GREEN POLICIES, AGGREGATE INVESTMENT DYNAMICS AND VINTAGE EFFECTS*

Giuseppe Fiori   Nora Traum

September 9, 2018

Abstract

This paper develops a neoclassical growth model with heterogeneous firms to study the effects of environmental policies. The model framework links the distribution of plants to an endogenous capital accumulation and technology adoption decision, making it the first to study both the *timing* of capital replacement and the endogenous movements in the plant distribution following environmental policy legislation. We demonstrate that the distribution of plants is central for the macroeconomic implications of a carbon tax. Short-run qualitative and quantitative responses to a carbon tax enactment vary depending upon whether or not plants vary in emission rates. Heterogeneous emission rates, a feature we show to be consistent with plant-level data, induce the economy's average energy efficiency to rise following a carbon tax and imply dynamics that differ from a representative firm model. Policies that initially exempt older establishments and alternative revenue-recycling scenarios alter the short and long run effects.

Keywords: energy policy, investment behavior, carbon tax
JEL Codes: E22, E62, H23, Q58

---

*Giuseppe Fiori: Department of Economics, Poole College of Management, North Carolina State University, Campus Box 8110, Raleigh, NC 27695-8110, United States (website: www.giuseppefiori.net and e-mail: gfiori@ncsu.edu); Nora Traum: HEC Montréal 3000, chemin de la Côte-Sainte-Catherine Montréal (Québec) Canada H3T 2A7 (website: www.hec.ca/en/profs/nora.traum.html and e-mail: nora.traum@hec.ca). First Version: February 15, 2015. We would like to thank Fanny Henriet, Laura Taylor, Roger von Haefen, Pietro Peretto and conference and seminar participants at the 2015 CEF Conference, Duke University's Triangle Dynamics Workshop, North Carolina State, SKEMA Business School, William & Mary, and Banque de France for helpful comments. Financial support from North Carolina State University's Sustainability Initiative Grant is gratefully acknowledged.

1 INTRODUCTION

Substantial differences exist within-industry in the characteristics of producers, e.g. the age of their capital stock, management, and productivity levels. A growing literature in macroeconomics incorporates heterogeneous firms into theoretical models, but the majority are silent as to how economic forces influence a producer's individual attributes and productivity. Yet policies often target certain characteristics of firms (e.g. special tax treatments, preferential contracts to specific producers, and policies aimed at the size or efficiency of producers), giving direct incentives for producers to adapt and change these attributes over time. The key contribution of this paper is to model the dynamic decision of producers to upgrade and replace old technologies with new ones following changes in taxation. When producers are taxed based on their specific attributes, a change in tax policy can alter their decisions to produce with certain technologies, which can have notable aggregate consequences.

To illustrate how heterogeneity in producers affects the aggregate implications of a policy directed at a firm characteristic, we focus on the effects of a tax on producer's emission rates, i.e. a carbon tax. This policy is particularly pertinent as substantial heterogeneity in energy and emissions exists within-industry in the U.S. manufacturing sector, implying the policy's aggregate effect depends on how the underlying distribution of firms respond to the policy. Empirical evidence suggests that heterogeneity in emissions is sizeable and exceeds the degree of heterogeneity in many other measures of productivity (see Lyubich et al., 2018). Moreover, several recent empirical works show that the cross-sectional dispersion in plant-level emission intensities correlates with differences in total factor productivity, management, and plant size.[1] We document that additionally a

---

[1] Shapiro and Walker (2018) find that U.S. establishments with higher total factor productivity have lower emission intensities. Bloom et al. (2010) find that better managed UK establishments have lower energy intensities and CO_2 emissions. Several studies have found that smaller plants have larger emissions inten-

negative relationship between the age of plant equipment and emission rates also exists.

This documented heterogeneity in emission rates implies two important considerations when a designing policy targeting emissions. First, a uniform tax has unequal tax incidence across plants, being more lenient or strict on different producers, depending on their emission rates. Second, this unequal tax incidence can create incentives for plants to change their productivity and energy efficiency over time, dynamically altering the within-industry distribution of energy and emissions. To account for this potential dynamic variation, this paper develops a general equilibrium framework that explicitly models the timing of firms' decisions to replace capital and adopt new technology in response to policy measures. Old and new technologies result in different emission levels and efficiencies of capital, labor and energy. The timing of upgrading technology is subject to a non-convex adjustment cost and is endogenously decided by plants. To do so, plants weigh the benefits of adopting a new technology or keeping their current one. Depending on the size of the fixed cost, some plants invest and upgrade while others postpone; thus, old and new technologies coexist in the economy by choice.

The response of a given plant to a tax on emissions depends on its current level of technology, which determines its energy efficiency. While some plants choose to invest and upgrade to a more efficient technology to reduce the burden of the tax, others delay adjustments, as taxing emissions makes energy more expensive, reducing the optimal size of the plant. Our model is the first to explicitly account for the endogenous evolution of the distribution of firms following environmental policy changes in a heterogeneous agent, general equilibrium framework. Our main result is to demonstrate that the aggregate implications of a carbon tax policy depend on the initial distribution of firms and quantify how the policy affects the timing of the decision to invest and upgrade.

---

sities within developing countries (see for instance Dasgupta et al. (2002) for air pollution in Mexico and Brazil and Qi et al. (2014) for water pollution in China).

As in the seminal work by Thomas (2002), state-dependent investment is modeled using a generalized (S,s) framework.[2] Firms combine physical capital, labor and energy to produce a homogenous good. Technological progress is exogenous, but technological productivity and energy efficiency are embodied in new capital goods, as in Fiori (2015). As the upgrading decision involves an investment choice, our theory shares many features that have been largely employed in state- of-the-art business cycle theories to reproduce investment behavior at the plant-level. The modelling of the fixed cost closely follows the seminal work of Khan and Thomas (2008) and Bachmann, Caballero and Engel (2013). Our innovation, key to study the effects of green taxes on technology adoption and production, is the introduction in a quantitative setup of an endogenous upgrading decision. Thus, the model delivers a time-varying distribution of establishments over both capital and technology.

We analyze a wide range of policy scenarios associated with the introduction of a carbon tax. The implications of a carbon tax on the capital replacement decision are a priori ambiguous. A carbon tax increases factor prices of producers. On the one hand, higher factor prices make investment in more energy efficient technology desirable. On the other hand, higher factor prices may reduce the size of producers, depressing investment incentives. We find that the cross-sectional distribution of plants is an important determinant of the short-run effects. When all establishments have the same emission rates, the contractionary effects of a carbon tax lead the number of investors and average energy efficiency in the economy to decline. In contrast, if producers vary in emission rates, a flat carbon tax has unequal tax incidence. In this case, a carbon tax provides stronger incentives for older establishments to invest, increasing the average energy efficiency and reducing the

---

[2] The approach is related to Caballero and Engel's (1999) generalized (S, s) model in its use of stochastic adjustment costs to simultaneously yield lumpy plant-level investment and smooth aggregates. Also related are Khan and Thomas (2003, 2008), Bachmann et al. (2013), and Bachmann and Bayer (2014), which employ state-dependent investment models to study business cycle properties of aggregate series.

average age of capital in the economy. Moreover, responses vary from those with a representative firm paradigm. The size of these effects depend upon the initial distribution of producers and the degree to which emission rates are heterogenous.

