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ABSTRACT

We analyze the quantitative labor market and aggregate effects of a carbon tax in a framework with pollution externalities and equilibrium unemployment. Our model incorporates endogenous labor force participation and two margins of adjustment influenced by carbon taxes: (1) firm creation and (2) green production-technology adoption. A carbon-tax policy that reduces carbon emissions by 35 percent – roughly the emissions reductions that will be required under the Biden Administration's new commitment under the Paris Agreement – and transfers the tax revenue to households generates mild positive long-run effects on consumption and output; a marginal increase in the unemployment and labor force participation rates; and an expansion in the number and fraction of firms that use green technologies. In the short term, the adjustment to higher carbon taxes is accompanied by gradual gains in output and consumption and a negligible expansion in unemployment. Critically, abstracting from endogenous firm entry and green-technology adoption implies that the same policy has substantial adverse short- and long-term effects on labor income, consumption, and output. Our findings highlight the importance of these margins for a comprehensive assessment of the labor market and aggregate effects of carbon taxes.

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1 Introduction

The potential adverse effects of taxing carbon emissions on employment and aggregate economic activity are a central theme in current discussions of environmental policy and regulation (OECD, 2017; Hafstead and Williams III, 2019; Metcalf and Stock, 2020a,b). This topic has taken on greater importance with the Biden Administration's April 2021 announcement of targeting emission reductions of 50 to 52 percent from 2005 levels by 2030.[1] The growing interest in introducing and broadening the scope of carbon taxes in the U.S. raises three important questions: What are the quantitative effects of these taxes on labor markets and macroeconomic outcomes? How do changes in firm entry and production-technology adoption due to carbon taxes shape these macroeconomic outcomes? Finally, do the short-term effects differ from the long-term effects?

We address these three questions in a general equilibrium model with labor search frictions and pollution externalities. In contrast to existing studies, our framework incorporates two additional and interrelated margins of adjustment to carbon taxes: (1) firm creation (subject to sunk entry costs) and (2) the ability of firms to adopt green (non-polluting) technologies (subject to fixed costs). The rationale for including these two margins is simple: the regulatory costs associated with environmental policy not only affect the labor and capital decisions of existing firms and the decisions over emissions abatement—an *intensive* margin of adjustment to carbon taxes—but also the incentive of potential firms to enter the market in the first place *as well as* these firms' technology-adoption decisions—an *extensive* margin of adjustment to these same taxes. At the same time, both firm entry and technology adoption decisions can influence labor market and macroeconomic outcomes. Critically, the inclusion of a technology adoption margin allows us to consider policy-induced *endogenous* changes in the economy's underlying technological composition of production (captured by the prevalence of polluting versus green production technologies). By explicitly considering these important margins of adjustment, our framework allows for a more comprehensive assessment of the labor-market and macroeconomic effects of carbon taxes.

[1] White House Fact Sheet on Greenhouse Gas Pollution Reduction Target, April 22, 2021, available at https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

The Biden Administration's commitment to reducing greenhouse gas pollution by 50 to 52 percent from 2005 levels by 2030 is an ambitious target. Based on modeling in the U.S. Energy Information Administration's 2021 Annual Energy Outlook, emissions in 2030 in EIA's reference (no new policy) case will have fallen by nearly one-quarter from 2005 levels (4.583 billion metric tons relative to 2005 emissions of 6 billion metric tons). Thus, emissions will need to fall an additional 35 percent between now and 2030 to achieve the Biden Administration's goal.

Using our model under a baseline carbon-tax scheme designed to reduce long-run emissions by 35 percent with carbon-tax revenue rebated lump-sum to households, we find that this policy generates mild positive long-run effects on consumption, output, and labor force participation; negligible long-run adverse effects on unemployment; and a long-run increase in the number and share of firms that adopt green technologies. Moreover, the positive long-term effects of carbon taxes extend to the transition path as well. Indeed, the gradual increase in carbon taxes is accompanied by greater consumption and output, and a very limited increase in unemployment. Thus, higher carbon taxes have positive short- and long-term macroeconomic effects and negligible detrimental effects on the labor market.

To highlight the relevance of our findings and stress the importance of firm entry and green-technology adoption decisions, we compare our results to those of a simpler model that abstracts from these two extensive margins. In this simpler model, the same carbon-tax-induced reduction in emissions has non-trivial *negative* short- *and* long-term effects on labor income, consumption, and output, as well as stronger adverse effects on unemployment. However, these detrimental effects are at odds with recent empirical evidence that point to positive output effects from carbon taxes (Metcalf and Stock, 2020a,b). Therefore, our framework is able to reconcile this evidence. In doing so, we highlight how technology adoption decisions play a decisive role in generating muted adverse labor-market effects alongside positive macroeconomic outcomes in response to carbon taxes. At the same time, our analysis shows how changes in firm entry in response to carbon taxes play a key role in contributing to the short-term expansion in consumption as carbon taxes gradually increase to reach their higher long-term level.

Our work is related to the growing theoretical literature on the labor market and macroeconomic effects of carbon taxes and environmental policy. Several papers in this literature focus on the link between pollution emissions and business cycles from a positive standpoint, but abstract from considering labor market outcomes and the potential differences between the short- and long-term aggregate effects of carbon taxes (that is, the transition path to an environment with higher carbon taxes).[2] Only recently has the literature started to explore the relationship between environmental policy, macroeconomic outcomes, and labor markets, including unemployment (Hafstead and Williams III, 2018, Gibson and Heutel, 2020, Aubert and Chiroleu-Assouline, 2019, and Castellanos and Heutel, 2021). At the same time, a few papers have studied the link between market structure, firm entry, and environmental policy (see Kreickemeier and Richter, 2018; and Annicchiarico, Correani, and Di Dio, 2018). Another recent strand of work explores how technology adoption interacts with firm entry and exit (Coria and Kyriakopoulou, 2018) and, separately, how environmental policy influences the adoption of green technologies (Acemoglu et al., 2016; Fried, 2018).[3] Critically, none of these papers consider the link between carbon taxes and labor market outcomes, which lie at the center of our analysis. Closest to our work are Acemoglu et al (2016), who propose a framework where firms choose to produce using either a dirty or clean technology and invest in research and development, Hafstead and Williams III (2018), who use a two-sector ("dirty" and "clean") framework with equilibrium unemployment and find that carbon-tax-induced reductions in emissions entail both output and unemployment costs, and Annicchiarico, Correani, and Di Dio (2018), who use a one-sector model with endogenous firm entry and frictionless labor markets and find that greater carbon taxes lead to lower output, partly via lower firm creation. Our findings show that the adverse effects from carbon taxes in both Hafstead and Williams III (2018) and Annicchiarico, Correani, and Di Dio (2018) depend critically on whether firms can adopt green technologies.

We contribute to the literature on the labor market and macroeconomic consequences of carbon taxes in three ways. First, while this literature has steadily expanded, the majority of models focus exclusively on unemployment and the reallocation of workers between sec-

[2]See Fischer and Springborn (2011), Heutel (2012), Annicchiarico and Di Dio (2015), Annicchiarico, Correani, and Di Dio (2017), Annicchiarico and Diluiso (2019), and Khan, Metaxoglou, Knittel, and Papineau (2019), among others.

[3]For recent work on the link between pollution, environmental regulation, firm entry, and trade, see Shapiro and Walker (2018).

tors without considering how policy changes affect the search behavior of individuals.[4] The inclusion of labor force participation in our framework embodies this labor-supply-side margin. Second, these same studies abstract from the effects of policy changes on labor markets and aggregate outcomes via (1) firm entry and exit, and (2) firms' decisions to adopt green technologies. Our work shows that the interaction of these margins plays a crucial role in shaping the qualitative and quantitative effects of higher carbon taxes on both labor market outcomes *and* aggregate economic activity in the short and long term, with technology adoption—and therefore policy-induced *endogenous* changes in the economy's underlying technological composition of production—playing a decisive role in generating positive aggregate effects from carbon taxes. This last finding is, to the best of our knowledge, new, and stands in contrast to those of existing related papers, which generally find that carbon taxes have adverse labor-market and macro effects. Moreover, our model-based results provide a theoretical rationale behind recent empirical evidence on the positive macro effects of carbon taxes (Metcalf and Stock, 2020a,b). Finally, the combination of firm entry and exit and technology adoption with frictional labor markets contributes to the existing literature on market structure, technology adoption, and environmental policy, which abstracts from the implications of adopting green technologies on the labor market. More broadly, we bring together two important margins of adjustment to carbon taxes that, thus far, have been studied in isolation, and show that their inclusion plays a central role in shaping the qualitative and quantitative labor-market and macroeconomic implications of carbon taxes.

The rest of the paper is structured as follows. Section 2 describes the model. Section 3 outlines our calibration strategy and presents the main results from our quantitative analysis. Section 4 concludes.

2 The Model

The economy is comprised of firms, a government, a population of unit mass, and a representative household with a measure one of household members that owns all firms. Search

[4]The only recent exception is Castellanos and Heutel (2021), who consider sectoral labor force participation.

frictions in the labor market give rise to equilibrium unemployment. Households consume, make labor force participation decisions, and invest resources in firm creation so that firm entry is endogenous. As we describe in more detail below, once firms enter the market, they can choose the technological composition of their production process: one of the two production technologies available to the firm generates harmful carbon dioxide emissions as a by-product and is subject to carbon taxes, while the other is "green" and does not generate these emissions, but its adoption is subject to fixed costs of operation. Revenue from carbon taxes is transferred lump-sum to households.

The production and labor market structure is an adaptation of the framework in Finkelstein Shapiro and Mandelman (2021) (henceforth FSM), who modify the production structure of the well-known Ghironi and Melitz (2005) (henceforth GM) trade framework to capture technology-adoption and its impact on labor market outcomes. The structure in FSM has relevant features for the analysis of carbon taxes, mainly the inclusion of technology-adoption decisions by firms, endogenous firm entry, and job-search decisions by households via endogenous sectoral labor force participation. In contrast to FSM, we introduce pollution externalities and focus on how firms' decisions over entry and technology adoption are influenced by carbon taxes. With this mind, the model description below follows closely the general setup in FSM.

2.1 Firm and Production Structure

There is an unbounded number of monopolistically-competitive firm entrants whose entry is subject to a sunk entry resource cost φ_e. Once firms enter, they draw their idiosyncratic productivity a from a common distribution $G(a)$ with support $[a_{\min}, \infty)$,where the resulting level of a remains unchanged until the firm exits with exogenous probability $0 < \delta < 1$. Each firm produces a single output variety ω based on a, where $y_t(\omega)$ denotes the output of a given firm producing variety ω. Thus, in the rest of the model description, we refer to a firm producing variety ω with productivity level a simply as firm a.

When a household decides to create a new firm, all it knows is the productivity distribution, $G(a)$, but not the firm's realized productivity. Upon entering and incurring the sunk entry cost, the new firm's productivity level is realized, allowing it to choose one of two technologies.

A regular (r) technology is available that generates carbon dioxide (harmful) emissions—emissions for short. These emissions are subject to a carbon tax but can be mitigated via expenditures on emissions abatement. A green (g) technology is also available that does not generate emissions. Using the green technology, however, entails incurring a fixed resource cost φ_g associated with the adoption of the technology. Appendix A.1 formally shows that there is an endogenous threshold level of productivity such that firms with realized productivity below this threshold choose the r technology and firms with realized productivity above this threshold choose the g technology. Households will choose to create a new firm based on the new firm's expected future profits, which will depend on the distribution of the productivity parameter a and the resulting technology that is optimal for the firm to choose. The choice technology makes the measure of firms in each category endogenous.

Both production technologies rely on labor, which is subject to search and matching frictions, and physical capital as inputs. Emissions from using the r technology add to the economy's stock of carbon dioxide pollution that, in turn, has negative externalities on production for all firms in the economy, as we detail below.

2.1.1 Total Output

Total output is given by $Y_t = \left(\int_{\omega\in\Omega} y_t(\omega)^{\frac{\varepsilon-1}{\varepsilon}} d\omega\right)^{\frac{\varepsilon}{\varepsilon-1}}$, where Ω is the potential measure of firms in the economy and $\varepsilon > 1$ is the elasticity of substitution across individual output varieties. In turn, the aggregate price index is $P_t = \left(\int_{\omega\in\Omega} p_t(\omega)^{1-\varepsilon} d\omega\right)^{\frac{1}{1-\varepsilon}}$. As in GM, only a subset of firms $\Omega_t \subset \Omega$ are ultimately active in any given period.

2.1.2 Firm Structure

In what follows, we separate the production process from technology-adoption and pricing decisions by introducing intermediate goods producers and firms that use these intermediate goods. This facilitates the comparison of our framework to related models that abstract from firm entry and technology-adoption margins without affecting the general economic environment.[5]

Firm Profits and Threshold Productivity Level As noted earlier, we can think of a firm a as having access to two possible production lines that differ in their technology. Individual profits from producing with the r technology, $\pi^y_{r,t}(a)$, are given by

$$\pi^y_{r,t}(a) = \left[\rho_{r,t}(a) - \frac{mc_{r,t}}{a}\right] y_{r,t}(a),$$

while profits from producing with the g technology, $\pi^y_{g,t}(a)$, are given by

$$\pi^y_{g,t}(a) = \left[\rho_{g,t}(a) - \frac{mc_{g,t}}{a}\right] y_{g,t}(a) - \varphi_g,$$

where $\rho_{j,t}(a) \equiv p_{j,t}(a)/P_t$, $mc_{j,t}$, and $y_{j,t}(a)$ denote, respectively, the real output price, the real marginal cost, and the firm output associated with using technology $j \in \{g, r\}$, and φ_g is the fixed cost of g-technology adoption. Firm a is indifferent between production technologies when

$$\pi^y_{g,t}(a_{g,t}) = \pi^y_{r,t}(a_{g,t}), \tag{1}$$

where $a_{g,t}$ is the threshold idiosyncratic productivity level above which firms adopt the g technology.[6]

Optimal Pricing Given the aggregation of total firm output in Section 2.1.1, it is easy to show that the demand function for firm a's output is given by $y_{j,t}(a) = (\rho_{j,t}(a))^{-\varepsilon} Y_t$ for $j \in \{g, r\}$. Then, firm a chooses $\rho_{j,t}(a)$ to maximize $\pi^y_{j,t}(a)$ subject to the demand function

[5]While this separation of production from technology adoption is common in the macroeconomics literature, it may seem unusual to environmental economists. We note that we could equivalently characterize the production process as one where firms use factors of production to produce a final good. Firms enter, learn their productivity level, and choose a production technology (regular or green). Having learned their productivity level, in equilibrium, they match the technology choice to their productivity level appropriately (as discussed below). Firms use capital and labor to produce $y_t(a)$ with a constant-returns-to-scale production function. Marginal revenue implied for intermediate goods producers in Section 2.1.3 below simply becomes marginal cost for final goods producers just below.

