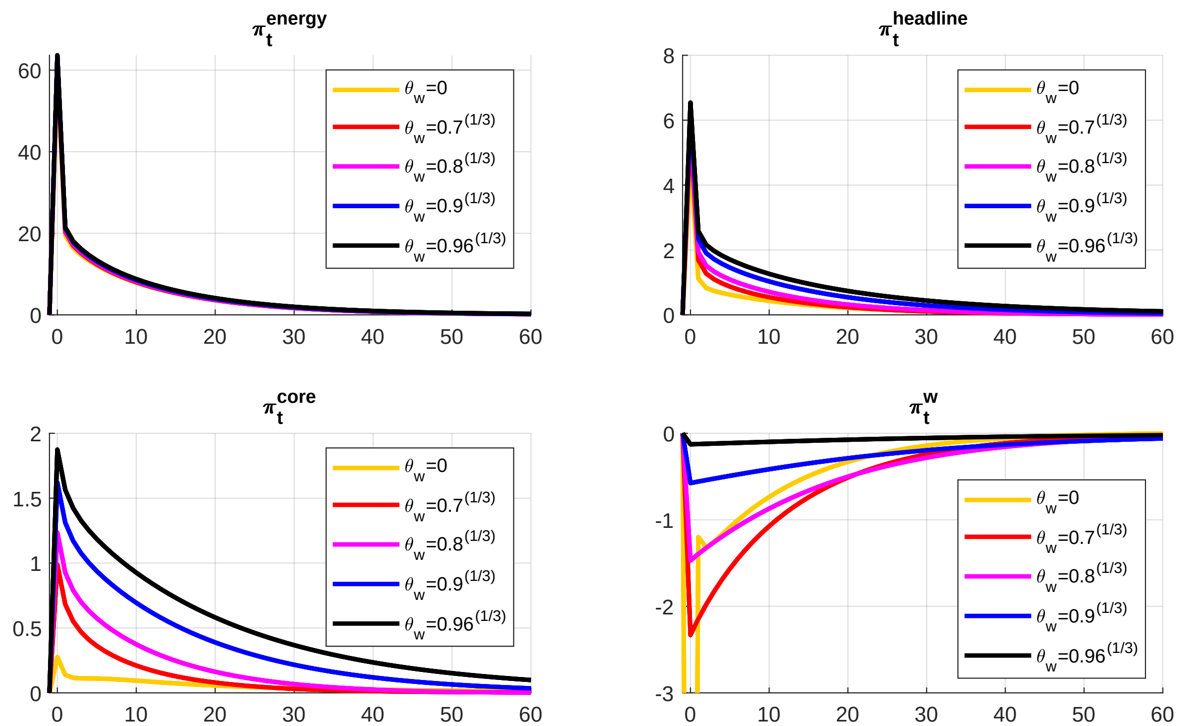
Notes: The figure shows the path of the the carbon tax for the experiment described in section 4.4.

Figure A2. Dynamics of the carbon tax, flexible price consumption/output, and emissions.



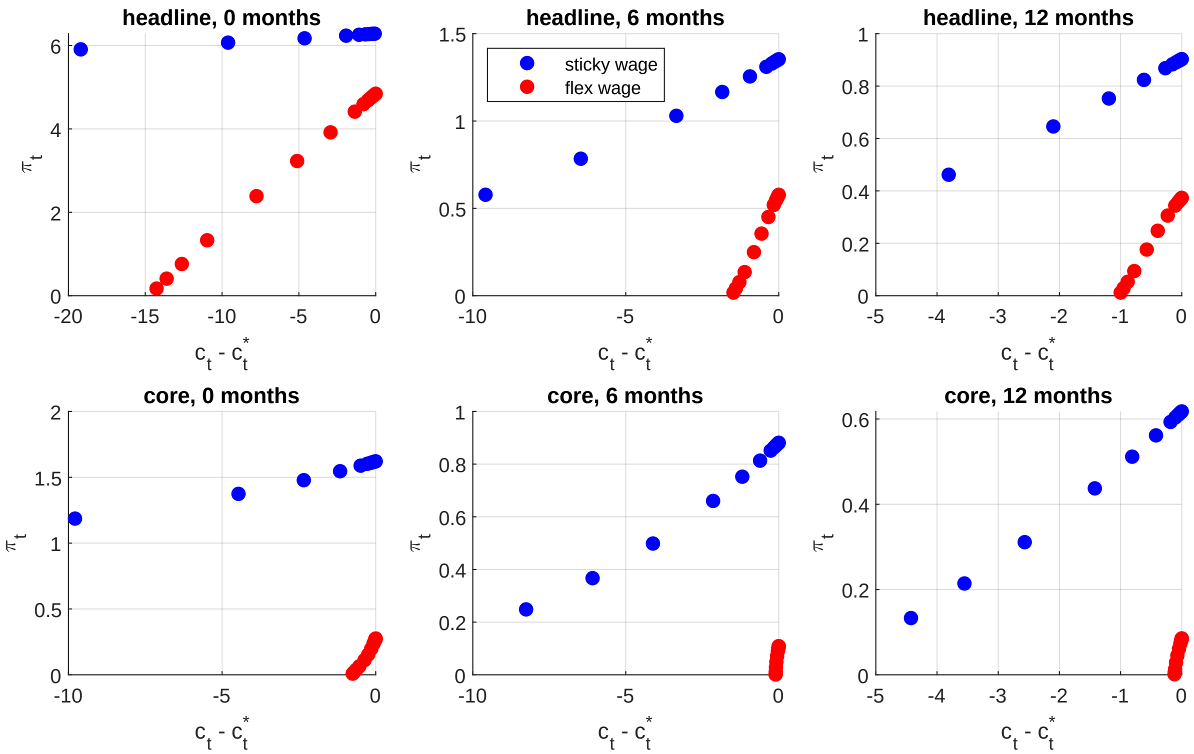
Notes: Left panel shows τ_t, the level of the carbon tax in dollars per metric ton of CO2 emissions; middle and right panels show flexible-price consumption and emissions, respectively, as 100×log-deviations from the new steady state.

Figure A3. Inflation dynamics under strict output gap targeting



Notes: All lines show annualized log-deviations of each variable relative to the new steady state, i.e. we plot 1200× the log deviation.

Figure A4. Inflation/output tradeoff at different horizons



Notes: Horizontal axes show the output gap (100× the log-deviation of $c_t - c_t^*$ from its steady state value of zero) in the period the tax is announced (left panels), 6 months after (middle panels) and 12 months after (right panels). Vertical axes show annualized month-over-month inflation at the same horizons (i.e.1200× the log-deviation of π_t from its steady state value of zero). The top row panel shows headline inflation and the output gap, under monetary policy rules of the form $\alpha\pi_t + (1-\alpha)(c_t - c_t^*) = 0$, for various values of α (strict output gap targeting corresponds to $\alpha = 0$). Blue dots show outcomes under sticky wages ($\theta_w = 0.9^{1/3}$); red dots show flexible wages ($\theta_w = 0$). The bottom row shows core inflation and the output gap, and considers rules which put weight α on core inflation, $1-\alpha$ on the output gap and no weight on headline inflation.

Table A1. Mean price change frequency of a good in a given sector and CO2 emissions/value added across 396 sectors in USA in 2012

Sector	Code	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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	CO2/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