In practice, governments typically announce specific rules for which carbon tax revenues are employed.[3] For instance, British Columbia returns all carbon tax revenue through personal and business income tax cuts and low-income tax credits. Denmark returns part of the revenue through environmental subsidies. We quantify how the government's utilization of revenues from the carbon tax affects the dynamic evolution of aggregate variables. Towards this end, a rich set of fiscal instruments are incorporated into the model, including lump-sum tax/transfers, labor taxes, consumption taxes, and government spending. We find that offsetting carbon tax revenues with reductions in distortionary taxation is beneficial in the long run, but short run dynamics may vary depending on the manner in which the carbon policy is introduced.

As taxes are often politically unpopular, regulations frequently are considered instead. Many environmental regulations are vintage differentiated, "grandfathering" or exempting established firms from the regulation. The most cited example of such practice in the U.S. is the New Source Review Program from the Clean Air Act of 1970, which has been shown to have reduced investment and increased the age of capital of "grandfathered" plants.[4] To investigate this issue, we conduct a policy experiment in which older vintages are exempted initially from the tax policy. We find the number of investors decreases while the average age of capital increases following this grandfathering-style policy, consistent with empirical evidence.

This paper complements a large-scale global modeling effort to determine optimal carbon prices, as in Nordhaus (1994, 2008), Nordhaus and Boyer (2000), Hassler and Krusell

---

[3] Sandmo (1975) first suggested using Pigouvian taxes to offset distortionary taxation. The use of environmental tax revenues are also discussed in Goulder (1995), Goulder et al. (1999), and IMF (2002).

[4] See for instance Bushnell and Wolfram (2012), Heutel (2011), and Nelson et al. (1993).

(2012), and Krusell and Smith (2015). Optimal carbon taxes also are considered in Acemoglu et al. (forthcoming) and Golosov et al. (2014) and references therein. This study abstracts from the environmental benefits associated with policy options to focus analysis on new implications that arise from explicit accounting of the distribution of establishments. Acemoglu et al. (forthcoming) also study the timing of innovation in energy technology. Our work complements this analysis by studying the timing of adoption of new technology once it is available to current establishments.[5]

We build on a growing literature of the effects of environmental policies in quantitative general equilibrium models. Rausch et al. (2010) and Fullerton and Monti (2013) study distributional effects of green policies on households. Most closely related to our analysis are Shapiro and Walker (2018) and Bosetti and Maffezzoli (2013), which also examine the effects of green policies in heterogeneous agent economies. Shapiro and Walker (2018) use a Melitz-style model to examine the effects of environmental regulation. Bosetti and Maffezzoli (2013) use a standard incomplete markets model with idiosyncratic uncertainty to examine the distributional effects of a carbon tax on households. In contrast to these studies, our framework links the distribution of plants to an endogenous capital accumulation decision. Finally, our work is related to the partial equilibrium analysis of Heutel (2011), which studies an individual vintage plant's response to environmental regulation.

Our paper is also related to the large literature of vintage capital. A review of the literature can be found in Boucekkine et al. (2008). Unlike most of this literature, we fully characterize the dynamics of the model outside of the steady state.

Finally, our paper complements a literature examining how the distribution of heterogeneous firms can alter the a aggregate effects of a policy. Restuccia and Rogerson (2008) argue that policies can alter the allocation of resources across producers that have

---

[5] The analysis also is related to the Porter (1991) hypothesis, in that establishments can respond to a carbon tax by altering their productivity.

heterogeneous productivity. Miao and Wang (2014) show the aggregate implications of a corporate tax change depend on how many firms have recently made large capital adjustments. Our model provides a framework that can be adapted to study these alternative tax policies and assess how production inputs—including total factor productivity, investment, and energy—endogenously respond to policy measures.

The rest of the paper is organized as follows. Section 2 provides some evidence on the linkage between emission rates and plant age. Section 3 presents the model. Section 4 studies the effects of introducing a carbon tax and demonstrates how the effects of a carbon tax depend on the distribution of plants in the economy. Section 5 discusses the robustness of our results to various modeling assumptions, and section 6 concludes.

2 EMISSION RATES AND EQUIPMENT AGE

In this section we estimate an emissions function for U.S. electricity plants to quantify the elasticity of emissions with respect to age. We find this elasticity is significantly positive for almost all types of emissions and primary fuel inputs considered. This result is not new to the literature, see for instance Heutel (2011). We highlight its robustness and emphasize its importance for the effects of a carbon tax enactment in the next sections.

The data for power plants comes from two sources. First, the Energy Information Administration's EIA-860 survey contains information about every power plant in the U.S., including age, capacity, and some abatement choices for every generator of each plant. Second, the EPA's Emissions and Generation Resource Integrated Database (eGRID) provides emissions data and primary fuel sources for all power plants in the U.S. We use eGRID data for 2004, 2005, 2007, 2009, and 2010.[6] We estimate an emissions function at the plant level. To create a plant-level age, we take the weighted average of the age of each

---

[6] Data for 2006 and 2008 are not available.

plant's generators, where we use the summery capacity of each generator for weights.[7] Figure 1 provides a snapshot of this data by plotting the coal power plant's emission rates by age in 2010 and suggesting a negative relationship between the age of plant equipment and emissions exists.

To understand the relationship between emissions and the age of plant equipment, we estimate the following emissions function via OLS:

$$\ln emr_{it} = \alpha + \beta \ln age_{it} + X_{it} + \epsilon_{it}, \tag{1}$$

where *emr* is the plant's output emission rate (measured in pounds per megawatt), *age* is the weighted average of the plant generator's years online as of 2010, and X_{it} denotes controls for the type of primary fuel input and state and year fixed effects. We estimate this function for four distinct emissions: sulfur dioxide SO_2, nitrous oxide NO_x, carbon dioxide CO_2, and methane CH_4.

Table 1 reports the estimation results. We report results for plants with coal as the primary fuel input separately from alternative fuel inputs. Unreported state and year dummies, as well as controls for fuel input types, are included in all regressions to account for unobserved heterogeneity and time effects. In almost all cases, the elasticity of emissions with respect to age to significantly positive at the 1% significance level. The elasticity for sulfur dioxide with respect to age is the highest, estimated to be almost unitary for coal power plants (0.91). The elasticity for nitrous oxide also is quantitatively significant. Although the elasticity for carbon dioxide is much lower (0.11 and 0.06 for non-coal and coal plants), it is still significantly greater than zero.

In the next section, we develop a general equilibrium model that features a similar

---

[7] The Energy Information Administration has employed similar weights in its publications of electric power generators age. Our results are robust to alternative weighting using winter capacity of generators, an average of winter and summer capacity, or by a generator's net electricity generation (for cases where this information is reported).

emissions function for firms. The elasticity of emissions with respect to age is an important parameter in this model, as it determines the extent to which emissions rates vary with the firms' distribution since last upgrading their equipment.

3 THEORETICAL FRAMEWORK

To study the effects of green policies we develop a general equilibrium framework that explicitly models the timing of firms' decisions to replace old technologies with new ones. Old and new technologies results in different level of emissions and efficiency of capital, labor and energy. The timing of upgrading technology is subject to a non-convex adjustment cost and is endogenously decided by plants. Our framework builds on the investment literature that studies the role of plant-level non-convexity in a general equilibrium framework. Notable examples include Thomas (2002), Khan and Thomas (2008), and Bachmann et al. (2013). The key innovation in our setup consists of introducing the possibility for plants to upgrade their current technology. Plants weighs the benefits of adopting a new technology and keep the current one. Depending on the size of the fixed cost, some plants invest and upgrade while others postpone it: old and new technologies coexist in the economy. The burden of the carbon tax for a given plant depends, among other characteristics, on the current level of technology available to the firm that determines the mapping between energy usage and emissions. Taxing emissions shapes the economic incentive that determine the plant's optimal size and its decision to upgrade technology. Taxing emissions makes energy usage more expensive affecting the optimal size of the plant. At the same time, the tax increases the return on investing and upgrading to a more efficient technology because it reduces the burden of the tax. Our general equilibrium analysis studies these incentives.