[6]See FSM for an analogous indifference condition in the context of firms' decisions to adopt digital technologies, and Zlate (2016) in the context of firms' decisions to offshore production. It can be shown that if $a_{g,t}$ is not at the extreme ends of the support of the distribution, then the slope of $\pi^y_{g,t}(a_{g,t}) > \pi^y_{r,t}(a_{g,t})$, for g and r firms only intersect once (at $a_{g,t}$). See Appendix A.1 for a proof.

for $y_{j,t}(a)$. The resulting optimal real price for firm a is given by $\rho_{j,t}(a) = \frac{\varepsilon}{\varepsilon-1}\frac{mc_{j,t}}{a}$.

Evolution of Firms Denote by N_t the measure of total active firms and by $N_{e,t}$ the measure of new entrants. Then, the evolution of the total number of firms in the economy is

$$N_t = (1-\delta)\left[N_{t-1} + N_{e,t-1}\right]. \tag{2}$$

Recalling that firms draw their idiosyncratic productivity from a distribution $G(a)$ and that $a_{g,t}$ is the threshold level of productivity above which firms use the g technology, the number of r firms $N_{r,t}$ is given by $N_{r,t} = G(a_{g,t})N_t$ and the number of g firms $N_{g,t}$ is given by $N_{g,t} = \left[1 - G(a_{g,t})\right] N_t$.

Firm Averages Denote by $\widetilde{a}_{r,t}$ the average idiosyncratic productivity level of r firms and by $\widetilde{a}_{g,t}$ the average idiosyncratic productivity level of g firms. Formally, these averages are given by $\widetilde{a}_{r,t} = \left[\frac{1}{G(a_{g,t})}\int_{a_{min}}^{a_{g,t}} a^{\varepsilon-1}dG(a)\right]^{\frac{1}{\varepsilon-1}}$ and $\widetilde{a}_{g,t} = \left[\left(\frac{1}{1-G(a_{g,t})}\right)\int_{a_{g,t}}^{\infty} a^{\varepsilon-1}dG(a)\right]^{\frac{1}{\varepsilon-1}}$. Then, we can define average individual-firm profits as $\widetilde{\pi}_t^y = \frac{N_{r,t}}{N_t}\widetilde{\pi}_{r,t}^y + \frac{N_{g,t}}{N_t}\widetilde{\pi}_{g,t}^y$ where $\widetilde{\pi}_{r,t}^y \equiv \pi_{r,t}^y(\widetilde{a}_{r,t})$ and $\widetilde{\pi}_{g,t}^y \equiv \pi_{g,t}^y(\widetilde{a}_{g,t})$ are average individual-firm profits from producing with the r and g technologies, respectively. Analogously, average real prices and average individual-firm output are given by $\widetilde{\rho}_{r,t} \equiv \rho_{r,t}(\widetilde{a}_{r,t})$ and $\widetilde{\rho}_{g,t} \equiv \rho_{g,t}(\widetilde{a}_{g,t})$ and by $\widetilde{y}_{r,t} \equiv y_{r,t}(\widetilde{a}_{r,t})$ and $\widetilde{y}_{g,t} \equiv y_{g,t}(\widetilde{a}_{g,t})$, respectively. Of note, as we show in Section 2.2, given that firms' idiosyncratic productivity is revealed only after incurring a sunk cost and entering the market, firm creation decisions are influenced by, among other factors, the expected value of $\widetilde{\pi}_t^y$.

2.1.3 Intermediate Goods Producers

There is a measure 1 of perfectly-competitive producers of intermediate goods for r and g firms. These producers use category-specific labor, which is subject to search and matching frictions, and capital. The production of intermediate goods for r firms generates pollution emissions e_t that add to the economy's stock of pollution x_t (where this stock is taken as given by firms). We follow the literature and assume that the stock of pollution evolves as $x_t = \rho_x x_{t-1} + e_t + e_t^{row}$, $0 < \rho_x < 1$, where e_t^{row} denotes exogenous emissions from the rest of the world. Emissions e_t are taxed, but r firms can mitigate these emissions via abatement expenditures. In contrast, the production of intermediate goods for g firms does not generate pollution emissions and is not subject to carbon taxes.

Formally, intermediate goods producers choose the number of vacancies $v_{g,t}$ and $v_{r,t}$ which are needed to hire workers to produce each category of intermediate goods; the total amount of desired capital k_{t+1}; the desired measure of g and r workers $n_{g,t}$ and $n_{r,t}$; and the fraction of emissions abatement μ_t to maximize $\mathbb{E}_0 \sum_{t=0}^{\infty} \Xi_{t|0} \pi_t^i$ subject to[7]

$$\begin{aligned} \pi_t^i = &[D(x_t) mc_{r,t} H(n_{r,t}, k_{r,t}) - w_{r,t} n_{r,t} - \psi_r v_{r,t} - \tau_t e_t - \Gamma_t] \\ &+ [D(x_t) mc_{g,t} F(n_{g,t}, k_{g,t}) - w_{g,t} n_{g,t} - \psi_g v_{g,t}] \\ &- [k_{t+1} - (1-\delta) k_t], \end{aligned}$$

the perceived evolution of each category of employment

$$n_{r,t} = (1-\varrho) n_{r,t-1} + v_{r,t} q(\theta_{r,t}), \tag{3}$$

and

$$n_{g,t} = (1-\varrho) n_{g,t-1} + v_{g,t} q(\theta_{g,t}), \tag{4}$$

and total physical capital

$$k_t = k_{g,t} + k_{r,t}, \tag{5}$$

where $\Xi_{t|0}$ is the household's stochastic discount factor (defined further below), the term

$$\Gamma_t = \gamma \mu_t^{\eta} D(x_t) H(n_{r,t}, k_{r,t}), \tag{6}$$

is the total cost of abating emissions from the production of intermediate goods for r firms, and

$$e_t = (1-\mu_t) \left[D(x_t) H(n_{r,t}, k_{r,t})\right]^{1-\nu}, \tag{7}$$

is the total amount of emissions generated by such production net of abatement, where $\gamma > 0$, $\eta \geq 1$, and $0 < \nu \leq 1$. Note that both the cost of abating emissions, Γ_t, and the emissions

[7] Recall that households own all firms (and take their profits as given). Hence the joint profit maximization assumption here.

themselves, e_t, are a function of the production of intermediate goods for r firms. $H(n_{r,t}, k_{r,t})$ and $F(n_{g,t}, k_{g,t})$ are constant-returns-to-scale and increasing and concave functions in each argument (we assume that aggregate productivity is constant and normalized to 1). ψ_j and $w_{j,t}$ are, respectively, the flow cost of posting vacancies and the real wage of workers in category $j \in \{g, r\}$, and $0 < \delta < 1$ is the capital depreciation rate.[8] τ_t is the tax on emissions and $D(x_t)$ is a pollution-damages function that is decreasing in the economy's stock of pollution x_t and taken as given by producers. As such, an increase in pollution effectively reduces output for a given amount of labor and capital. Turning to the evolution of each category of employment, $0 < \varrho < 1$ is the exogenous probability of job separation and $q(\theta_{j,t})$ is the endogenous job-filling probability in category j, which is a function of market tightness $\theta_{j,t}$. Finally, we follow the labor-market timing convention in Arseneau and Chugh (2012) whereby filled vacancies in period t become productive in the same period.

The first-order conditions yield an optimal emissions abatement rate μ_t

$$\tau_t \left(D(x_t)H(n_{r,t}, k_{r,t})\right)^{-\nu} = \gamma\eta\mu_t^{\eta-1}, \tag{8}$$

capital Euler equations

$$1 = \mathbb{E}_t\Xi_{t+1|t}\left[D(x_{t+1})mc_{r,t+1}H_{k_r,t+1} - \tau_{t+1}e_{k_r,t+1} - \Gamma_{k_r,t+1} + (1-\delta)\right], \tag{9}$$

and

$$1 = \mathbb{E}_t\Xi_{t+1|t}\left[D(x_{t+1})mc_{g,t+1}F_{k_g,t+1} + (1-\delta)\right], \tag{10}$$

as well as standard job creation conditions for employment in each category

$$\frac{\psi_r}{q(\theta_{r,t})} = \left[\begin{array}{c} D(x_t)mc_{r,t}H_{n_r,t} - \tau_t e_{n_r,t} \\ -\Gamma_{n_r,t} - w_{r,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\frac{\psi_r}{q(\theta_{r,t+1})} \end{array}\right], \tag{11}$$

and

$$\frac{\psi_g}{q(\theta_{g,t})} = \left[D(x_t)mc_{g,t}F_{n_g,t} - w_{g,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\frac{\psi_g}{q(\theta_{g,t+1})}\right], \tag{12}$$

[8] Following the macro literature on endogenous firm entry, we assume that the capital depreciation rate and the firm exit rate are the same. Introducing differences in firm exit and capital depreciation rates does not change our main conclusions.

where $e_{n_r,t}$ and $e_{k_r,t}$, denote the marginal increase in emissions from one more worker and one more unit of capital in the production of intermediate goods for r firms, respectively, and $\Gamma_{n_r,t}$ and $\Gamma_{k_r,t}$ denote the marginal increase in the resource cost of emissions abatement associated with having one more worker and one more unit of capital in the production of intermediate goods for r firms, respectively.[9]

Intuitively, intermediate goods producers equate the marginal cost of emissions abatement—given by the resource cost incurred as a result of the marginal increase in emissions abatement—to the marginal benefit of emissions abatement—given by the marginal output gain (net of pollution damages) from not having to pay the carbon tax. The capital Euler equations are standard. Finally, the job creation conditions equate the marginal cost of posting a vacancy for each category of employment to the expected marginal benefit of doing so. In the case of posting a vacancy to hire workers who produce intermediate goods for r firms, producers take into account the regulation cost associated with emissions generation and the marginal resource cost of emissions abatement associated with having one more r worker. Note that the damages from pollution affect the expected marginal benefit of hiring workers across categories.

2.2 Households and Firm Creation

There is a representative household with a measure one of household members who can be employed, unemployed and searching for employment, or outside of the labor force. Households own all firms and spend resources to create firms. In addition, all proceeds from taxing emissions from the production of intermediate goods for r firms are transferred lump-sum to households.

Formally, households choose consumption c_t, the measures of searchers in each employment category $s_{g,t}$ and $s_{r,t}$, the desired measures of workers in each category $n_{g,t}$ and $n_{r,t}$, the number of new firms $N_{e,t}$ and the desired total number of firms N_{t+1} to maximize

[9] That is, $e_{n_r,t} = (1-\nu)(1-\mu_t)\left(D(x_t)H(n_{r,t},k_{r,t})\right)^{-\nu} D(x_t)H_{n_r,t}$ and $\Gamma_{n_r,t} = \gamma\mu_t^{\eta} D(x_t)H_{n_r,t}$. Analogous expressions hold for $k_{r,t}$.

$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\mathbf{u}(c_t) - \mathbf{h}(lfp_{g,t}, lfp_{r,t})\right]$ subject to the budget constraint

$$c_t + \varphi_e N_{e,t} + T_t = w_{g,t} n_{g,t} + w_{r,t} n_{r,t} + \chi \left[(1 - f(\theta_{g,t}))s_{g,t} + (1 - f(\theta_{r,t}))s_{r,t}\right] + \widetilde{\pi}_t^y N_t + \pi_t^i + \tau_t e_t,$$

the perceived evolution of employment in each category $j \in \{g, r\}$

$$n_{j,t} = (1 - \varrho) n_{j,t-1} + s_{j,t} f(\theta_{j,t}), \tag{13}$$

and the evolution of final-goods firms

$$N_{t+1} = (1 - \delta)\left[N_t + N_{e,t}\right], \tag{14}$$

where labor force participation in each category is given by $lfp_{g,t} = n_{g,t} + (1 - f(\theta_{g,t}))s_{g,t}$ and $lfp_{r,t} = n_{r,t} + (1 - f(\theta_{r,t}))s_{r,t}$. The utility from consumption and disutility from labor force participation have standard properties, with $\mathbf{u}(c_t)$ being increasing and concave, and $\mathbf{h}(lfp_{g,t}, lfp_{r,t})$ being increasing and convex in $lfp_{j,t}$ for $j \in \{g, r\}$. Total labor income is given by $w_{g,t} n_{g,t} + w_{r,t} n_{r,t}$. In turn, $\widetilde{\pi}_t^y N_t$ and Π_t denote total average profits from firms and intermediate-goods producers, respectively. $\tau_t e_t$ are lump-sum transfers from taxing emissions, χ denote unemployment benefits, and $f(\theta_{j,t})$ is the job-finding probability in employment category $j \in \{g, r\}$ (defined in Section 2.3 below). In turn, $\varphi_e N_{e,t}$ represents the total resource cost from creating new firms. Finally, T_t are lump-sum taxes that finance unemployment benefits.

The first-order conditions yield labor force participation conditions for each employment category $j \in \{g, r\}$

$$\left(\frac{\mathbf{h}_{lfp_{j,t}} - \mathbf{u}'(c_t)\chi}{f(\theta_{j,t})\mathbf{u}'(c_t)}\right) = w_{j,t} - \chi + (1 - \varrho)\mathbb{E}_t \Xi_{t+1|t} \left(1 - f(\theta_{j,t+1})\right) \left(\frac{\mathbf{h}_{lfp_{j,t+1}} - \mathbf{u}'(c_{t+1})\chi}{f(\theta_{j,t+1})\mathbf{u}'(c_{t+1})}\right), \tag{15}$$

and a final-goods firm creation condition

$$\varphi_e = (1 - \delta)\mathbb{E}_t \Xi_{t+1|t} \left[\widetilde{\pi}_{t+1}^y + \varphi_e\right], \tag{16}$$

where $\Xi_{t+1|t} \equiv \beta \mathbf{u}'(c_{t+1})/\mathbf{u}'(c_t)$. Intuitively, for each employment category, households equate the expected marginal cost of searching for a job, which is given by the marginal disutility from participating in the labor market net of unemployment benefits and adjusted by the probability of finding a job, to the expected marginal benefit, given by the wage net of unemployment benefits and the continuation value from staying employed in the future. In turn, households equate the marginal cost of creating a firm, given by the sunk entry resource cost, to the expected marginal benefit, which is given by expected average individual-firm profits and the continuation value if the firm survives into the next period with probability $(1-\delta)$.

2.3 Matching Processes and Wage Determination

Let $m(s_{g,t}, v_{g,t})$ and $m(s_{r,t}, v_{r,t})$ be standard constant-returns-to-scale matching functions for g and r employment that take vacancies and searchers in their respective categories as arguments. Then, the job-filling and job-finding probabilities for category $j \in \{g, r\}$ are given by $q(\theta_{j,t}) = m(s_{j,t}, v_{j,t})/v_{j,t}$ and $f(\theta_{j,t}) = m(s_{j,t}, v_{j,t})/s_{j,t}$, respectively, where market tightness is $\theta_{j,t} = v_{j,t}/s_{j,t}$. Following the search and matching literature, we assume that wages are determined via bilateral Nash bargaining between firms and workers. Using the value functions in Appendix A.2, we can show that the Nash real wages for each category are given by

$$w_{r,t} = \nu_n \left[D(x_t) mc_{r,t} H_{n_{r,t}} - \Gamma_{n_r,t} - \tau_t e_{n_r,t} + (1-\varrho)\mathbb{E}_t \Xi_{t+1|t} \psi_r \theta_{r,t+1} \right] + (1-\nu_n)\chi, \qquad (17)$$

and

$$w_{g,t} = \nu_n \left[D(x_t) mc_{g,t} F_{n_{g,t}} + (1-\varrho)\mathbb{E}_t \Xi_{t+1|t} \psi_g \theta_{g,t+1} \right] + (1-\nu_n)\chi, \qquad (18)$$

where $0 < \nu_n < 1$ is the bargaining power of workers.

2.4 Symmetric Equilibrium and Market Clearing

The price of *aggregate* output is given by the following expression: $1 = N_{r,t} \left(\widetilde{\rho}_{r,t}\right)^{1-\varepsilon} + N_{g,t} \left(\widetilde{\rho}_{g,t}\right)^{1-\varepsilon}$. Imposing symmetric equilibrium, market clearing in each output category implies that[10]

$$D(x_t)H(n_{r,t}, k_{r,t}) = N_{r,t}\left(\frac{\widetilde{y}_{r,t}}{\widetilde{a}_{r,t}}\right), \tag{19}$$

and

$$D(x_t)F(n_{g,t}, k_{g,t}) = N_{g,t}\left(\frac{\widetilde{y}_{g,t}}{\widetilde{a}_{g,t}}\right). \tag{20}$$

Of note, using these two expressions alongside the job creation, capital accumulation, and abatement decisions of intermediate goods producers imply that, as part of our model analysis in Section 3, we can refer to the decisions of j firms and the decisions of producers of intermediate goods for j firms interchangeably. Turning to the government budget constraint, households pay lump-sum taxes to finance unemployment benefits and revenue from carbon taxes is transferred lump-sum to households.

Finally, the economy's resource constraint is given by

$$Y_t = c_t + \psi_r v_{r,t} + \psi_g v_{g,t} + \varphi_e N_{e,t} + \varphi_g N_{g,t} + k_{t+1} - (1-\delta)k_t + \Gamma_t. \tag{21}$$

Appendix A.4 presents the full list of equilibrium conditions. Per the market clearing conditions for the production of intermediate goods, pollution damages are embedded in Y_t so that the resource constraint is inclusive of these damages. Using expressions (19) and (20) alongside the job creation, capital accumulation, and abatement decisions of intermediate goods producers imply that, as part of our model analysis in Section 3, we can refer to the decisions of producers of intermediate goods for j firms and the decisions of j firms interchangeably.

3 Quantitative Analysis

As is well known in the macro literature on endogenous firm entry, models with a firm creation margin feature a love-of-variety component. Thus, when comparing the model's variables to their empirical counterparts, we follow GM such that the data-consistent counterpart of a

[10]The two market-clearing conditions below follow from equating the revenue $D(x_t)mc_{r,t}H(n_{r,t}, k_{r,t})$ from producing r intermediate goods with the average costs $(mc_{r,t}/\widetilde{a}_{r,t})\,\widetilde{y}_{r,t}$ for the final goods firms using the r technology, and similarly for the g firms.

given real variable in the model λ_t^m is $\lambda_t^d = \lambda_t^m (N_t)^{\frac{1}{1-\varepsilon}}$ (see Appendix A.3 for more details).

3.1 Calibration: Baseline Economy

Functional Forms Following the literature, we assume that consumption and labor force participation are separable: $[\mathbf{u}(c_t) - \mathbf{h}(lfp_{g,t}, lfp_{r,t})] = \frac{c_t^{1-\sigma_c}}{1-\sigma_c} - \left[\frac{(\kappa_g(lfp_{g,t}) + \kappa_r(lfp_{r,t}))^{1+1/\phi_n}}{1+1/\phi_n}\right]$, where σ_c,$\kappa_g, \kappa_r > 0$ and $\phi_n > 0$ dictates the elasticity of participation (see Arseneau and Chugh, 2012, for a similar functional form in a model with a single employment category). Following the macro literature on endogenous firm entry, we use a Pareto distribution for $G(a) = \left[1 - (a_{\min}/a)^{k_p}\right]$ with shape parameter $k_p > \varepsilon - 1$.[11] This implies that the average idiosyncratic productivities can be written as $\widetilde{a}_{r,t} = \widetilde{a}_{g,t} \left(\frac{a_{g,t}^{k_p-(\varepsilon-1)} - a_{min}^{k_p-(\varepsilon-1)}}{a_{g,t}^{k_p} - a_{min}^{k_p}}\right)^{\frac{1}{\varepsilon-1}} a_{min}$ and $\widetilde{a}_{g,t} = \left(\frac{k_p}{k_p-(\varepsilon-1)}\right)^{\frac{1}{\varepsilon-1}} a_{g,t}$, and that the number of g firms is $N_{g,t} = (a_{min}/a_{g,t})^{k_p} N_t$.

The production functions for intermediate goods are Cobb-Douglas: $H(n_{r,t}, k_{r,t}) = (n_{r,t})^{1-\alpha_r}(k_{r,t})^{\alpha_r}$ and $F(n_{g,t}, k_{g,t}) = (n_{g,t})^{1-\alpha_g}(k_{g,t})^{\alpha_g}$, where $0 < \alpha_g, \alpha_r < 1$. Recall that the total abatement cost Γ_t is proportional to the output that generates emissions, so that $\Gamma_t = \gamma \mu_t^\eta D(x_t) H(n_{r,t}, k_{r,t})$, where $\gamma > 0$ and $\eta > 1$ (Heutel, 2012). The matching functions for each category are given by $m(s_{j,t}, v_{j,t}) = s_{j,t} v_{j,t} / \left[s_{j,t}^\xi + v_{j,t}^\xi\right]^{1/\xi}$ where $\xi > 0$ for $j \in \{g, r\}$ (see den Haan, Ramey, and Watson, 2000).

The carbon dioxide pollution damages function is $D(x_t) = exp\left[-D_0(x_t - \bar{x}_t)\right]$ where $D_0 > 0$ dictates the strength of the pollution externality and $\bar{x}_t = D_1 x_t$ denotes pre-industrial atmospheric carbon dioxide concentration, with $0 \leq D_1 < 1$ (see Annicchiarico, Correani, and Di Dio, 2018; Annicchiarico and Diluiso, 2019).

Parameters from Existing Literature A period is a quarter. We set $\alpha_g = \alpha_r = 0.32$, $\beta = 0.985$, $\delta = 0.025$, and $\sigma_c = 2$, which are common values in the macro literature. Based on micro estimates for the extensive-margin elasticity of participation from Chetty et al. (2011, 2013), we set $\phi_n = 0.26$ as a baseline. Following GM and others, we normalize $a_{min} = 1$ and choose $\varepsilon = 3.8, k_p = 4.2$ as a baseline. These values deliver empirically-consistent

[11] In addition to being highly tractable, as noted in Redding (2011), the Pareto distribution approximates the firm-size distribution reasonably well.

markups and are commonly-adopted values in the literature. In turn, we set $\varrho = 0.05$ and $\nu_n = 0.5$,both of which are consistent with standard values in the search and matching literature. Following Heutel (2012), we set $\rho_x = 0.9979$, $\nu = 0.304$, and $\eta = 2.8$, which are consistent with estimates from Nordhaus (2008), and set $D_1 = 0.6983$ (Annicchiarico, Correani, and Di Dio, 2018; Annicchiarico and Diluiso, 2019). This value delivers a share of post-industrial atmospheric carbon dioxide concentration of one fourth of the total pollution stock. Following Hafstead and Williams III (2018) and others, we set $\gamma = 1$. Finally, we set carbon taxes $\tau = 0$ as a baseline, which is consistent with the current absence of a nationwide carbon tax in the U.S.

Calibrated Parameters To calibrate the remaining parameters, we note that agriculture, construction, mining, utilities, transportation, and durable-goods manufacturing are commonly considered to be the main generators of carbon emissions. Therefore, we choose targets for the employment and output shares of r firms that are broadly consistent with the corresponding combined shares of employment and output in these industries.

Absent evidence on differential hiring costs between the two employment categories, we set $\psi_r = \psi_g = \psi$ as a baseline. Then, parameters $D_0, e^{row}, \psi, \kappa_r, \kappa_g, \xi, \chi, \varphi_e$, and φ_g are chosen to match the following targets based on U.S. data and related literature: a ratio of carbon dioxide pollution damages to GDP of 0.0069 (Heutel and Gibson, 2020); a cost of creating a firm of 1 percent of income per capita (consistent with data on the cost of creating a business in the U.S. per World Bank data); an average unemployment rate of 6 percent (consistent with quarterly data from 1985:Q1 to 2019:Q4); an unemployment insurance (UI) replacement rate of 50 percent of average wages (consistent with data on average U.S. replacement rates); an average quarterly labor force participation (LFP) rate of 63 percent (consistent with quarterly data from 1985:Q1 to 2019:Q4); a share of r employment in the labor force of 0.165; a ratio of the total cost of posting vacancies to GDP of roughly 1 percent (a standard target in the macro-labor literature); a share of total r-firm output in total output of 0.20; and a share of U.S. emissions in worldwide emissions of 0.20 (consistent with existing data on emissions for the U.S. and the rest of the world).[12] The resulting parameter values are:

[12]The target for the share of total r-firm output in total output corresponds to the average value added of agriculture, mining, utilities, transport, construction, chemicals, petroleum manufacturing, and durables

$D_0 = 0.000010582, e^{row} = 3.6180, \psi = 2.1648, \kappa_r = 0.7699, \kappa_g = 0.6599, \xi = 0.4046, \chi = 30.9263, \varphi_e = 0.6821$, and $\varphi_g = 0.0051$. Table 1 summarizes the parameters, their values, and their sources or targets.

Table 1: Parameter Values, Description, and Sources or Targets in Benchmark Model

Parameters from Literature			
Parameter	Value	Description	Source
α_g, α_r	0.32	Capital share	Standard value in lit.
β	0.985	Discount factor	Standard value in lit.
σ_c	2	CRRA param.	Standard value in lit.
ϕ_n	0.26	Elast. of LFP	Chetty et al. (2011, 2013)
ε	3.8	Elast. substit. firm output	Ghironi and Melitz (2005)
k_p	4.2	Pareto shape param.	Ghironi and Melitz (2005)
a_{min}	1	Min. idiosyncratic prod.	Normalization
ϱ	0.05	Job separation probability	Search lit.
ν_n	0.5	Worker bargaining power	Search lit.
ξ	0.4046	Matching elasticity param.	Unempl. rate of 6 percent
D_1	0.6983	Damages parameter	Annicchiarico, et al. (2018)
η	2.8	Elast. of abatement rate	Nordhaus (2008)
γ	1	Weight, abate. cost function	Hafstead and Williams III (2018)
ν	0.304	Elast. parameter, emissions	Heutel (2012)
ρ_x	0.9979	Persistence of pollution	Heutel (2012)

Calibrated Parameters			
Parameter	Value	Description	Target
D_0	0.000010582	Damages parameter	Pollution damages/GDP = 0.0069
ψ_r, ψ_g	2.5128	Vacancy posting cost	Vacancy costs/GDP = 0.01
e^{row}	2.6464	Emissions rest of world	$e^{row}/(e + e^{row}) = 0.80$
κ_r	0.7699	r LFP disutility param.	$lfp = 0.63$
κ_g	0.6599	g LFP disutility param.	$n_r/lfp = 0.165$
χ	30.9263	Unemployment benefits	$\chi = 0.50w$
φ_e	0.6821	Sunk entry cost	$\varphi_e/Y = 0.01$
φ_g	0.0051	Fixed cost tech. adoption	r-Output Share = 0.20

manufacturing as a share of GDP based on annual data from 2005 to 2019 from the Bureau of Economic Analysis (BEA). The target for the share of r employment in the labor force is based on the average share of employment in these industries over the same time period (also from the BEA).

3.2 Labor Market and Aggregate Effects of Carbon Taxes

Recall that our baseline calibration sets the tax on emissions τ to 0. We analyze an increase in τ such that long-run emissions fall by 35 percent (a target for emission reductions that is roughly consistent with the Paris Agreement commitment). Moreover, when analyzing the transition path to the higher carbon-tax-rate steady state and for illustrative purposes, we implement a *gradual* increase in carbon taxes that takes 20 quarters (or 5 years) to fully materialize, with uniform increments per quarter. This last policy experiment is both plausible and sensible since introducing carbon taxes is unlikely to happen via a large, one-time increase in carbon taxes.

3.2.1 Steady-State Equilibria

Table 2 shows steady state values of select variables under the baseline (pre carbon tax) calibration, the values post carbon tax, and the resulting percent or percentage-point change in these variables when we increase the carbon tax to reduce steady-state emissions by 35 percent.

In the long run, output and consumption increase by roughly 0.29 and 0.17 percent, respectively. Labor force participation increases by 0.38 percentage points (that is, from a baseline rate of 63 percent to 63.38 percent), while the unemployment rate increases marginally by only 0.05 percentage points (that is, from a baseline rate of 6 percent to 6.05 percent).