3.1 PRODUCTION AT THE PLANT LEVEL

This subsection describes production and upgrading decision for each plant in the economy. There is a continuum of production units that produce an homogenous good using as inputs capital, labor, and energy. Labor and energy can be freely adjusted in each period, while upgrading technology and capital adjustment are subject to a fixed cost denominated in units of labor. These adjustment costs, denoted by ξ, are independently and identically distributed across establishments and across time with a known cumulative distribution of $G(\xi)$ and finite upper support B. The fixed cost is denominated in units of labor to ensure that plants cannot outgrow adjustment costs along the balanced growth path.

Output is produced by perfectly competitive plants via an increasing and concave production function F defined over capital (K), labor (L), energy (E) and the technology available to the firm (Z). As in Krusell and Smith (2015), F takes the form of a constant elasticity of substitution (CES) production function that aggregates energy E and a Cobb-Douglas composite consisting of capital K and labor L. The production function is given by

$$Y_{j,t} = \left[\omega^{\frac{1}{\epsilon}} \left(Z^{KL}_{j,t} K^{\gamma}_{j,t-1} L^{\nu}_{j,t}\right)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} (Z^{E}_{j,t} E_{j,t})^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} \; \forall j = 0...J, \tag{2}$$

where $\gamma + \nu < 1$, ϵ is the price elasticity of energy and $1-\omega$ is a quasi-share parameter for energy. The efficiency of inputs of production depends upon Z, the technology vintage acquired through adoption common to all the plants that have upgraded at a given time. By paying the adjustment cost, plants can adopt the latest technology and optimally choose their size. The subscript j denotes a production unit that has adopted the newest technology j periods ago. The leading vintage ($j = 0$) of technology and energy efficiency, $Z^{KL}_{0,t}$ and $Z^{E}_{0,t}$, both evolve deterministically with respective growth rates $\Theta_{Z^{KL}}$ and $\Theta_{Z^{E}}$. Subsequent vintages inherit the level of technology and energy efficiency from the last time of capital replacement: $Z^{KL}_{j,t} = Z^{KL}_{0,t-j}$ and $Z^{E}_{j,t} = Z^{E}_{0,t-j}$. Energy is imported from abroad at a given international price P_t^e.

In each period, a plant is defined by its vintage productivity Z, its predetermined stock of capital K, and its fixed cost associated with capital adjustment $\xi \in [0, \bar{\xi}]$, which is denominated in units of labor. In every period, the plant chooses its current level of employment and energy usage, production occurs; labor, energy and emission taxes are paid. We indicate with W the real wage and with P^e the real price of energy (acquired on the international market). The government levies a tax on emissions (EM) that are proportional to energy usage, but potentially vary with plant vintages: $EM_{j,t} = \Omega_j E_{j,t}$. The standard assumption in the literature is to assume units of emissions such that $\Omega_j = 1$ $\forall\, j$.

3.2 Energy Usage and Emissions

The empirical evidence presented in the previous section indicates that emission rates vary with equipment age. In light of this, we consider the case where Ω_j satisfies $\frac{\partial \Omega_j}{\partial j} > 0$, so that older plants, which also have lower levels of productivity, have higher emission rates.[8] Plants are subject to a carbon tax, τ_t^e, on their total emissions.

3.3 Upgrading Decision at the Plant Level

In each period, plants receive a current realization of the fixed adjustment cost. After observing this realization, plants decide whether to upgrade its vintage technology and choose the optimal size. If a plant decides to pay the fixed cost, ξW_t, in units of labor (where W_t denotes the real wage), in the following period it obtains vintage $Z_{0,t+1}^{KL}$, $Z_{0,t+1}^{E}$, and the optimal size $K_{0,t+1}$:

$$Z_{0,t+1}^{KL} = Z_{0,t}^{KL} \Theta_{Z_0^{KL}} \; \forall j = 0 \ldots J, \tag{3}$$

---

[8] Recent micro evidence suggests that emissions vary with other plant characteristics. Shapiro and Walker (2018) find that U.S. establishments with higher total factor productivity have lower emission intensities. Bloom et al. (2010) find that better managed UK establishments have lower energy intensities and CO_2 emissions. Several studies have found that smaller plants have larger emissions intensities within developing countries, see for instance Dasgupta et al. (2002) and Qi et al. (2014).

$$Z^E_{0,t+1} = Z^E_{0,t}\Theta_{Z^E_0} \; \forall j = 0...J, \tag{4}$$

$$K_{0,t+1} = (1 - \delta - \delta^s_j)K_{j,t} + I_{j,t} \; \forall j = 0...J, \tag{5}$$

where δ is the standard rate of depreciation of capital and δ^s_j captures the notion that when an investing plant upgrades its technology, part of its current, vintage capital stock may not be operable with the new technology. If an establishment stays inactive, its stock of capital next period is the depreciated current level of capital:

$$Z^{KL}_{j+1,t+1} = Z^{KL}_{j,t} \; \forall j = 0...J, \tag{6}$$

$$Z^E_{j+1,t+1} = Z^E_{j,t} \; \forall j = 0...J, \tag{7}$$

$$K_{j+1,t+1} = (1 - \delta)K_{j,t} \; \forall j = 0...J. \tag{8}$$

Each plant's current flow of profit is determined by its total revenues less wage payments, energy usage and emissions taxes, investment, and adjustment costs. Given diminishing returns, plants make profits that are rebated to households in lump-sum fashion.

3.4 PLANT AGGREGATION

All plants that choose to invest will inherit the leading vintage of technology and energy efficiency and face the same distribution of adjustment costs. As a result, they share the same expected stream of future marginal revenues for any given choice of future capital. Thus, investors obtain $Z^{KL}_{0,t+1}$ and $Z^E_{0,t+1}$ choose a common size with target capital $K_{0,t+1}$, and plants adjusting at a given time are identical immediately after investing. The cross-sectional distribution of establishments over capital and technology levels is therefore summarized by the distribution of plants across j, i.e. *time-since-adjustment*. Each vintage shares the same time since the last capital adjustment and has the same capital stock, productivity, and energy efficiency.

Because of the continuity in the support of the adjustment cost, the choice whether to adjust follows a reservation policy. Within each vintage, there exists a marginal plant whose draw of the fixed cost makes it is just worthwhile to invest, i.e. whose fixed cost implies the benefit and cost of investment are equal. All plants of the same group that draw costs at or below this group-specific threshold also invest, implying that the investing fraction for each group, $\alpha_{j,t}$, is retrievable from the fixed cost's cumulative density function (cdf).

At each date, the cross-sectional distribution of time-since-adjustment can also be represented using alternative dimensions of heterogeneity. The vectors $\mathbf{K}_t = \{K_{j,t}\}$, $\mathbf{Z}_t^{KL} = \{Z_{j,t}^{KL}\}$, and $\mathbf{Z}_t^{E} = \{Z_{j,t}^{E}\}$ summarize heterogeneity in capital holdings, technology, and energy efficiency. The fraction of plants associated with each group is given by the predetermined vector $\boldsymbol{\vartheta}_t = \{\vartheta_{j,t}\}$. Each $\vartheta_{j,t}$ describes the number of firms owning vintage j capital stock and technology. The evolution of the distribution is determined as follows. Let $\boldsymbol{\alpha}_t = \{\alpha_{j,t}\}$ denote the fraction of adjustment rates. The evolution of the distribution of plants $\boldsymbol{\vartheta}_{t+1}$ is determined by the following equations:

$$\vartheta_{0,t+1} = \sum_{j=0}^{J} \alpha_{j,t}\vartheta_{j,t}, \tag{9}$$

$$\vartheta_{j+1,t+1} = (1-\alpha_{j,t})\vartheta_{j,t} \;\; \forall j = 1,2...J. \tag{10}$$

The group of plants that have upgraded their technology in the current period is the weighted sum of adjusters in each group. If a plant decides not to adjust at date t, it becomes vintage $t+1$ in the subsequent period. The measure of efficiency in the economy is weighted average of the individual efficiency across plants. This implies that the level of aggregate efficiency is endogenously determined by the upgrading choice observed at the plant-level. The total stock of capital in the economy is the weighted sum of the stock of capital across plants.

3.5 HOUSEHOLDS

The economy features a continuum of identical households that have access to a complete set of state-contingent claims. As there is no heterogeneity across households, these assets are in zero net supply in equilibrium. Moreover, they own shares in the portfolio of plants and supply labor. The household values consumption and leisure and maximizes the intertemporal utility function

$$\sum_{t=0}^{\infty} \beta^t \left[\ln C_t - \psi \frac{L_t^{1+\eta}}{1+\eta} \right]. \tag{11}$$

Consumption is taxed at the rate τ^c, and financed by labor income, taxed at the rate τ^l, lump-sum transfers from the government, TR, and profits received from the plants, Π. The presence of alternative tax instruments allows us to study alternative revenue-recycling scheme following the increase in revenues determined by the introduction of the carbon tax. The household's flow budget constraint is given by

$$(1+\tau_t^c)C_t = (1-\tau_t^l)W_t L_t + TR_t + \Pi_t. \tag{12}$$

3.6 GOVERNMENT

The government's budget constraint is given by

$$G_t + TR_t = \tau_t^l W_t L_t + \tau_t^c C_t + \tau_t^e P_t^e M_t, \tag{13}$$

where G_t denotes government expenditure and M_t is aggregate emissions. Fiscal instruments are set exogenously. In our baseline experiments where the government legislates a carbon tax ($\tau^e > 0$), the lump-sum transfer TR_t is assumed to endogenously adjust to ensure equation (13) holds. In addition, we consider alternative "revenue-recycling" schemes where, following the carbon tax introduction, either the labor tax rate, consumption tax rate, or level of government expenditures adjusts to satisfy the government budget constraint.

3.7 AGGREGATE VARIABLES The cross-sectional distribution of $time - since - adjustment$ enters the state-space of the model and determines aggregate variables in the economy. Because the model does not admit an aggregate production function, total output, energy usage and emissions, and the capital stock are weighted sum of the respective plant-level variables:

$$Y_t = \sum_{j=0}^{J} \vartheta_{j,t} Y_{j,t}, \quad E_t = \sum_{j=0}^{J} \vartheta_{j,t} E_{j,t}, \quad M_t = \sum_{j=0}^{J} \vartheta_{j,t} \Omega_j E_{j,t}, \quad K_t = \sum_{j=0}^{J} \vartheta_{j,t} K_{j,t}.$$

Aggregate investment is determined by the weighted sum of plant-level investment, where the weights are given by the fraction of plants that decide to pay the fixed cost $(\vartheta_{j,t}\alpha_{j,t})$:

$$I_t = \sum_{j=0}^{J} \vartheta_{j,t} \, \alpha_{j,t} I_{j,t}.$$

Given the equilibrium heterogeneity in input efficiency Z^{KL} and Z^{E}, the cross-sectional distribution $\boldsymbol{\vartheta}$ determines the average productivity of the economy. Because of this, the level of average efficiency is endogenously determined by plants upgrading decisions.

The economy is subject to a set of aggregate constraints. Energy is imported from abroad at a given international price P^e_t, and its supply is perfectly elastic. Trade is balanced by assumption: energy imports are financed by final good exports.[9] Thus, the sum of household consumption, aggregate investment and the cost of energy cannot exceed total production:

$$C_t + G_t + I_t + P^e_t E_t \leq Y_t. \tag{14}$$

Total hours worked by the household must satisfy the weighted sum of employment in

---

[9] This modeling convention is standard and has a long history in the literature, see Hassler and Krusell (2012) for a recent example.

production and adjustment activities in each sector:

$$\sum_{j=0}^{J} \vartheta_{j,t}\, L_{j,t} + \sum_{j=0}^{J} \vartheta_{j,t}\, \Xi(\alpha_{j,t}) \leq L_t. \tag{15}$$

where the average adjustment cost for each group is defined as

$$\Xi(\alpha_{j,t}) = \int_0^{G^{-1}(\alpha_{j,t})} x dG(x). \tag{16}$$

3.8 TECHNOLOGY DYNAMICS

The level of input efficiency $Z^{KL}_{0,t}$ and $Z^{E}_{0,t}$ evolve deterministically over time at the rate $\Theta_{Z^{KL}_{0,t}}$ and $\Theta_{Z^{E}_{0,t}}$, respectively:

$$Z^{KL}_{j,t} = Z^{KL}_{0,t-j} = \frac{Z^{KL}_{0,t}}{\prod_{s=t-j}^{0} \Theta_{Z^{KL}_{0,s}}}, \tag{17}$$

$$Z^{E}_{j,t} = Z^{E}_{0,t-j} = \frac{Z^{E}_{0,t}}{\prod_{s=t-j}^{0} \Theta_{Z^{E}_{0,s}}}. \tag{18}$$

This implies that delaying upgrading technology increases the distance from the technological frontier. Due to the absence of empirical evidence that allow us to disentangle them, we assume that $Z^{KL}_{j,t} = Z^{E}_{j,t} = Z_{j,t}$, and interpret both efficiency measures as tied to the overall level of technological progress in the economy.[10] The aggregate variables of the economy inherit the deterministic trend in technology. A stationary representation of the model implies the following restrictions in the growth rate of individual variables. Along the balanced growth path, the following trends of aggregate variables are observed: $\Theta_{Y,t} = \Theta_{C,t} = \Theta_{G,t} = \Theta_{W,t} = \Theta_{K,t} = \Theta_{Z_0,t}^{\frac{1}{1-\gamma}}$, $\Theta_{E,t} = \Theta_{Z_0,t}^{\frac{\gamma}{1-\gamma}}$, $\Theta_{P^e,t} = \Theta_{Z_0,t}$. In the next subsection we report the key equations of the model in stationary form and we denote by lower case variables that are in deviation from their trend.

---

[10] Although a balanced-growth path requires that $Z^{E}_{j,t}$ be related to overall technological growth, $Z^{E}_{j,t}$ can feature its own technological component.