Employment in r firms falls by almost 19 percent, while employment in g firms increases by almost 5 percent. Given the initial allocation of employment across categories, total employment increases by 0.55 percent. Wages in both categories of employment increase marginally. The abatement rate chosen by r firms increases by 25 percentage points, while the ratio of tax revenue to GDP increases by 0.18 percentage points.[13] Finally, the number of g firms increases by 14 percent, while the total number of firms falls by roughly 1.2 percent, implying a reduction in firm entry. All told, a carbon-tax-based reduction in emissions has positive (though mild) effects on real wages, consumption, and output, and very limited

[13] The equilibrium abatement rate in the baseline calibration is effectively zero since there is no incentive to abate emissions if carbon taxes are zero.

adverse effects on unemployment given the magnitude of the reduction in emissions. Carbon tax revenue as a share of output equals 0.18 percent. Using 2020 GDP as a baseline for comparison, this translates into revenue of roughly $40 billion annually. This estimate is considerably lower than estimates from studies such as the U.S. Treasury study (Horowitz et al., 2017). However, as we discuss below, the estimated tax rate and revenue are lower compared to an environment that abstracts from firm creation and green technology adoption decisions.

Table 2: Steady State Changes in Response to Carbon Tax–Benchmark Model

Variable	Benchmark Model Values **Before Tax (Baseline)**	Benchmark Model Values **After Tax**	**Percent Change** Rel. to Baseline
Emissions e	0.91	0.59	-35
Total Output	6.97	6.99	0.291
Consumption	4.59	4.60	0.174
Empl. r	0.10	0.09	-18.517
Empl. g	0.49	0.51	4.611
Total Empl.	0.59	0.60	0.551
Real Wage r	6.27	6.28	0.118
Real Wage g	5.37	5.38	0.117
Capital k_r	79.96	64.94	-18.784
Capital k_g	399.78	398.40	-0.346
Firms (N)	592.99	585.77	-1.218
g Firms (N_g)	246.76	281.36	14.019
			Percentage-Pt. Change Rel. to Baseline
Unempl. Rate	6.00%	6.05%	0.046
LFP Rate	63.00%	63.38%	0.378
Abate. Rate μ	0.00%	25.01%	25.013
Share of g-Firm Output	80.00%	83.534%	3.534
Share of g Firms	41.61%	48.03%	6.419
Tax Rev./Output	0.00%	0.18%	0.179

Notes: The first two columns show values rounded to two decimal places. Values in blue denote beneficial changes (relative to the baseline economy) of select variables of particular interest whereas values in red denote adverse changes (relative to the baseline economy) of select variables of particular interest.

Table 3: Steady State Changes in Response to Carbon Tax–Benchmark Model vs. Simpler Model Variants

Variable	**Benchmark Model**	**No Firm Entry**	**No Firm Entry, No Tech. Adopt.**
	(1)	(2)	(3)
	Percent Change Rel. to Baseline	**Percent Change** Rel. to Baseline	**Percent Change** Rel. to Baseline
Emissions e	-35	-35	-35
Total Output	0.291	0.924	-1.279
Consumption	0.174	0.261	-1.073
Empl. r	-18.517	-36.695	-26.554
Empl. g	4.611	9.119	6.279
Total Empl.	0.551	1.077	0.516
Real Wage r	0.118	0.586	-2.369
Real Wage g	0.117	0.590	-2.382
Capital k_r	-18.784	-36.314	-28.358
Capital k_g	-0.346	0.564	-2.741
Firms (N)	-1.218	-	-
g Firms (N_g)	14.019	-	-
	Percentage-Pt. Change Rel. to Baseline	**Percentage-Pt. Change** Rel. to Baseline	**Percentage-Pt. Change** Rel. to Baseline
Unempl. Rate	0.046	0.019	0.185
LFP Rate	0.378	0.691	0.450
Abate. Rate μ	25.013	10.800	19.010
Share of g-Firm Output	3.534	7.023	4.006
Share of g Firms	6.419	13.618	-
Tax Rev./Output	0.179	0.355	1.397

Note: Values in blue denote beneficial changes (relative to the baseline economy of each model version) of select variables of interest whereas values in red denote adverse changes (relative to the baseline economy of each model version) of select variables of interest.

In Table 3, we report results from two model variants alongside our benchmark results from Table 2. First, we consider a version of our model where we shut down the firm-entry margin but still allow technology-adoption decisions (column (2) of Table 3).[14] Second, we consider a version of our model that abstracts from both firm entry and green-technology adoption (column (3) of Table 3). This second variant maintains two firm categories—one that uses the regular (polluting) technology and one that uses the green technology—and allows for capital and labor to be reallocated across firm categories in response to a change in carbon taxes, but does not allow firms using the r technology to endogenously adopt the g technology. That is, there is no technology adoption margin and therefore no possibility for endogenous changes in the underlying technological production structure of the economy (in terms of the prevalence of polluting versus green production technologies). In this sense, the model in column (3) is closest to existing two-sector models with equilibrium unemployment and pollution externalities in the literature (see, for example, Hafstead and Williams III, 2018). For each model, we show the percent change and, when appropriate, the percentage-point change, of select variables in response to the increase in carbon taxes relative to the baseline calibration (i.e., when $\tau = 0$) of each respective model.

The benchmark-model variant without endogenous firm entry (column (2)) delivers qualitative results similar to those of the benchmark model (column (1)), though the positive effects on wages, the share of g firms, consumption, and output are larger, the increase in abatement is smaller, and the (quantitatively limited) increase in unemployment is smaller. The most notable results pertain to the model that abstracts from both firm entry and technology adoption. Indeed, for the same 35-percent reduction in emissions in the long run, the introduction of carbon taxes in the absence of firm entry and technology-adoption decisions generates non-trivial *reductions* in real wages, consumption, and output. Moreover, the increase in the unemployment rate is larger, though still limited considering the output reduction. In particular, output and consumption fall by more than 1 percent relative to their pre-policy baseline, and the unemployment rate increases from 6 percent to 6.19 percent (compare the changes in column (1) to those of column (3)). Thus, the adverse effects of carbon taxes on output are not directly reflected in a large increase in unemployment. In-

[14] Specifically, this variant of the benchmark model normalizes the total number of firms to 1 so that there is a continuum of firms over the [0,1] interval, a measure of which decide to incur the fixed cost of green-technology adoption and become g firms based on their idiosyncratic productivity. For completeness, Table A2 in Appendix A.7 discusses a related version of the benchmark model where we shut down the abatement margin while keeping both firm entry and technology adoption.

stead, wages are largely responsible for absorbing the increase in carbon taxes, which in turn leads to a reduction in labor income and consumption. As we show next, in the absence of the firm-entry and green-technology adoption margins, the adverse long-term labor market and aggregate effects of greater carbon taxes manifest themselves in the short term as well.

3.2.2 Transitional Dynamics

The presence of search and matching frictions, costly firm creation, and costly technology adoption all imply that the transition path to the new steady state can take time and may potentially entail short-term employment, consumption, and output costs. To assess the extent of these potential costs, we consider the transition path of the economy amid a gradual and uniform increase in carbon taxes that delivers a long-run decline in emissions of 35 percent as in Section 3.2.1. Since, from a practical standpoint, the increase in carbon taxes to reach a long-term reduction in emissions of 35 percent is likely to be gradual, we assume that the total increase in carbon to hit this emissions-reduction target taxes takes 20 quarters (or 5 years) to materialize, with uniform increases in the carbon tax each quarter.

Figures 1 and 2 plots the transition path of select variables in response to the gradual increase in carbon taxes.[15] For comparability, the two figures show the transition path of: (1) the benchmark model (solid blue line), (2) the benchmark model variant without firm entry (dash-dotted green line), and (3) the benchmark model variant with neither firm entry nor technology adoption (dotted red line). Of note, due to the economy's underlying structure and frictions, the full, long-term effect of the carbon tax may take time to materialize. This explains the discrepancy between the long-term changes in certain variables in Table 2 and the short- and medium-term changes of the same variables in Figures 1and 2. Importantly, we note that emissions have fallen nearly by 35 percent by the end of 20 quarters (five years) in all scenarios, assuring that the new U.S. Paris Agreement target is achievable by 2030.

[15]Following the macro-labor/endogenous-firm-entry literature that analyzes transitional dynamics after a permanent change in policy, we solve the full non-linear version of the model under perfect foresight using the historical algorithm as described in Juillard (1996) (for an application of these methods to the analysis of labor-market and goods-market reforms, see Cacciatore and Fiori, 2016).

Figure 1: Transitional Dynamics in Benchmark Model and Model Variants (Gradual Reduction in Emissions via Carbon Tax)

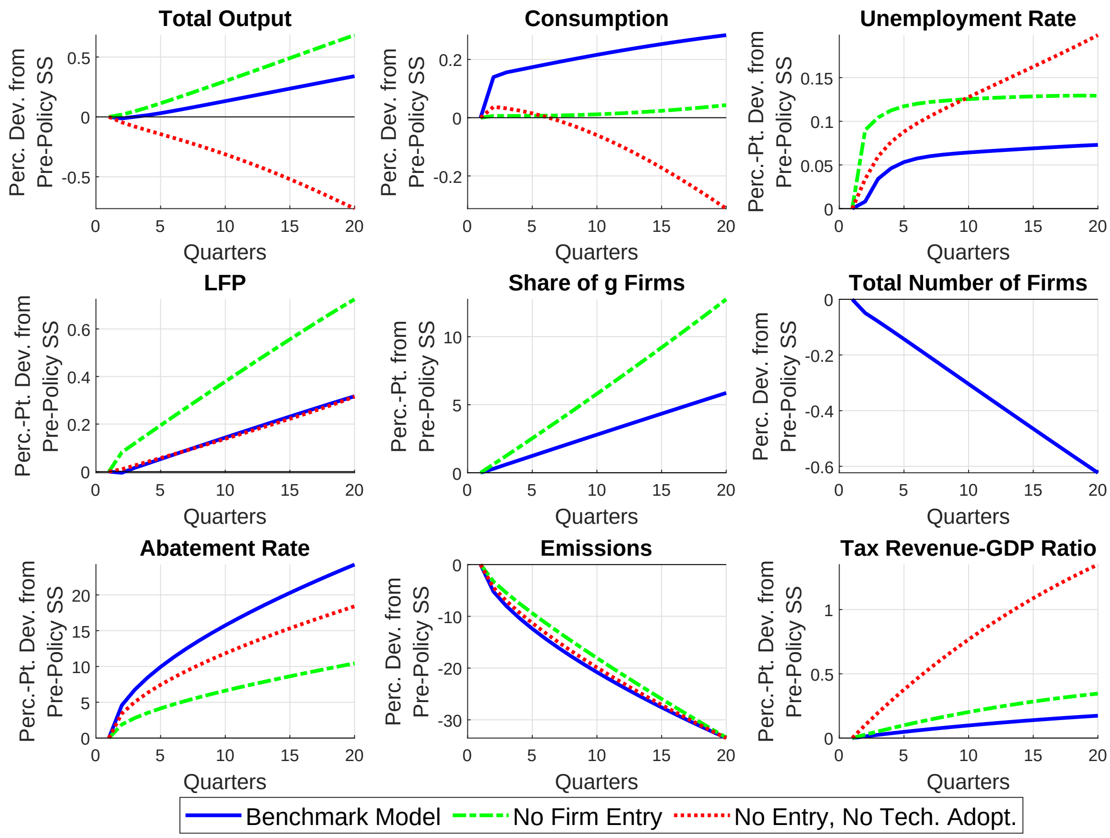
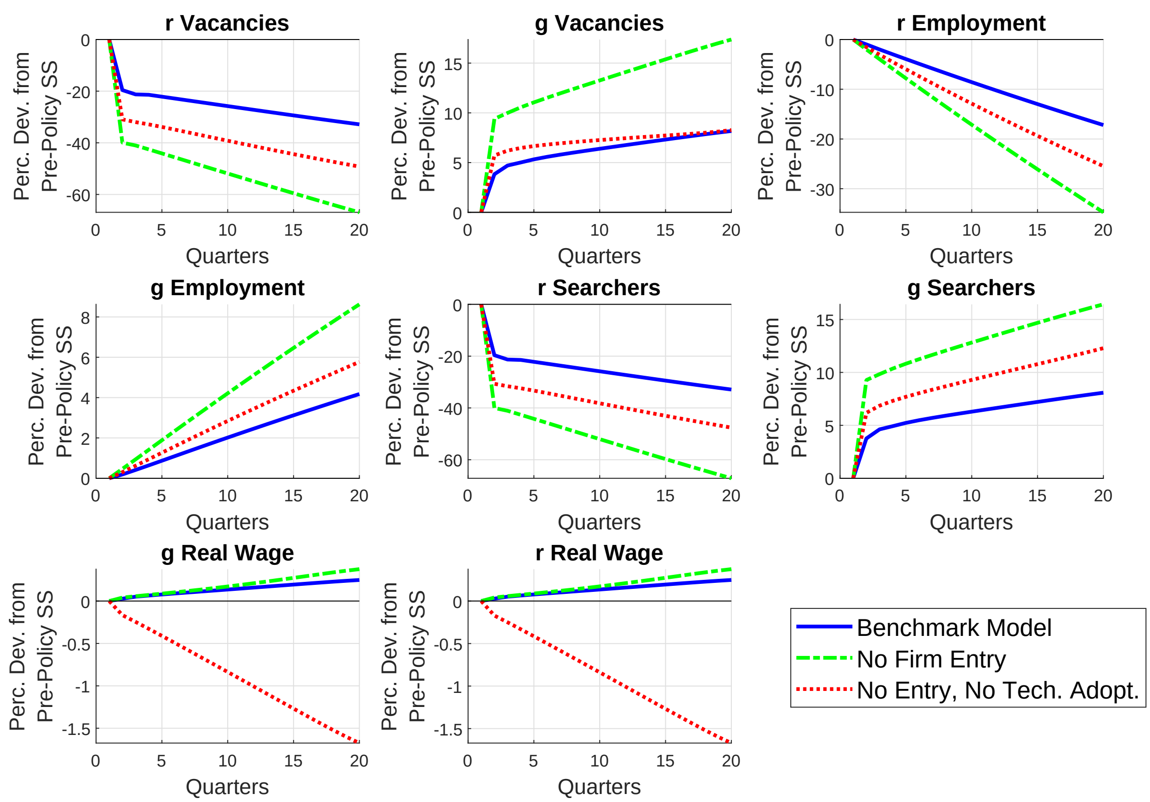


Figure 2: Transitional Dynamics in Benchmark Model and Model Variants (Gradual Reduction in Emissions via Carbon Tax, Continued)



We first discuss the transition path of our benchmark model and turn to the transition dynamics of the two benchmark-model variants in Section 3.3. Recall that column (1) of Table 2 showed that higher carbon taxes generate higher steady-state consumption and output, and marginally higher unemployment. Intuitively, as the tax on emissions increases gradually, r firms respond by devoting more resources to abatement. Both the carbon tax and the additional resources devoted to abatement reduce r firms' marginal benefit to having a worker and accumulating capital (see the job creation condition and the capital Euler equation of r firms). As a result, r firms use less capital, post less vacancies and hire less workers, which leads to a reduction in r employment and r output. All told, both the increase in abatement and the reduction in r-firm output contribute to the reduction in emissions.