3.9 Stationary Equilibrium

The production function expressed in stationary form is:

$$y_{j,t} = \left[\omega^{\frac{1}{\epsilon}} \left(z_{j,t} \frac{k_{j,t-1}}{\Theta_K}^{\gamma} L_{j,t}^{\nu} \right)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} (z_{j,t} e_{j,t})^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} ; \forall j = 0...J. \tag{19}$$

A competitive equilibrium satisfies the following efficiency conditions derived from the profit optimization of each plant. We first discuss the optimality conditions for labor and energy, the inputs of production that can be freely adjusted every period. Each plant equates the cost of every input to its marginal product (denoted by MPL and MPE for labor and energy, respectively). Plant-level employment satisfies the static condition for labor, for $j = 0, ..., J$:

$$w_t = MPL = \nu(\omega y_{j,t})^{\frac{1}{\epsilon}} \left(\frac{1}{\Pi_{s=t-j}^{0} \Theta_{Z_0,s}} \right)^{\frac{(\epsilon-1)}{\epsilon}} \Theta_{K,t}^{-\frac{\gamma(\epsilon-1)}{\epsilon}} k_{j,t-1}^{\frac{\gamma(\epsilon-1)}{\epsilon}} L_{j,t}^{\frac{\nu(\epsilon-1)}{\epsilon}-1}. \tag{20}$$

Plant-level energy usage satisfies, for $j = 0, ..., J$:

$$p^e(1 + \tau_t^E \Omega_j) = MPE = \frac{1}{\Pi_{s=t-j}^{0} \Theta_{Z_0,s}} \left[\frac{(1-\omega) y_{j,t}}{\frac{e_{j,t}}{\Pi_{s=t-j}^{t} \Theta_{Z_0,s}}} \right]^{\frac{1}{\epsilon}}. \tag{21}$$

Despite plants face the same price of energy p^e, the *effective* price that determines the energy usage depends upon the mapping between energy usage and emissions. When Ω_j is increasing in j, the effective cost of energy increases with the plant's distance from the technological frontier. For a given value τ_t^E, plants with older technology face a steeper tax schedule. As a result, the introduction of a carbon tax reduces the size of a plant, if energy is an input of production that is less than perfectly substitutable by labor or capital. This is the familiar *static* effect of a tax.

The conditions for the optimal capital allocation states that the marginal cost of installing capital (which is one) equals the expected marginal value of installing an additional unit of capital:

$$\mu_{0,t} = 1, \tag{22}$$

which for each $j = 0, ..., J$ is defined by:

$$\mu_{j,t} = \mathbb{E}_t \left\{ \frac{\beta_{t,t+1}}{\Theta_{C,t+1}} \left[\begin{array}{c} \gamma(\omega y_{j,t+1})^{\frac{1}{\epsilon}} \left(\frac{1}{\Pi^{0}_{s=t+1-j} \Theta_{Z_0,s}} \right)^{\frac{(\epsilon-1)}{\epsilon}} \Theta_{K,t+1}^{-\frac{\gamma(\epsilon-1)}{\epsilon}} k_{j,t}^{\frac{\gamma(\epsilon-1)}{\epsilon}-1} L_{j,t+1}^{\frac{\nu(\epsilon-1)}{\epsilon}} \\ +(1-\delta-\delta^{s}_{j})\alpha_{j,t+1} + (1-\delta)(1-\alpha_{j,t+1})\mu_{j+1,t+1} \end{array} \right] \right\}. \tag{23}$$

The introduction of the carbon tax increases the marginal product of capital for a given value of k_j reducing the optimal size of the plant.

We now turn to characterize the upgrading decision of the plant that, in turn, determine the hazard rates $\boldsymbol{\alpha}$, and thus the cross-sectional distribution represented by the vector $\boldsymbol{\vartheta}$.

The finite upper support for the fixed cost cdf, combined with a technological gap, makes upgrading increasingly valuable across vintages. As in Thomas (2002), this greatly simplifies the state space of the model, as the economic history is redundant beyond a finite number of lags. Once the gap from the technological frontier has increases enough, the value of investing offsets the highest possible fixed cost. In equilibrium, there exists an endogenously chosen vintage J at which full adjustment occurs: $\alpha_J = 1$. In each sector, for $j < J$, the optimal fractions of adjusting are interior solutions equating the anticipated value of adjusting one additional plant from group j to the additional cost entailed, $w_t G^{-1}(\alpha_{j,t})$ in units of labor, and investment required. That is, for each $j = 0, ..., J-1$:

$$v_{0,t} - v_{j+1,t} = i_{j,t} + w_t G^{-1}(\alpha_{j,t}), \tag{24}$$

where

$$v_{j,t}= \mathbb{E}_t \left\{ \beta_{t,t+1} \left[\begin{array}{c} y_{j,t+1}-w_{t+1}(L_{j,t+1}+\Xi(\alpha_{j,t+1}))-p^e(1+\tau^e_{t+1}\Omega_j)e_{j,t+1} \\ -\alpha_{j,t+1}(i_{j,t+1}-v_{0,t+1}+v_{j+1,t+1})+v_{j+1,t+1} \end{array} \right] \right\}, \tag{25}$$

where $\beta_{t,t+1}$ is equal to the stochastic discount factor $\beta\frac{\lambda_{t+1}}{\lambda_t}$. $v_{j,t}$ represents the expected value of a plant with capital $k_{j,t}$ in the next period. There will be a marginal firm for which equation (24) holds with equality that identifies $\alpha_{j,t}$, the fraction of plants for given vintage j that decides to invest and can be interpreted as hazard rates. $\alpha_{j,t}$ is increasing in j, the number of periods of inaction of a plant. The higher the gap between the productivity of the latest vintage and its current vintage, the higher the probability that a plant will invest. It is worth noticing that the introduction of a carbon tax has a *dynamic* effect in that it impacts both the value of upgrading/postponing investment. A higher effective carbon tax makes a given vintage j, more likely to invest in a new technology to escape the tax burden, especially when the emission rate is increasing in j.

Finally, household optimization implies the marginal rate of substitution between leisure and consumption equates to the real wage w_t:

$$(1-\tau^l_t)w_t = \psi L^\eta_t(1+\tau^c_t)c_t. \tag{26}$$

3.10 REPRESENTATIVE FIRM MODEL

The model described above nests as a specific case the standard one-sector neoclassical growth model with a C.E.S production function. When the upper support of the distribution of the idiosyncratic shock, B is set to zero, all plants can continuously adopt the new technology and adjust their stock of capital in each period. As a result, the dynamics of the economy are characterized by a representative firm. We briefly outline this version of the model, as we find useful to compare the results of environmental policy experiments in section 4 to this representative agent benchmark. The household and government behave as in sections 3.5 and 3.6. Emissions are assumed to be proportional to energy usage: $M_t = \Omega E_t$. The representative firm maximizes expected, discounted profits given by

$$\sum_{t=0}^{\infty} \beta_{t,t+1} \left[Y_t - W_t L_t - P_t^e (1 + \tau_t^e \Omega) E_t - K_{t+1} + (1-\delta) K_t \right], \tag{27}$$

where $\beta_{t,t+1} = \beta^t \frac{\lambda_t}{\lambda_0}$ is the stochastic discount factor of the household and output is defined as in (2). Appendix A lists the stationary equilibrium conditions for this version of the model.

3.11 CALIBRATION & MODEL SOLUTION

Table 2 lists our benchmark calibration. One period in the model represents one quarter. The discount factor β is set to 0.99 to target a real annual interest rate of 4%. As in King and Rebelo (1999), the preference parameter that governs the disutility of labor (ψ) is chosen to target a steady-state labor effort of 0.2. The long-run growth rate of technology is set to 1.4% to target the average growth rate of output of 1.6% observed in the United States during the post-WWII sample. The world price of energy in steady state is normalized to one, and the energy price elasticity ϵ is set to 0.25 to reflect the low short run substitutability of energy with capital and labor inputs estimated by Kilian and Murphy (2014).[11] We calculate the U.S. average energy usage by firms to GDP ratio over the period 1970-2012 to be approximately 0.05.[12] Based on this, we calibrate ω to imply steady state energy usage is 5% of gross output. Production exhibits mild, decreasing returns to scale ($\gamma + \nu = .905$) as in Thomas (2002); labor's share of output is 0.58 (as in King and Rebelo (1999)). The rate of capital depreciation (δ) is set to 0.015, a standard choice in this literature (see Fiori (2012) for a discussion). For

---

[11] We take this value as representative of the estimates in the literature for the short-run price elasticity of oil demand, see Kilian and Murphy (2014) and references therein.

[12] Table 3.6 of the Energy Information Administration's (EIA) Annual Energy Review (AER) provides annual nominal expenditures on energy products, defined as the total of oil, gas, and electricity, by residential, commercial, industrial, and transportation sectors. We define total firm spending on energy products as the sum of commercial and industrial spending on energy products, plus spending in the transportation sector on energy products due to firms.

our benchmark calibration, we set $\delta_j^s = 0$ for all j, and explore the implications of having $\delta_j^s > 0$ in section 5.2.

We rely on the investment literature to discipline with micro evidence the distribution for adjustment cost. As in Thomas (2002), the cumulative distribution for adjustment costs is set to imply a uniformly distributed cost between 0 and B. The upper support of the distributions (B) is set to agree with evidence on investment spikes reported by Doms and Dunne (1998). In the average year, only 8% of plants raise their capital stocks by 30% or more, giving rise to lumpy investors. Setting $B = 0.075$ matches the fraction of lumpy investors, while their investment activities in the model account for 31% of aggregate investment (25% in the data).[13] The dashed line of figure 2 reports the steady-state distribution of firms $(\boldsymbol{\vartheta})$, while the dotted line reports the hazard rates (α_j). The maximum time-since-adjustment J is equal to 35; in other words, the maximum time-since-adjustment for a plant is about 10 years.

Steady state fiscal parameters are set in order with post-WWII averages in the United States. The government consumes 20% of output in steady state, roughly equivalent to the average U.S. total government consumption to GDP ratio. The consumption tax rate is 0.07, reflecting an average rate across all levels of U.S. government. The labor tax is set to 0.2, which equals the average federal labor income tax rate calculated using the method of Jones (2002) (see Leeper et al. (2010) for more details).

The model solution procedure follows Thomas (2002) and Gourio and Kashyap (2007). The computation of the steady state requires a numerical procedure because J, the maximum time-since-adjustment, is endogenously determined. We first guess a value for J. Conditional on this value, we guess the target capital k_0, the fraction of plants investing $\boldsymbol{\alpha}_j$, the energy levels of firms e_j, and the real wage w. After using these values to solve for

---

[13] Given the quarterly calibration of the model, the target for lumpy investors is 2% at quarterly frequency: plants that are lumpy investors in period t (i.e. they experience an investment rate above 30%) along the balanced growth path will again be lumpy investors beyond period $t + 4$.

the remaining variables, equations (20), (21), (22), and (25) are used to verify and update the guess. This procedure continues for values of J until α_J is endogenously equal to 1 (i.e., plants with level of capital k_J adjust with probability 1). We consider perfect foresight exercises that give a permanent change in policy parameters. Transition dynamics from the initial equilibrium to the final equilibrium are found by solving the model as a nonlinear forward looking deterministic system.

4 GREEN POLICY IMPLICATIONS

We begin our discussion of green policies by analyzing the introduction of a carbon tax. We assume that the government introduces in the current period a carbon tax, so that $\tau^e > 0$, and this tax is permanent. At the same time, the government announces how carbon tax revenues will be utilized. For our benchmark experiments, the revenues are assumed to be rebated to the households in lump-sum fashion. Alternative financing scenarios are discussed in section 4.2. In all the policy experiments that follow, for comparability we calibrate the carbon tax to achieve a long term reduction in energy usage of 1%. In reality, carbon taxes usually are designed to equal a measured cost of emissions, to achieve a revenue goal, or to achieve an emissions target. Our experiments are analogous to the latter, as emissions are proportional to energy usage in the economy.

Figure 3 shows the responses of variables when $\Omega_j = 1$, that is when all plants' emissions are equal to energy usage, the common assumption in the literature. The responses of output, energy, investment, the target capital stock, the number of plants investing (i.e. investors), and the average age of capital in the economy are plotted as percentage deviations from the initial steady state. In this case, the carbon tax necessary to achieve a 1% reduction in energy in the long-run is 3.3%. A carbon tax effectively increases the factor price of energy. Given the low substitutability of energy and other inputs, plants lower their target capital stock. Across all horizons, output, energy, and the target capital stock decrease. These factors create opposing incentives on a plant's capital accumulation decision. On the one hand, a higher effective energy price makes investment in more energy efficient technology desirable. On the other hand, a higher factor price reduces the size of producers and depresses the expected value of a plant at the technological frontier ($v_{0,t}$ in equation 25), which reduces investment incentives. The responses in figure 3 show that the latter effect dominates in the short run. On impact, plants delay investment, and the number of investors decreases. Since fewer establishments are upgrading their capital and technology, the average energy efficiency in the economy declines (not pictured) and the average age of the capital stock increases. Over time, the number of investors rises as plants that have delayed investment and whose capital stock is depreciating find it more profitable to replace capital. In the long run, a permanently higher effective price on energy creates a permanent shift in the distribution of plants, with a higher number of establishments investing each period to maintain higher energy efficiency.

A plant's investment decision depends on how the future expected path of the carbon tax affects the plant's future, effective energy costs. When emission rates vary with plant vintage, a flat carbon tax has unequal tax incidence across vintages. This feature can alter the timing of capital replacement and the target capital stock. Figure 4 illustrates this issue by repeating the carbon tax policy when $\Omega_j = j + 1$ (dashed lines). In this case, older plants, which also have lower levels of productivity, have higher emission rates, consistent with empirical evidence.[14] For comparison, the initial scenario when $\Omega_j = 1$ also is plotted (solid lines). The carbon tax rate is calibrated so that the long run drop in total energy usage is the same for both cases, implying a tax of 22%. In addition,

---

[14] See Shapiro and Walker (2018) and Bloom et al. (2010) for instance. For this experiment, all that is needed is for $\frac{\partial \Omega_j}{\partial j} > 0$. Assuming this partial derivative is constant, its value is inconsequential; since we calibrate the carbon tax τ^e to achieve a long run reduction in energy of 1%, alternative values simply imply different τ^e necessary to achieve the reduction.

this implies that the long run average cost of the tax as a share of plant output (defined as $\sum_{j=0}^{J} \vartheta_{j,t} \frac{\tau_t^e p_t^e \Omega_j e_{j,t}}{y_{j,t}}$) is identical across cases. Despite these similarities by construction, figure 4 shows sizable differences across the two economies in both the short and long run.

The responses in the economy with heterogeneous emission rates are much more appreciable. In this case, the burden of the carbon tax falls more heavily on older vintages, as they have relatively higher emission rates. This induces plants to have a lower target capital stock, as they reduce their size in anticipation of the heavy future tax incidence. At the same time, plants have higher incentives to invest, as their emission rates decline with newer capital and technology. In the short run, the number of investors increases dramatically – 12 percentage points above the initial steady state – and remains substantially high in the long run. In turn, the average energy efficiency increases and average age of the capital stock declines. Despite the spike in investors, the contraction in the target capital stock causes aggregate investment to decrease in the short and long run.