At the same time, by increasing the relative cost of using the r technology, the increase in carbon taxes makes it relatively more attractive for r firms to incur the fixed cost of adopting the g technology. As a result, the number (and fraction) of g firms increases. All else equal, the reduction in labor demand by r firms *initially* puts downward pressure on wages across the board and, coupled with the increase in the number of firms that adopt the g technology, leads to greater labor demand by g firms and to greater g employment in equilibrium. Given the presence of labor market frictions, the reallocation of employment away from r and into g firms is accompanied by a gradual but limited increase in the unemployment rate as well as an increase in labor force participation, where the latter is driven by both an increase in g employment and in the mass of g searchers (of note, the marginal increase in unemployment is explained by the reallocation of searchers away from jobs in r firms to jobs in g firms). The increase in output takes time to materialize as resources are reallocated towards abatement, the creation of g firms, and capital accumulation for these firms. In contrast, the increase in consumption takes hold earlier compared to output. This takes place for two reasons. First, carbon-tax revenue is transferred lump-sum to the household, which bolsters household consumption. Second, the incentive to create firms amid greater carbon taxes falls, which frees up household resources for consumption that would otherwise be used to cover the resource costs of firm creation.

Similar mechanisms are at play when we abstract from endogenous firm entry, the only difference being the magnitude of the responses with respect to the benchmark model. In particular, the absence of a firm-creation margin implies that in the short and medium term, more resources are devoted to cover the fixed costs of green-technology adoption as opposed to consumption, leading to a larger increase in the share of g firms. Hence the smaller increase in consumption and the larger increase in output as carbon taxes steadily rise. At the same time, the larger expansion in the share of g firms increases the incentive for household members to search for employment in these firms, thereby leading to a larger short-run increase in g searchers and therefore in unemployment. Ultimately, though, recall that the long-term unemployment rate increases by less compared to the benchmark model due to the larger long-term expansion in the share of g firms.

Finally, abstracting from both firm entry and technology adoption generates a short- and medium-term contraction in both consumption and output, as well as a more steady and sustained increase in unemployment (even if the increase in absolute terms remains limited given the sizable reduction in emissions). That is, absent these two margins of adjustment, increasing carbon taxes entails both short- and long-term consumption and output costs.

3.2.3 Model Mechanisms

The primary way in which carbon taxes affect firms' decisions in our framework is via their impact on the marginal cost of r firms. The key question is how firm entry and technology adoption shape the change in this marginal cost in response to carbon taxes. Indeed, amid positive carbon taxes and for each increase in production inputs (capital and labor), r firms must not only incur extra expenditures to cover the resulting change in abatement costs (which depend on r-firm output), but also pay for the incremental change in carbon-tax expenditures due to the resulting increase in emissions. In other words, the marginal cost of r firms is directly impacted by carbon taxes and by abatement decisions.

To see this more clearly, without loss of generality, consider a version of the benchmark model without physical capital, with an elasticity of emissions with respect to r-firm output of 1, and with zero unemployment benefits. Furthermore, continue to assume that $\psi_g = \psi_r = \psi$. Then, using the job-creation condition, the market clearing condition, the optimal pricing condition, and the Nash wage expression for r firms, Appendix A.5 shows that we can write the steady-state real marginal cost of r firms as[16]

$$mc_r = \frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi}{(1-\nu_n)q(\theta_r)}\right]}{\frac{N_r \widetilde{y}_r}{\widetilde{a}_r n_r}} + \left(\tau(1-\mu) + \gamma\mu^{\eta}\right). \tag{22}$$

where recall that $\widetilde{y}_r$ denotes average output of an r firm, $N_r\widetilde{y}_r$ is total r-firm output, $N_r\widetilde{y}_r/n_r$ is aggregate r-firm labor productivity, and therefore $N_r\widetilde{y}_r/\widetilde{a}_r n_r$ is aggregate r-firm labor productivity adjusted by firms' average idiosyncratic productivity (that is, r labor productivity in efficiency units). In turn, the term $\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi}{(1-\nu_n)q(\theta_r)}\right]$ embodies the effective cost of hiring an r worker and the term $(\tau(1-\mu) + \gamma\mu^{\eta})$ captures the net contribution of carbon taxes and abatement expenditures to the marginal cost of r firms. Another way to inter-

[16] Note that in the presence of pollution externalities, the steady-state market clearing condition for r firms in the absence of physical capital is $D(x)n_r = N_r\widetilde{y}_r/\widetilde{a}_r$.

pret the first term on the right hand side of expression (22) is as the *total* effective cost of hiring workers $\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi}{(1-\nu_n)q(\theta_r)}\right]\widetilde{a}_r n_r$ (that is, the effective hiring cost times the number of workers inclusive of the firm's average idiosyncratic productivity, $\widetilde{a}_r n_r$) adjusted by total firm output $N_r\widetilde{y}_r$. Intuitively, all else equal, higher hiring costs per worker, higher carbon taxes τ, and a higher abatement rate μ all put upward pressure on the marginal cost. In contrast, greater labor productivity puts downward pressure on the marginal cost.

Analogously, the steady-state expression for the real marginal cost of g firms is

$$mc_g = \frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi}{(1-\nu_n)q(\theta_g)}\right]}{\frac{N_g\widetilde{y}_g}{\widetilde{a}_g n_g}}.$$

where the main difference with respect to the marginal cost of r firms is the absence of carbon taxes and abatement costs. Then, it is clear from the two expressions above that carbon taxes have a differential impact on firms' marginal costs depending on the technology they adopt.

For the purposes of understanding how carbon taxes affect the reallocation of resources between firm categories, what matters is not the marginal cost of a given category, but the marginal cost of r firms relative to the marginal cost of g firms. In particular, Appendix A.5 shows that we can write this relative marginal cost as

$$\frac{mc_r}{mc_g} = \Theta(a_g)\frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]}{q(\theta_r)}\right]n_r/\widetilde{y}_r}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]}{q(\theta_g)}\right]n_g/\widetilde{y}_g} + \Phi(a_g, N)\frac{(\tau(1-\mu)+\gamma\mu^\eta)}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi}{(1-\nu_n)q(\theta_g)}\right]n_g/\widetilde{y}_g}, \tag{23}$$

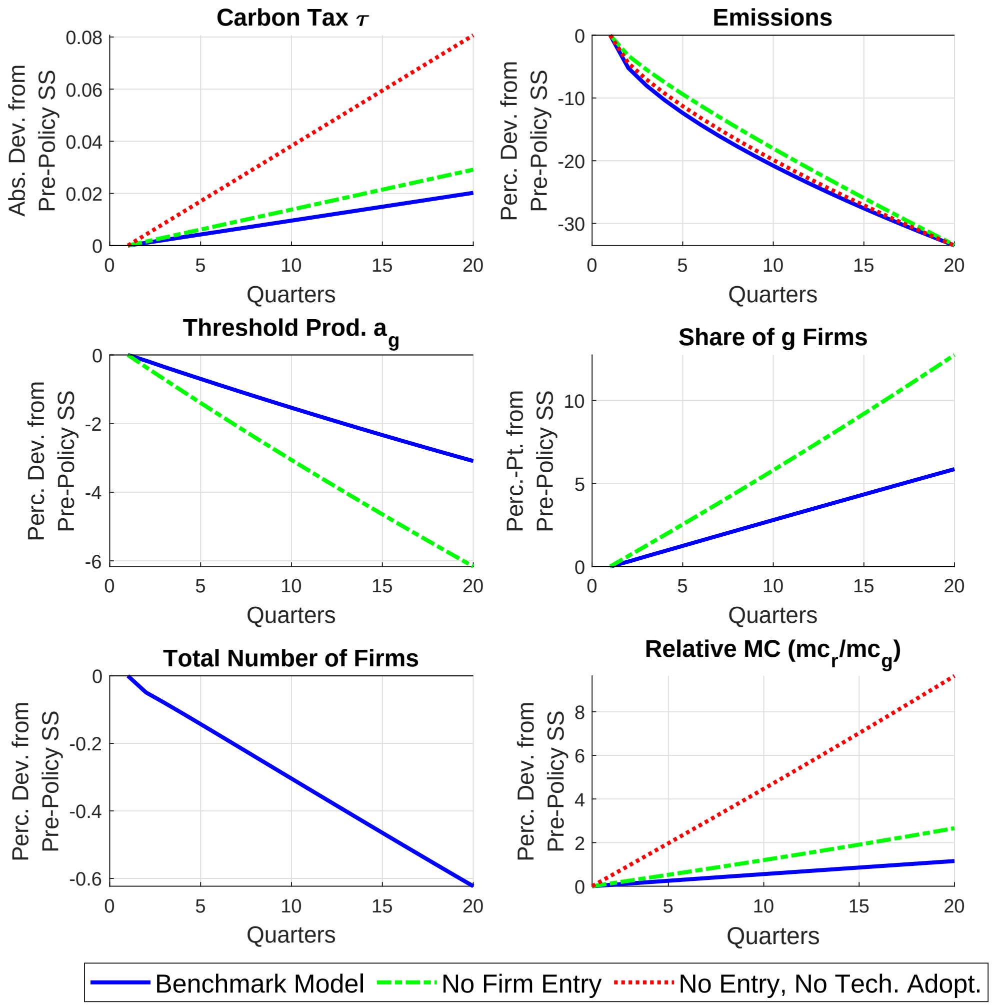
where $\partial\Theta(a_g)/\partial a_g < 0$, $\partial\Phi(a_g, N)/\partial N > 0$, and $\partial\Phi(a_g, N)/\partial a_g < 0$. Intuitively, the relative marginal cost is: decreasing in the ratio of g firms' cost of hiring workers based on their payroll relative to the firm's output, $\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi}{(1-\nu_n)q(\theta_g)}\right]n_g/\widetilde{y}_g$; increasing in the corresponding ratio for r firms; and increasing in both carbon taxes and the abatement rate. Critically, expression (23) shows how (1) the threshold idiosyncratic productivity level above which firms adopt the green technology, a_g, and (2) the total number of firms, N, shape the strength with which the ratio of labor costs to output, carbon taxes, and abatement affect the relative marginal cost.

To see this more clearly, Figure 3 plots the absolute increase in carbon taxes needed to achieve a 35-percent reduction in emissions after 5 years (relative to the pre-policy level of 0), the change in emissions, as well as the resulting changes in the idiosyncratic productivity threshold $a_{g,t}$,the total number of firms, and the relative marginal cost $(mc_{r,t}/mc_{g,t})$. Following our earlier analysis, the figure shows the benchmark model (solid blue line), the model without firm entry (dash-dotted green line), and the model with neither firm entry nor technology adoption margins (dotted red line). Of note, carbon taxes are expressed as a percentage of aggregate output. While it is not possible to translate these price increases directly into a price per ton of emissions, Figure 3 shows that the tax rate needed to reduce emissions by 35 percent is reduced by roughly three-quarters relative to a model with no firm entry and technology adoption.

Figure 3 shows how the reductions in a_g and N both contribute to limiting the change in carbon taxes needed to reduce emissions. In turn, these reductions feed into a smaller increase in firms' relative marginal cost as carbon taxes increase. Indeed, compared to the benchmark model, the ratio of marginal costs increases at a faster pace in the absence of firm entry and technology adoption, leading to a larger percent reduction in r-firm employment and output. Importantly, this takes place without a strong-enough positive response by g firms that offsets these reductions. The end result is the short-and long-term declines in consumption and output documented in Table 2 as well as in Figures 1 and 2.

A comparison of our benchmark model to the model without endogenous firm entry shows that the underlying driving force behind the positive effects of carbon taxes on consumption and output is firms' ability to respond to carbon taxes via technology adoption. The faster pace at which the share of g firms expands absent firm entry limits the increase in carbon taxes that is needed to reduce emissions, and the resulting reallocation of resources from r to g firms is able to more than offset the fall in employment and output among r firms. These responses explain the larger increase in output compared to the benchmark model shown in Table 2 and Figures 1 and 2. The same mechanisms are operational in the benchmark model, the only difference being that the reduction in the total number of firms as carbon taxes increase limits the quantitative extent to which the reallocation of resources from r firms to g firms bolsters employment and output.

Figure 3: Changes in Relative Marginal Cost and Carbon Tax (Gradual Reduction in Emissions via Carbon Taxes)



Taken together, our results make three important points regarding the qualitative and quantitative consequences of carbon taxes on labor markets and macroeconomic outcomes. First, we find that carbon taxes need not have adverse aggregate effects: once we account for two important margins of adjustment that firms can use—mainly the decision to enter and the decision to adopt greener technologies—greater carbon taxes can deliver positive (though quantitatively limited) consumption and output effects, even as carbon taxes have a net adverse effect on the total number of firms in the economy. These findings are consistent with recent empirical evidence on the macroeconomic effects of these taxes, and stand in contrast to existing quantitative studies in the literature predicting adverse effects on aggregate consumption and output. Second, firms' ability to change production technologies in response to carbon taxes plays a fundamental role in shaping the positive macroeconomic effects of these taxes and limiting any adverse effects that policy may have on unemployment. Third, firm-entry decisions play an important role in generating positive short- and medium-term consumption effects in response to carbon taxes (even if this is accompanied by a net reduction in the number of firms in the economy). This last point is particularly relevant for the assessing the short- and long-term welfare effects of these taxes.

3.2.4 Robustness Checks

Appendix A.6 presents results for alternative baseline calibrations of the benchmark model that assume: (1) a higher value for parameter k_p (which reduces the dispersion in idiosyncratic productivity draws); (2) a lower elasticity of labor force participation; (3), a higher job separation rate; and (4) a lower elasticity in total emissions-abatement costs to changes in abatement rates (see Appendix A.6 for more details). The results in Appendix A.6 confirm that our main conclusions remain unchanged.

4 Conclusion

The potential adverse effect on employment and aggregate economic activity from taxing carbon emissions is a key concern in policy circles. We explore the quantitative impact of a carbon tax on labor market and macroeconomic outcomes in a model with equilibrium unemployment and pollution externalities. Specifically, we consider a carbon tax that reduces emissions by 35 percent—a target consistent with the Biden Administration's new commitment under the Paris Agreement. In contrast to existing quantitative studies, our framework incorporates two key margins of adjustment to carbon taxes beyond emissions abatement by firms: firm entry and green-technology adoption decisions. Under a scheme where carbon-tax revenue is transferred lump-sum to households, we show that the tax bolsters labor income, consumption, output, and labor force participation, and has marginal adverse unemployment effects. In addition, the carbon tax does not entail short-term output or consumption costs as the economy gradually adjusts to higher carbon taxes. Moreover, we find that allowing for firm entry and green-technology adoption reduces the tax rate needed to achieve the desired reduction in emissions. This contributes to the tax's negligible impact on consumption and output in both the short and long term.

Further analysis of the model stresses the role of joint firm-entry and green-technology adoption decisions in shaping the net positive effects of a carbon tax on aggregate outcomes and the limited adverse effects on unemployment, with green-technology adoption—and what that implies about the policy-induced *endogenous* changes in the economy's underlying technological composition of production—being a central mechanism driving these outcomes. Critically, we show that abstracting from firm entry and technology adoption implies that greater carbon taxes have non-trivial adverse short- *and* long-term effects on labor income, consumption, and output, as well as comparatively larger adverse effects on unemployment. More broadly, our quantitative findings show that carbon-tax-induced reductions in emissions need not be accompanied by higher unemployment and lower consumption and output, a finding that reconciles recent empirical evidence on the macroeconomic effects of carbon taxes.

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A Appendix

A.1 Technology Adoption Indifference Condition and Marginal Costs

Individual firm profits from producing with the r technology are

$$\pi^y_{r,t}(a) = \left[\rho_{r,t}(a) - \frac{mc_{r,t}}{a}\right] y_{r,t}(a),$$

while individual firm profits from producing with the g technology are given by

$$\pi^y_{g,t}(a) = \left[\rho_{g,t}(a) - \frac{mc_{g,t}}{a}\right] y_{g,t}(a) - \varphi_g.$$

Taking into account the demand curve each firm in category $j \in \{g, r\}$ faces, $y_{j,t}(a) = (\rho_{j,t}(a))^{-\varepsilon} Y_t$, a given firm sets its optimal price such that

$$\rho_{j,t}(a) = \left(\frac{\varepsilon}{\varepsilon - 1}\right) \frac{mc_{j,t}}{a}.$$

Then, using this last expression along the optimal demand function, individual firm profits for a given firm in category r can be written as

$$\begin{aligned}
\pi^y_{r,t}(a) &= \left[\rho_{r,t}(a) - \frac{mc_{r,t}}{a}\right] (\rho_{r,t}(a))^{-\varepsilon} Y_t \\
&= \left[\left(\frac{\varepsilon}{\varepsilon - 1}\right) \frac{mc_{r,t}}{a} - \frac{mc_{r,t}}{a}\right] \left(\left(\frac{\varepsilon}{\varepsilon - 1}\right) \frac{mc_{r,t}}{a}\right)^{-\varepsilon} Y_t \\
&= \left(\frac{1}{\varepsilon - 1}\right) \frac{mc_{r,t}}{a} \left(\left(\frac{\varepsilon}{\varepsilon - 1}\right) \frac{mc_{r,t}}{a}\right)^{-\varepsilon} Y_t \\
&= \left[\left(\frac{1}{\varepsilon - 1}\right) \left(\frac{\varepsilon}{\varepsilon - 1}\right)^{-\varepsilon} Y_t\right] \left(\frac{mc_{r,t}}{a}\right)^{1-\varepsilon} \\
&= B_t \left(\frac{a}{mc_{r,t}}\right)^{\varepsilon - 1},
\end{aligned}$$

where $B_t > 0$. Following analogous steps, we have

$$\pi^y_{g,t}(a) = B_t \left(\frac{a}{mc_{g,t}}\right)^{\varepsilon-1} - f_g.$$

Now, denote by $a_{g,t}$ the threshold idiosyncratic productivity level such that a firm is indifferent between production technologies:

$$\pi^y_{r,t}(a_{g,t}) = \pi^y_{g,t}(a_{g,t}).$$

This can be rewritten as

$$B_t \left(\frac{a_{g,t}}{mc_{r,t}}\right)^{\varepsilon-1} = B_t \left(\frac{a_{g,t}}{mc_{g,t}}\right)^{\varepsilon-1} - f_g.$$

Thus, if $f_g > 0$, it must be that

$$\left(\frac{a_{g,t}}{mc_{g,t}}\right)^{\varepsilon-1} > \left(\frac{a_{g,t}}{mc_{r,t}}\right)^{\varepsilon-1},$$

or

$$mc_{r,t} > mc_{g,t}.$$

This makes intuitive sense since firms would never adopt the green technology and pay the fixed cost of doing so unless there is a benefit (here, in the form of lower marginal costs of production).

Now consider the slope of the individual-firm profit function in category $j \in \{g, r\}$ with respect to idiosyncratic productivity a:

$$\frac{\partial \pi^y_{j,t}}{\partial a} = B_t (\varepsilon - 1) \left(\frac{1}{mc_{j,t}}\right)^{\varepsilon-1} a^{\varepsilon-2}.$$

Given the result about marginal cost above, at any given value of a, we have

$$\frac{\partial \pi^y_{g,t}}{\partial a} > \frac{\partial \pi^y_{r,t}}{\partial a}.$$

A.2 Value Functions: Labor Market

Denote by $\mathbf{W}_{j,t}$ the *net* value to the household of having a worker employed in the production of j intermediate goods for $j \in \{g, r\}$. It is easy to show that

$$\mathbf{W}_{j,t} = \frac{\mathbf{h}'(lfp_{j,t}) - \chi}{f(\theta_{j,t})\mathbf{u}'(c_t)}, \tag{24}$$

for $j \in \{g, r\}$ (see Arseneau and Chugh, 2012). Analogously, denote by $\mathbf{J}_{g,t}$ and $\mathbf{J}_{t,t}$ the net values to intermediate-goods firms of having workers employed in the production of g and r intermediate goods. These values are given by

$$\mathbf{J}_{g,t} = D(x_t)mc_{g,t}F_{n_{g,t}} - w_{g,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\mathbf{J}_{g,t+1}, \tag{25}$$

and

$$\mathbf{J}_{r,t} = D(x_t)mc_{r,t}H_{n_r,t} - \tau_t e_{n_r,t} - \Gamma_{n_r,t} - w_{r,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\mathbf{J}_{r,t+1}. \tag{26}$$

Then, the Nash wage for employment category $j \in \{g, r\}$ is implicitly given by

$$\mathbf{W}_{j,t} = \left(\frac{\nu_n}{1-\nu_n}\right)\mathbf{J}_{j,t}, \tag{27}$$

where $0 < \nu_n < 1$ is the bargaining power of workers.

A.3 Data-Consistent vs. Model-Consistent Variables

Recall that the aggregate price level is given by $P_t = \left(\int_{\omega\in\Omega} p_t(\omega)^{1-\varepsilon} d\omega\right)^{\frac{1}{1-\varepsilon}}$. In a symmetric equilibrium, the aggregate price can be written as

$$P_t = \left[G(a_{g,t})N_t\widetilde{\rho}_{r,t} + (1 - G(a_{g,t}))N_t\widetilde{\rho}_{g,t}\right]^{\frac{1}{1-\varepsilon}}, \tag{28}$$

or

$$P_t = N_t^{\frac{1}{1-\varepsilon}}\left[G(a_{g,t})\widetilde{\rho}_{r,t} + (1 - G(a_{g,t}))\widetilde{\rho}_{g,t}\right]^{\frac{1}{1-\varepsilon}}. \tag{29}$$

where recall that the average real prices associated with g and r firms are $\widetilde{\rho}_{g,t} \equiv \rho_{g,t}(\widetilde{a}_{g,t})$ and $\widetilde{\rho}_{r,t} \equiv \rho_{r,t}(\widetilde{a}_{r,t})$. Then, we can write

$$P_t = N_t^{\frac{1}{1-\varepsilon}} \widetilde{P}_t, \tag{30}$$

where $\widetilde{P}_t = [G(a_{g,t})\widetilde{\rho}_{r,t} + (1 - G(a_{g,t}))\widetilde{\rho}_{g,t}]^{\frac{1}{1-\varepsilon}}$. Finally, following GM, the data-consistent version of a real model variable λ_t^m is given by $\lambda_t^d = \lambda_t^m \frac{P_t}{\widetilde{P}_t} = \lambda_t^m (N_t)^{\frac{1}{1-\varepsilon}}$.

A.4 Equilibrium Conditions: Benchmark Model

Taking the exogenous process e_t^{row} as given, the allocations and prices $\{\widetilde{\pi}_{r,t}^y, \widetilde{\pi}_{g,t}^y, \widetilde{\rho}_{r,t}, \widetilde{\rho}_{g,t}, mc_{r,t}\}$, $\{mc_{g,t}, \widetilde{a}_{r,t}, \widetilde{a}_{g,t}, a_{g,t}, \widetilde{\pi}_t^y, N_{g,t}, \Gamma_t, e_t, \mu_t, v_{r,t}, v_{g,t}, n_{r,t}, n_{g,t}, N_t, N_{e,t}, s_{r,t}, s_{g,t}, w_{r,t}, w_{g,t}, \widetilde{y}_{r,t}, \widetilde{y}_{g,t}\}$, and $\{x_t, c_t, Y_t, N_{r,t}, k_t, k_{g,t}, k_{r,t}\}$ satisfy:

$$\widetilde{\pi}_{r,t}^y = \left[\widetilde{\rho}_{r,t} - \frac{mc_{r,t}}{\widetilde{a}_{r,t}}\right] \widetilde{y}_{r,t}, \tag{31}$$

$$\widetilde{\pi}_{g,t}^y = \left[\widetilde{\rho}_{g,t} - \frac{mc_{g,t}}{\widetilde{a}_{g,t}}\right] \widetilde{y}_{g,t} - \varphi_g, \tag{32}$$

$$1 = N_{r,t} \left(\widetilde{\rho}_{r,t}\right)^{1-\varepsilon} + N_{g,t} \left(\widetilde{\rho}_{g,t}\right)^{1-\varepsilon}, \tag{33}$$

$$\widetilde{\rho}_{g,t} = \frac{\varepsilon}{\varepsilon - 1} \frac{mc_{g,t}}{\widetilde{a}_{g,t}}, \tag{34}$$

$$\widetilde{\rho}_{r,t} = \frac{\varepsilon}{\varepsilon - 1} \frac{mc_{r,t}}{\widetilde{a}_{r,t}}, \tag{35}$$

$$\widetilde{a}_{g,t} = \left(\frac{k_p}{k_p - (\varepsilon - 1)}\right)^{\frac{1}{\varepsilon-1}} a_{g,t}, \tag{36}$$

$$\widetilde{a}_{r,t} = \widetilde{a}_{g,t} \left(\frac{a_{g,t}^{k_p-(\varepsilon-1)} - a_{min}^{k_p-(\varepsilon-1)}}{a_{g,t}^{k_p} - a_{min}^{k_p}}\right)^{\frac{1}{\varepsilon-1}} a_{min}, \tag{37}$$

$$N_{g,t} = \left(\frac{a_{min}}{a_{g,t}}\right)^{k_p} N_t, \tag{38}$$

$$N_{r,t} = N_t - N_{g,t}, \tag{39}$$

$$\widetilde{\pi}_t^y = \frac{N_{r,t}}{N_t}\widetilde{\pi}_{r,t}^y + \frac{N_{g,t}}{N_t}\widetilde{\pi}_{g,t}^y, \tag{40}$$

$$\pi^y_{g,t}(a_{g,t}) = \pi^y_{r,t}(a_{g,t}), \tag{41}$$

$$\Gamma_t = \gamma\mu_t^\eta D(x_t)H(n_{r,t}, k_{r,t}), \tag{42}$$

$$e_t = (1-\mu_t)\left[D(x_t)H(n_{r,t}, k_{r,t})\right]^{1-\nu}, \tag{43}$$

$$\tau_t\left[D(x_t)H(n_{r,t}, k_{r,t})\right]^{-\nu} = \gamma\eta\mu_t^{\eta-1}, \tag{44}$$

$$\frac{\psi_r}{q(\theta_{r,t})} = \begin{bmatrix} D(x_t)mc_{r,t}H_{n_r,t} - \tau_t e_{n_r,t} \\ -\Gamma_{n_r,t} - w_{r,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\frac{\psi_r}{q(\theta_{r,t+1})} \end{bmatrix}, \tag{45}$$

$$\frac{\psi_g}{q(\theta_{g,t})} = \left[D(x_t)mc_{g,t}F_{n_g,t} - w_{g,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\frac{\psi_g}{q(\theta_{g,t+1})}\right], \tag{46}$$

$$n_{r,t} = (1-\varrho)n_{r,t-1} + s_{r,t}f(\theta_{r,t}), \tag{47}$$

$$n_{g,t} = (1-\varrho)n_{g,t-1} + s_{g,t}f(\theta_{g,t}), \tag{48}$$

$$N_{t+1} = (1-\delta)\left[N_t + N_{e,t}\right], \tag{49}$$

$$\varphi_e = (1-\delta)\mathbb{E}_t\Xi_{t+1|t}\left[\widetilde{\pi}^y_{t+1} + \varphi_e\right], \tag{50}$$

$$\left(\frac{\mathbf{h}_{lfp_{r,t}} - \chi\mathbf{u}'(c_t)}{f(\theta_{r,t})\mathbf{u}'(c_t)}\right) = w_{r,t} - \chi + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\left[\left(\frac{\mathbf{h}_{lfp_{r,t+1}} - \chi\mathbf{u}'(c_{t+1})}{f(\theta_{r,t+1})\mathbf{u}'(c_{t+1})}\right)\right], \tag{51}$$

$$\left(\frac{\mathbf{h}_{lfp_{g,t}} - \chi\mathbf{u}'(c_t)}{f(\theta_{g,t})\mathbf{u}'(c_t)}\right) = w_{g,t} - \chi + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\left[\left(\frac{\mathbf{h}_{lfp_{g,t+1}} - \chi\mathbf{u}'(c_{t+1})}{f(\theta_{g,t+1})\mathbf{u}'(c_{t+1})}\right)\right], \tag{52}$$

$$w_{r,t} = \nu_n\left[D(x_t)mc_{r,t}H_{n_{r,t}} - \Gamma_{n_r,t} - \tau_t e_{n_r,t} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\psi_r\theta_{r,t+1}\right] + (1-\nu_n)\chi, \tag{53}$$

$$w_{g,t} = \nu_n\left[D(x_t)mc_{g,t}F_{n_{g,t}} + (1-\varrho)\mathbb{E}_t\Xi_{t+1|t}\psi_g\theta_{g,t+1}\right] + (1-\nu_n)\chi, \tag{54}$$

$$D(x_t)H(n_{r,t}, k_{r,t}) = N_{r,t}\left(\frac{\widetilde{y}_{r,t}}{\widetilde{a}_{r,t}}\right), \tag{55}$$

$$D(x_t)F(n_{g,t}, k_{g,t}) = N_{g,t}\left(\frac{\widetilde{y}_{g,t}}{\widetilde{a}_{g,t}}\right), \tag{56}$$

$$\widetilde{y}_{r,t} = \left(\widetilde{\rho}_{r,t}\right)^{-\varepsilon}Y_t, \tag{57}$$

$$\widetilde{y}_{g,t} = \left(\widetilde{\rho}_{g,t}\right)^{-\varepsilon}Y_t, \tag{58}$$

$$x_t = \rho_x x_{t-1} + e_t + e_t^{row}, \tag{59}$$

$$k_t = k_{g,t} + k_{r,t}, \tag{60}$$

$$1 = \mathbb{E}_t \Xi_{t+1|t} \left[D(x_{t+1}) mc_{r,t+1} H_{k_r,t+1} - \tau_{t+1} e_{k_r,t+1} - \Gamma_{k_r,t+1} + (1-\delta) \right], \tag{61}$$

$$1 = \mathbb{E}_t \Xi_{t+1|t} \left[D(x_{t+1}) mc_{g,t+1} F_{k_g,t+1} + (1-\delta) \right], \tag{62}$$

$$Y_t = c_t + \psi_r v_{r,t} + \psi_g v_{g,t} + \varphi_e N_{e,t} + \varphi_g N_{g,t} + k_{t+1} - (1-\delta) k_t + \Gamma_t, \tag{63}$$

where all other relevant variables in these conditions are defined in the main text.