The differences in plant level dynamics across the two economies, $\Omega_j = 1$ and $\Omega_j = j + 1$, are notable. To highlight the variation, figure 5 plots the dynamic evolution of the plant distribution following the carbon tax. The top panel displays the distribution (that is, the fraction of establishments of each vintage), while the bottom panel plots the percentage change in the distribution relative to the initial steady state. Both panels provide a snapshot of the distribution at different points in time: on impact of the tax (dotted dashed line), after 5 periods (dotted line), and after 10 periods (dashed lines). For now, we focus on the first two columns of the figure.

The first column of figure 5 shows that the carbon tax produces small variation in the distribution when plant emission rates are homogeneous ($\Omega_j = 1$). On impact, there is a decline in the number of plants with the newest vintage, reflecting the fact that the number of investors falls. This implies that the number of plants of later vintages ($j = 1, 2, 3...$)

also declines over time, as the plants of type $j = 0$ at time t become type $j = 1$ at time $t + 1$ when they do not invest. The dotted and dashed lines in the second row, first column panel of figure 5 demonstrate this dynamic evolution of plants over time. As more plants choose to invest in the long run, these declines in vintages decrease over time. The second column of figure 5, displaying the results when plant emission rates are heterogeneous ($\Omega_j = j + 1$), produces the opposite dynamics: following a carbon tax, there is a shift in the distribution towards the newest vintage, as the number of investors increases. In addition, the effects are quantitatively significant, as the number of older vintages shrinks by over 40% in the long run. Taken together, these results highlight that the quantitative predictions following a carbon tax reform depend on the initial distribution of establishments, particularly in the short run.

4.1 VINTAGE-DIFFERENTIATED POLICY

In practice, environmental policies often are vintage-differentiated. The most common application is "grandfathering" or exempting production units installed prior to a specific date from the policy, a practice customarily applied to new regulations. Reasons for such implementation normally are attributed to short-run fairness, so that the rules of the game for establishments are not changed midstream, or to political pressures.[15] To examine the economic consequences of such reforms, we consider a variant of the carbon tax policy where the carbon tax gradually affects establishments. We assume that in period 0, a government enacts a carbon tax that applies to the newest vintage ($j = 0$) in period 0, but exempts all older vintages. The tax is assumed to apply to all future vintages of higher technological progress as well, that is vintage $j = 0$ at times $t = 1, 2, ...$ In this way, in period 0, vintages of $j \geq 1$ are exempted from the policy and only are affected when they upgrade their capital and technology. Heutel (2011) and Shapiro and Walker (2018) argue that a carbon tax can capture the

---

[15] See Stavins (2006) for a review of vintage-differentiated environmental regulation.

implementation of various U.S. regulations. Thus, this policy also can be interpreted as characterizing the effects of certain "grandfathering" regulations.

Figure 6 displays the responses of variables to the gradual tax reform in our two economies: with plant emission rates that are homogeneous (solid lines) and with heterogeneous rates (dashed lines). Unlike the tax reform that affects all vintages simultaneously, the short-run qualitative responses of all variables are the same across the two economies. Following the tax policy, the number of investors declines by over 10%. Since plants are only subject to the policy when they update their capital and technology, the expected value of a plant at the technological frontier decreases. Thus, the effective price of new capital rises, and older capital is retired later. This leads the average age of the capital stock to increase markedly in the short run. In addition, the decline in investors causes aggregate investment to decrease in the short run as well. These results are consistent with empirical work on the effects of grandfathering regulation. The most cited example of such practice in the U.S. is the New Source Review Program from the Clean Air Act of 1970, which has been shown to have reduced investment and increased the age of capital of exempted plants (see for instance Bushnell and Wolfram (2012) and Nelson et al. (1993)).

Returning to figure 5, the last two columns display the dynamic evolution of the plant distribution following the gradual carbon tax. In this case, the distributional shifts are more sizable in the short run than the common tax case (see the first two columns).

4.2 ALTERNATIVE "REVENUE RECYCLING" SCENARIOS

As the fiscal use of carbon tax revenues often is cited as a motivation for the tax's implementation, we consider the effects of alternative "revenue recycling" scenarios. The top panel of figure 7 repeats the carbon tax policy when it affects all plants simultaneously in the economy with uniform emission rates ($\Omega_j = 1$). The solid lines repeat our benchmark case where tax revenues are rebated back to households in lump-sum fashion whereas the dotted lines use the revenues to reduce the consumption tax and dashed lines use revenues to reduce the labor tax.[16] Offsetting the carbon tax revenues with reductions in either distortionary tax, consumption or labor, results in a smaller aggregate contraction, since both create offsetting expansionary effects. A reduction in consumption taxes makes households more willing to consume goods, and in turn more willing to supply labor. Likewise, a reduction in labor taxes makes households more willing to work. The labor effect in both cases alleviates the contractionary supply-side implications of the higher effective energy price.

The bottom panel of figure 7 repeats the financing scenarios for the gradual carbon tax, in which some plants are initially exempted as in section 4.1. In the long run, the revenue recycling effects are the same as those from the uniform tax case, as all plants eventually are subject to the tax even with gradual reform. The short run dynamics, however, can differ markedly. On impact, offsetting the carbon tax revenues with the labor tax is more contractionary than the lump-sum rebates to households. In this case, carbon tax revenues are initially very small, as only plants of the newest vintage are subject to the tax and the number of investors decreases. When coupled with the overall contractionary effects in the economy, which depress government revenues, the labor tax is forced to *rise* to balance the government budget. Thus, the policy leads to two contractionary fiscal actions on impact, further dampening output and investment in the short run. These results provide a cautionary warning, suggesting that the revenue gains from a carbon tax could appear gradually, depending on how the policy is implemented.

4.3 COMPARISON WITH REPRESENTATIVE FIRM MODEL

Although we have shown that the plant distribution matters for individual establishment decisions, one might wonder

---

[16] For the perfect foresight experiments for this economy, an increase in government spending produces the same effects as a reduction in consumption taxes, as both create the same demand-side effects. We present results for the uniform emission rate case only as the heterogeneous emission rate economy exhibits the same qualitative patterns.

how much the distribution matters for the aggregate dynamics. To address this issue, we consider the effects of imposing a carbon tax as evaluated with the standard, representative firm model versus the two variants of the model with a plant distribution ($\Omega_j = 1$ and $\Omega_j = j + 1$). The results are presented in figure 8. For the representative firm model, we calibrate the tax to produce a long-run decline in energy of 1%. The results demonstrate that the responses of the heterogeneous firm model with homogeneous emission rates are virtually identical to the representative firm model. In contrast, the model with heterogeneous emission rates produces markedly different aggregate dynamics. These results further suggest the importance of the underlying micro-structure of an economy to characterize the effects of macroeconomic policies.

5 ROBUSTNESS

In this section, we investigate the robustness of our results to alternative policy experiments and model specifications.

5.1 POLICY SIZE For the baseline experiment, we calibrated the carbon tax shock to deliver a long-run reduction in energy of 1%. To determine how sensitive our inferences are to the shock size, figure 9 repeats the experiment when the government alternatively targets a 5% reduction in energy with the carbon tax (dashed lines) or a 10% reduction in energy (dotted lines). The respective sizes of the carbon tax in each experiment are 3.3%, 18.5%, and 40%. Larger carbon tax reforms deliver larger responses from macro aggregates, with the change in responses roughly proportional to the change in the tax reform.