A.5 Steady State Marginal Cost of r Firms

Consider a version of the benchmark model without capital, with an elasticity of emissions with respect to r-firm output of 1, and with zero unemployment benefits. This implies that $H(n_{r,t}) = n_{r,t}$, $e_t = (1-\mu_t)\left[D(x_t)n_{r,t}\right]$, $\Gamma_t = \gamma\mu_t^{\eta}\left[D(x_t)n_{r,t}\right]$, and $\chi = 0$. Then, the steady-state versions of the job-creation condition and the Nash wage, for r firms can be written as

$$\frac{\psi_r}{q(\theta_r)} = \left[D(x)mc_r - \tau(1-\mu)D(x) - \gamma\mu^{\eta}D(x) - w_r + (1-\varrho)\beta\frac{\psi_r}{q(\theta_r)}\right], \tag{64}$$

and

$$w_r = \nu_n\left[D(x)mc_r - \tau(1-\mu)D(x) - \gamma\mu^{\eta}D(x) + (1-\varrho)\beta\psi_r\theta_r\right], \tag{65}$$

where recall that the steady-state market-clearing condition for r-firm output is

$$D(x)n_r = \frac{N_r\widetilde{y}_r}{\widetilde{a}_r}. \tag{66}$$

Combining these three conditions, we obtain

$$\frac{\left[1-(1-\varrho)\beta\right]\psi_r}{q(\theta_r)} = \left[(1-\nu_n)\left(mc_r - \tau(1-\mu) - \gamma\mu^{\eta}\right)\left(\frac{N_r\widetilde{y}_r}{\widetilde{a}_r n_r}\right) - \nu_n(1-\varrho)\beta\psi_r\theta_r\right]. \tag{67}$$

Solving for mc_r,we have

$$mc_r = \frac{\frac{[1-(1-\varrho)\beta]\psi_r}{q(\theta_r)} - \nu_n(1-\varrho)\beta\psi_r\theta_r + (1-\nu_n)\left(\tau(1-\mu) + \gamma\mu^{\eta}\right)\left(\frac{N_r\widetilde{y}_r}{\widetilde{a}_r n_r}\right)}{(1-\nu_n)\left(\frac{N_r\widetilde{y}_r}{\widetilde{a}_r n_r}\right)}. \tag{68}$$

Rearranging terms, we have

$$mc_r = \frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi_r}{(1-\nu_n)q(\theta_r)}\right]}{\left(\frac{N_r\widetilde{y}_r}{\widetilde{a}_r n_r}\right)} + \left(\tau(1-\mu) + \gamma\mu^{\eta}\right). \tag{69}$$

Following similar steps, we can write the steady-state expression for the marginal cost of g firms as

$$mc_g = \frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi_g}{(1-\nu_n)q(\theta_g)}\right]}{\left(\frac{N_g\widetilde{y}_g}{\widetilde{a}_g n_g}\right)}. \tag{70}$$

Then, taking the ratio of the marginal cost of r firms to the marginal cost of g firms, we can write

$$\frac{mc_r}{mc_g} = \left(\frac{\widetilde{a}_r}{\widetilde{a}_g}\right)\left(\frac{N_g}{N_r}\right)\frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi_r}{q(\theta_r)}\right]\left(\frac{\widetilde{y}_g}{n_g}\right)}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi_g}{q(\theta_g)}\right]\left(\frac{\widetilde{y}_r}{n_r}\right)} + \frac{\left(\tau(1-\mu)+\gamma\mu^{\eta}\right)(1-\nu_n)\left(\frac{N_g\widetilde{y}_g}{\widetilde{a}_g n_g}\right)}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi_g}{q(\theta_g)}\right]}. \quad (71)$$

Now recall that in steady state, we have

$$\widetilde{a}_g = \left(\frac{k_p}{k_p-(\varepsilon-1)}\right)^{\frac{1}{\varepsilon-1}} a_g, \quad (72)$$

and

$$\widetilde{a}_r = \widetilde{a}_g \left(\frac{a_g^{k_p-(\varepsilon-1)} - a_{min}^{k_p-(\varepsilon-1)}}{a_g^{k_p} - a_{min}^{k_p}}\right)^{\frac{1}{\varepsilon-1}} a_{min}. \quad (73)$$

Assuming $a_{min} = 1$ without loss of generality, we can write

$$\frac{\widetilde{a}_r}{\widetilde{a}_g} = \left(\frac{k_p}{k_p-(\varepsilon-1)}\right)^{\frac{1}{\varepsilon-1}} \left(\frac{a_g^{k_p} - a_g^{\varepsilon-1}}{a_g^{k_p}-1}\right)^{\frac{1}{\varepsilon-1}}. \quad (74)$$

At the same time, under $a_{min} = 1$, we have $N_g = \left(\frac{1}{a_g}\right)^{k_p} N$ and $N_r = \left[1-\left(\frac{1}{a_g}\right)^{k_p}\right] N$, so that

$$\frac{N_g}{N_r} = \frac{\left(\frac{1}{a_g}\right)^{k_p}}{\left[1-\left(\frac{1}{a_g}\right)^{k_p}\right]} = \left(\frac{\left[1-\left(\frac{1}{a_g}\right)^{k_p}\right]}{\left(\frac{1}{a_g}\right)^{k_p}}\right)^{-1} = \frac{1}{\left(a_g^{k_p}-1\right)}. \quad (75)$$

Then, we can write

$$\frac{\widetilde{a}_r}{\widetilde{a}_g}\frac{N_g}{N_r} = \left(\frac{k_p}{k_p-(\varepsilon-1)}\right)^{\frac{1}{\varepsilon-1}} \left(\frac{a_g^{k_p} - a_g^{\varepsilon-1}}{\left(a_g^{k_p}-1\right)^{\varepsilon}}\right)^{\frac{1}{\varepsilon-1}} \equiv \Theta\left(a_g\right), \quad (76)$$

where we can show that $\Theta'\left(a_g\right) < 0$.

$$\frac{N_g}{\widetilde{a}_g} = \left(\frac{k_p}{k_p-(\varepsilon-1)}\right)^{\frac{1}{1-\varepsilon}} \left(a_g\right)^{-k_p-1} N = \Phi\left(a_g, N\right), \quad (77)$$

where $\Phi_N(a_g, N) > 0$ and $\Phi_{a_g}(a_g, N) < 0$.

Finally, we can write

$$\frac{mc_r}{mc_g} = \Theta(a_g) \frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi_r}{q(\theta_r)}\right] n_r/\widetilde{y}_r}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi_g}{q(\theta_g)}\right] n_g/\widetilde{y}_g} + \Phi(a_g, N) \frac{(\tau(1-\mu)+\gamma\mu^\eta)(1-\nu_n)}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi_g}{q(\theta_g)}\right] n_g/\widetilde{y}_g}, \quad (78)$$

where once again $\Theta'(a_g) < 0$, $\Phi_N(a_g, N) > 0$, and $\Phi_{a_g}(a_g, N) < 0$. If $\psi_g = \psi_r = \psi$ (per our baseline calibration), then this expression becomes

$$\frac{mc_r}{mc_g} = \Theta(a_g) \frac{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_r))]\psi}{q(\theta_r)}\right] n_r/\widetilde{y}_r}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi}{q(\theta_g)}\right] n_g/\widetilde{y}_g} + \Phi(a_g, N) \frac{(\tau(1-\mu)+\gamma\mu^\eta)(1-\nu_n)}{\left[\frac{[1-(1-\varrho)\beta(1-\nu_n f(\theta_g))]\psi}{q(\theta_g)}\right] n_g/\widetilde{y}_g}. \quad (79)$$

A.6 Robustness Analysis

Table A1 and Figures A1, A2, A3, and A4 below confirm that our main findings in the benchmark model remain unchanged under alternative baseline calibrations. In particular, we consider calibrations where: (1) k_p is higher ($k_p = 5.2$ vs. $k_p = 4.2$ in the benchmark calibration; this reduces the dispersion in productivity draws); (2) a lower elasticity of labor force participation ($\phi_n = 0.17$ per Chetty et al., 2013, vs. $\phi_n = 0.26$ per Chetty et al., 2013, as well, in the benchmark calibration); (3), the job separation rate is higher ($\varrho = 0.10$ as in Arseneau and Chugh, 2012, vs. $\varrho = 0.05$ in the benchmark calibration); and (4) the elasticity of emissions-abatement costs with respect to abatement rates is lower ($\eta = 2.2$ vs. $\eta = 2.8$ in the benchmark calibration).

Table A1: Steady State Changes in Response to Carbon Tax–Benchmark Model under Alternative Baseline Calibrations

Variable	**Benchmark Higher** k_p	**Benchmark Lower LFP Elasticity** ϕ_n	**Benchmark Job Sep. Rate** $\varrho = 0.10$	**Benchmark Lower** $\eta = 2.2$
	(1)	(2)	(3)	(4)
	Percent Change Rel. to Baseline	**Percent Change** Rel. to Baseline	**Percent Change** Rel. to Baseline	**Percent Change** Rel. to Baseline
Emissions e	-35	-35	-35	-35
Total Output	0.501	0.273	0.276	0.390
Consumption	0.325	0.156	0.171	0.221
Empl. r	-24.678	-18.525	-18.524	-25.956
Empl. g	6.166	4.596	4.599	6.481
Total Empl.	0.752	0.538	0.540	0.787
Real Wage r	0.359	0.114	0.120	0.153
Real Wage g	0.358	0.113	0.119	0.150
Firms N	-1.626	-1.244	-1.240	-1.803
g Firms N_g	14.206	13.985	13.991	20.145
	Percentage-Pt. Change Rel. to Baseline	**Percentage-Pt. Change** Rel. to Baseline	**Percentage-Pt. Change** Rel. to Baseline	**Percentage-Pt. Change** Rel. to Baseline
Unempl. Rate	0.050	0.047	0.053	0.068
LFP Rate	0.507	0.371	0.376	0.542
Abate. Rate μ	20.813	25.006	25.007	19.814
Share of g Firms (N_g/N)	8.544	6.417	6.418	9.814
Tax Rev./Output	0.143	0.179	0.179	0.238

Figure A1: Transitional Dynamics in Response to Carbon Tax–Benchmark Model, Calibration with Higher k_p

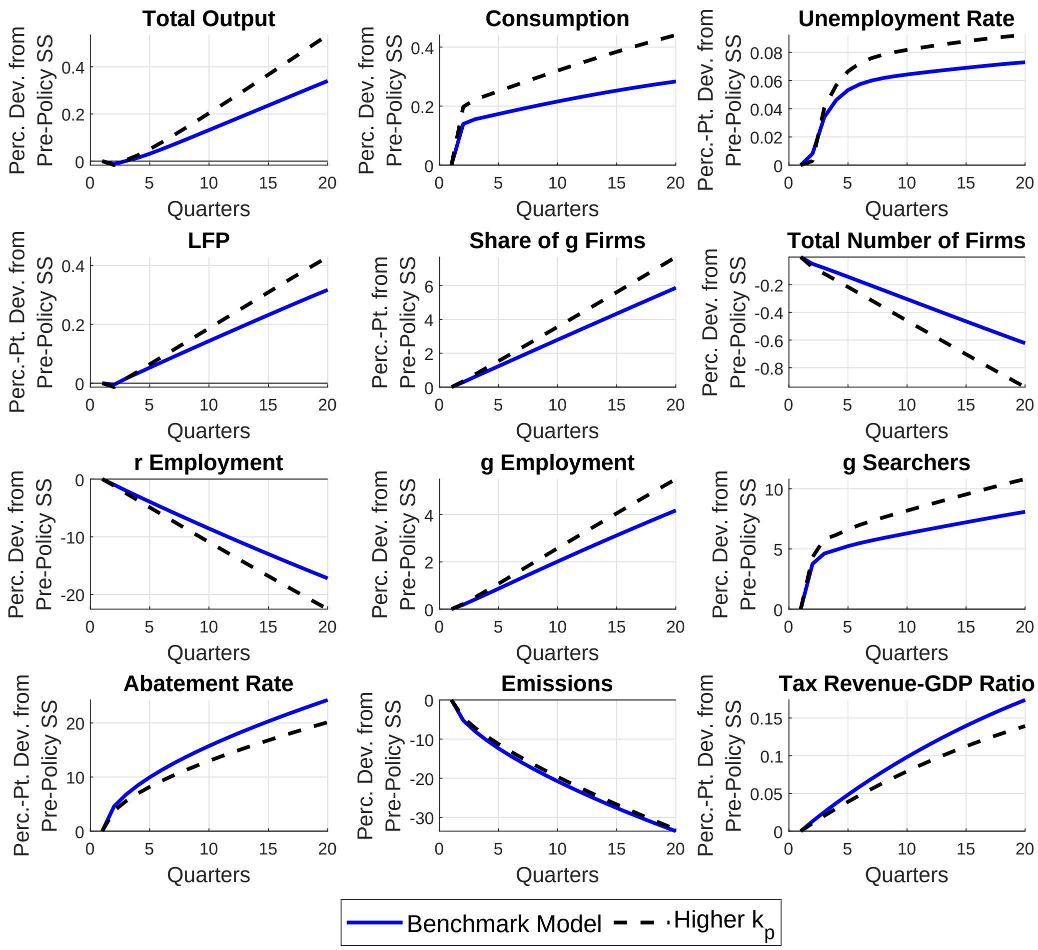


Figure A2: Transitional Dynamics in Response to Carbon Tax–Benchmark Model, Calibration with Lower Elasticity of Labor Force Participation

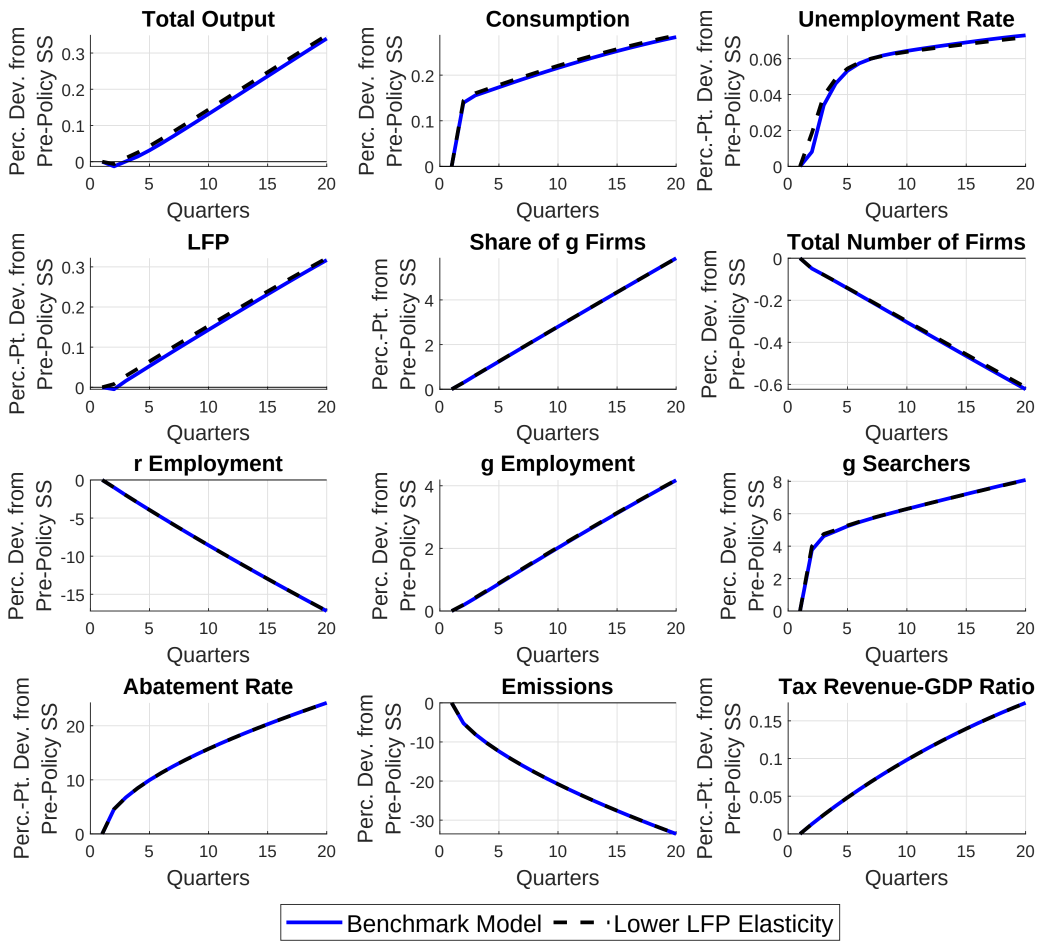


Figure A3: Transitional Dynamics in Response to Carbon Tax–Benchmark Model, Calibration with Higher Job Separation Rates

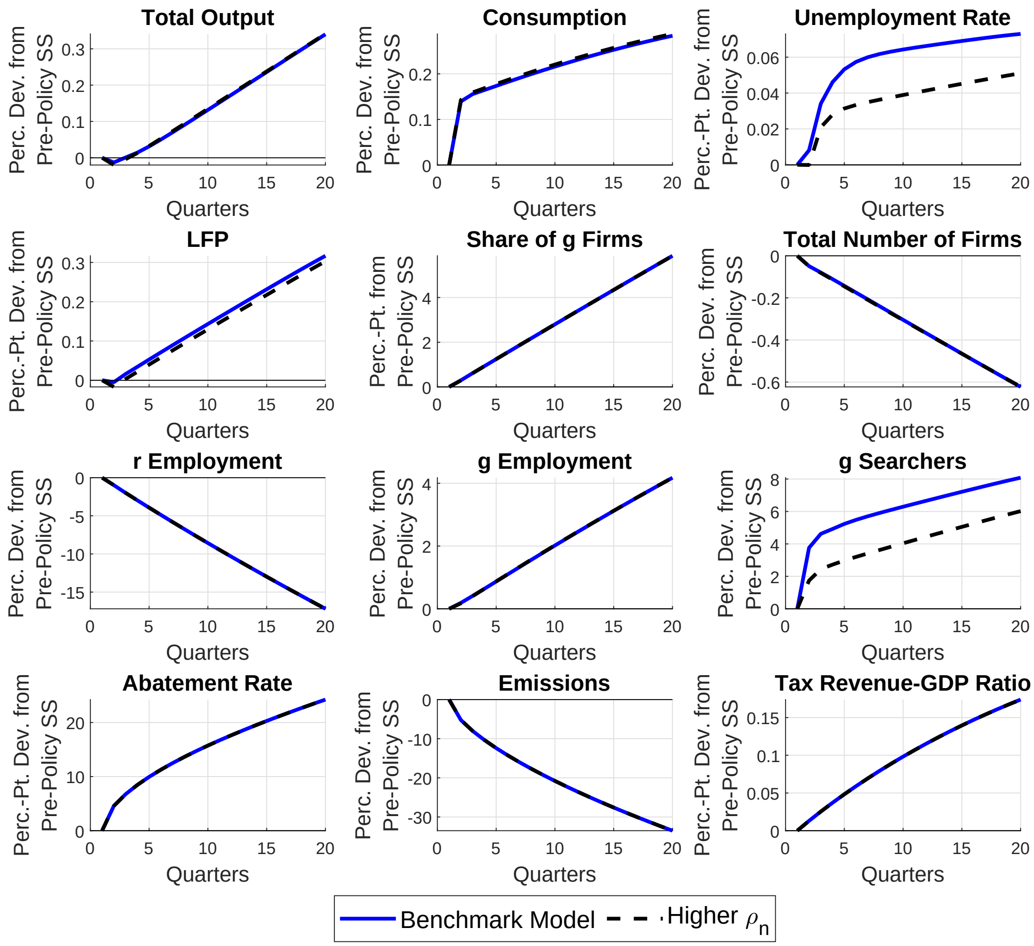
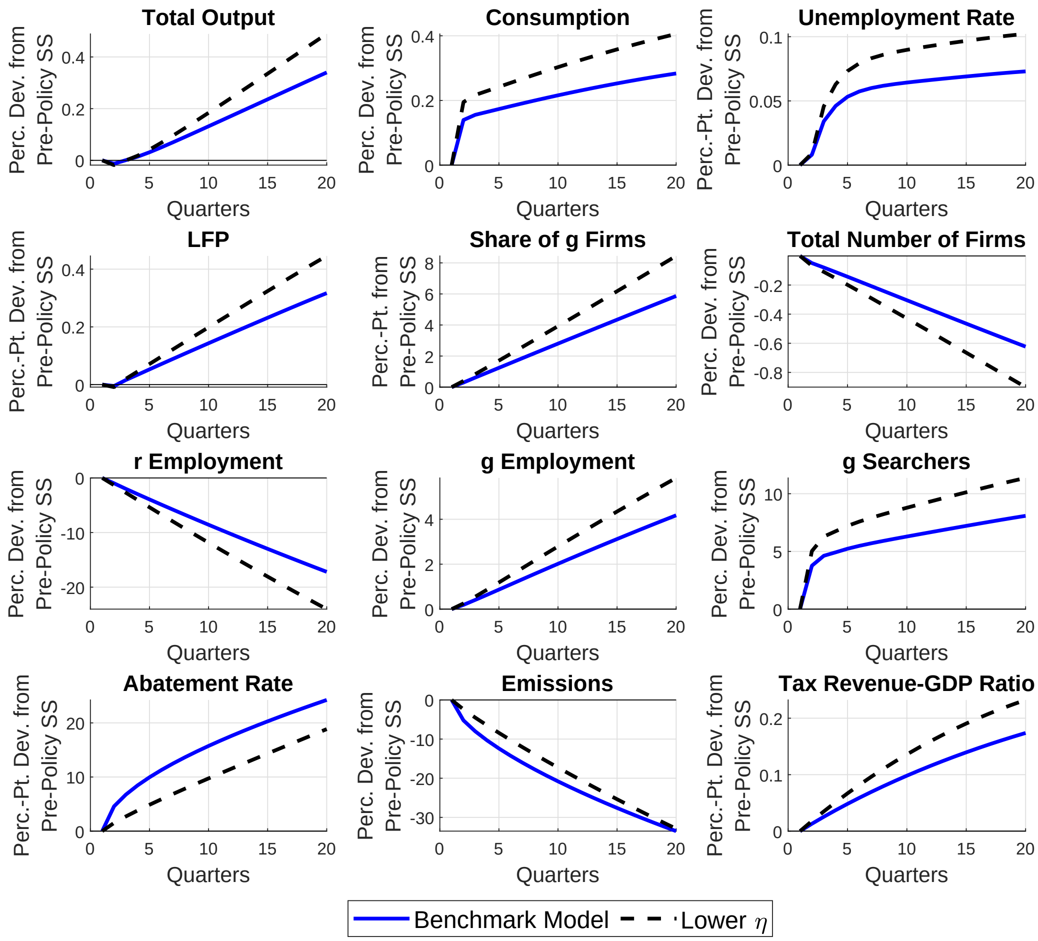


Figure A4: Transitional Dynamics in Response to Carbon Tax–Benchmark Model, Calibration with Lower Elasticity of Abatement Costs with Respect to Abatement Rate



A.7 Additional Model Results

Abatement Decisions Amid Firm Creation and Green-Technology Adoption Table A2 below compares the steady-state outcomes of the benchmark model to those of the same model shutting down the abatement margin. Recall that the latter can be interpreted as an *intensive* margin of adjustment to carbon taxes, whereas green-technology adoption can be interpreted as an *extensive* margin of adjustment. While the qualitative impact of carbon taxes remains unchanged without the possibility to abate emissions, the quantitative effects are noticeable: absent abatement, r employment would drop by more than 45 percent, the total number of firms would fall by 3.5 percent, and the unemployment rate would increase by 0.13 percentage points. The intuition behind these results is simple: without the ability to abate emissions, higher carbon tax rates are needed to hit the emission reduction target. These higher rates increase the marginal cost of r firms, which puts additional downward pressure on firm profits, further reducing the incentive to create firms compared to an environment where r firms can abate emissions. Surprisingly, despite the larger reduction in the number of firms, the increase in both consumption and output is larger compared to the benchmark model. These two outcomes are solely due to the sharper reallocation of resources towards g firms in the absence of abatement by r firms (note the larger expansion in the number and share of g firms compared to the benchmark model). All told, being able to abate emissions reduces the sensitivity of the economy to carbon taxes: it limits the consumption and output gains from resource reallocation but, importantly, also contributes to limiting the adverse effects of carbon taxes on unemployment.

Table A2: Steady State Changes in Response to Carbon Tax–Benchmark Model vs. Model without Abatement Margin

Variable	**Benchmark Model**	**Benchmark Model No Abatement**
	(1)	(2)
	Percent Change Rel. to Baseline	**Percent Change** Rel. to Baseline
Emissions e	-35	-35
Total Output	0.291	0.682
Consumption	0.174	0.340
Empl. r	-18.517	-46.001
Empl. g	4.611	11.535
Total Empl.	0.551	1.435
Real Wage r	0.118	0.317
Real Wage g	0.117	0.312
Firms (N)	-1.218	-3.576
g Firms (N_g)	14.019	38.515
	Percentage-Pt. Change Rel. to Baseline	**Percentage-Pt. Change** Rel. to Baseline
Unempl. Rate	0.046	0.126
LFP Rate	0.378	0.990
Abate. Rate μ	25.013	-
Share of g Firms (N_g/N)	6.419	18.165
Tax Rev./Output	0.179	0.394

Note: Values in blue denote beneficial changes (relative to the baseline economy of each model version) of select variables of interest whereas values in red denote adverse changes (relative to the baseline economy of each model version) of select variables of interest.

Alternative Values for Parameter k_p Recall that we assume that the idiosyncratic productivity of firms is drawn from a Pareto distribution $G(a) = \left[1 - (a_{\min}/a)^{k_p}\right]$ with shape parameter $k_p > \varepsilon - 1$. Following the macro literature on endogenous firm entry (Bilbiie, Ghironi, and Melitz, 2012), we choose $\varepsilon = 3.8$. In turn, as a baseline, we choose

$k_p = 4.2$ (for a similar value in a context of production offshoring decisions, see Zlate, 2016).

The value of k_p has direct implications on the average firm productivity differential between g and r firms. In particular, values of k_p smaller than $\varepsilon = 3.8$ deliver implausibly large productivity differentials. For example, setting $k_p = 3.4$ implies that average g-firm productivity is more than 50 percent greater than average r-firm productivity. In contrast, the larger is k_p relative to ε, the smaller—and more plausible—is the average firm productivity differential.[17] Importantly, the larger is the value of k_p relative to the value of ε, the smaller is the average firm productivity differential between g and r firms, and the larger are the positive effects of carbon taxes on real wages and output. As such, our baseline results can be seen as a lower bound on the positive effects of carbon taxes on labor market and macroeconomic outcomes.

[17] For example, a value of $k_p = 6$ implies that average g-firm productivity is 25 percent greater than average r-firm productivity, and a value of $k_p = 9$ implies that average g-firm productivity is 15 percent greater than average r-firm productivity.