5.2 IRREVERSIBLE INVESTMENT For our benchmark specification, we assumed that the non-depreciated portion of older capital stocks could be converted freely to the latest vintage of capital. Alternatively, one could argue that a portion of older vintage capital is irreversible. $\delta_j^s > 0$, from equation 5, captures the notion that when an investing plant upgrades its technology, part of its current, vintage capital stock may not be operable with the new technology and must be scrapped.

To investigate the effects of such irreversible investment, we conduct an experiment where we set $\delta_j^s = \delta^s \alpha_j$ and $\delta^s = 0.5$. In this case, the degree of capital irreversibility varies across vintages, with older vintages scrapping larger portions of capital because the capital is irreconcilable with the new technology. We recalibrate the upper support of the fixed cost distribution (B) to continue to match empirical evidence on investment spikes (see section 3.11 for more details) and calibrate the carbon tax to target a long run reduction in energy use of 1%. We find that the irreversibility plays no substantial role, as the quantitative results are virtually identical to our benchmark case.[17]

6 CONCLUSION

As climate concerns are increasingly discussed, policymakers weigh options to alleviate emissions. Understanding how such policy options affect investment behavior is of central importance, as encouraging more energy-efficient technology adoption is a key policy consideration. In this paper, we develop a framework to study how environmental policies affect the decision to replace old technologies with new ones. Our model can fit a variety of key stylized facts – newer, more productive plants emit less per unit energy than older, unproductive plants; productive plants produce more than unproductive plants; and plants make large and infrequent investments.

We find that the quantitative predictions following a carbon tax reform depend on the initial distribution of establishments, particularly in the short run. Qualitative and

---

[17] Results available from the authors upon request.

quantitative responses vary depending on whether the economy features plants with homogeneous or heterogeneous emission rates. Heterogeneous emission rates, a feature consistent with plant-level data, induce the economy's average energy efficiency to rise following a carbon tax and imply dynamics that differ from a representative firm model. In addition, policies that initially exempt older establishments and alternative revenue recycling scenarios alter the short and long run effects. Overall, the results suggest that the characteristics of the production structure at the microeconomic level are informative about the aggregate effects of green policies.

Our theoretical results have immediate implications for empirical research, calling attention for the need to more fully understand the plant-level characteristics of production. Distinguishing how plant dispersion varies across industries, regions, and countries is essential for predicting how environmental policies will affect technology adoption and how policies will affect trade and growth across nations. Our model provides one step in this direction, by offering a framework to analyze the complexities of environmental policies on investment decisions.

REFERENCES

ACEMOGLU, D., U. AKCIGIT, D. HANLEY, AND W. KERR (forthcoming): "Transition to Clean Technology," *Journal of Political Economy*.

BACHMANN, R. AND C. BAYER (2014): "Investment Dispersion and the Business Cycle," *American Economic Review*, 104, 1392–1416.

BACHMANN, R., R. CABALLERO, AND E. ENGEL (2013): "Aggregate Implications of Lumpy Investment: New Evidence and a DSGE Model," *American Economic Journal: Macroeconomics*, 5, 29–67.

BLOOM, N., C. GENAKOS, R. MARTIN, AND R. SADUN (2010): "Modern Management: Good for the Environment or Just Hot Air?" *Economic Journal*, 120, 551–572.

BOSETTI, V. AND M. MAFFEZZOLI (2013): "Taxing Carbon under Market Incompleteness," Fondazione Eni Enrico Mattei Working Papers No. 831.

BOUCEKKINE, R., D. DE LA CROIX, AND O. LICANDRO (2008): "Vintage Capital," in *New Palgrave Dictionary of Economics, Second Edition*, ed. by S. Durlauf and L. Blume, 628–631.

BUSHNELL, J. B. AND C. D. WOLFRAM (2012): "Enforcement of Vintage Differentiated Regulations: The Case of New Source Review," *Journal of Environmental Economics and Management*, 64, 137–152.

CABALLERO, R. J. AND E. M. ENGEL (1999): "Explaining Investment Dynamics in U.S. Manufacturing : A Generalized (S,s) Approach," *Econometrica*, 67, 783–826.

DASGUPTA, S., R. E. LUCAS, AND D. WHEELER (2002): "Plant Size, Industrial Air Pollution, and Local Incomes: Evidence from Mexico and Brazil," *Environment and Development Economics*, 7, 365–381.

DOMS, M. AND T. DUNNE (1998): "Capital Adjustment Patterns in Manufacturing Plants," *Review of Economic Dynamics*, 1, 409–429.

FIORI, G. (2012): "Lumpiness, Capital Adjustment Costs and Investment Dynamics," *Journal of Monetary Economics*, 59, 381–392.

——— (2015): "TBD," North Carolina State University manuscript.

FULLERTON, D. AND H. MONTI (2013): "Can Pollution Tax Rebates Protect Low-Wage Earners?" *Journal of Environmental Economics and Management*, 66, 539–553.

GOLOSOV, M., J. HASSLER, P. KRUSELL, AND A. TSYVINSKI (2014): "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica*, 82, 41–88.

GOULDER, L. (1995): "Environmental Taxation and the Double Dividend: A Reader's Guide," *International Tax and Public Finance*, 2, 157–183.

GOULDER, L., I. PARRY, R. WILLIAMS III, AND D. BURTRAW (1999): "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting," *Journal of Public Economics*, 72, 329–60.

GOURIO, F. AND A. KASHYAP (2007): "Investment Spikes: New Facts and A General Equilibrium Exploration," *Journal of Monetary Economics*, 54, 1–22.

HASSLER, J. AND P. KRUSELL (2012): "Economics and Climate Change: Integrated Assessment in a Multi-Region World," *Journal of the European Economic Association*, 10, 974–1000.

HEUTEL, G. (2011): "Plant Vintages, Grandfathering, and Environmental Policy," *Journal of Environmental Economics and Management*, 61, 36–51.

IMF (2002): *Fiscal Policy to Mitigate Climate Change: A Guide for Polickymakers*, IMF.

JONES, J. (2002): “Has Fiscal Policy Helped Stabilize the Postwar U.S. Economy?” *Journal of Monetary Economics*, 49, 709–746.

KHAN, A. AND J. THOMAS (2003): “Nonconvex Factor Adjustments in Equilibrium Business Cycle Models: Do Nonlinearities Matter?” *Journal of Monetary Economics*, 50, 331–360.

——— (2008): “Idiosyncratic Shocks and the Role of Nonconvexities in Plant & Aggregate Investment Dynamics,” *Econometrica*, 76, 395–436.

KILIAN, L. AND D. P. MURPHY (2014): “The Role of Inventories and Speculative Trading in the Global Market for Crude Oil,” *Journal of Applied Econometrics*, 29, 454–478.

KING, R. AND S. REBELO (1999): “Resuscitating Real Business Cycles,” *Handbook of Macroeconomics*, 1, 927–1007.

KRUSELL, P. AND A. A. SMITH (2015): “A Global Economy-Climate Model with High Regional Resolution,” Yale University manuscript.

LEEPER, E. M., M. PLANTE, AND N. TRAUM (2010): “Dynamics of Fiscal Financing in the United States,” *Journal of Econometrics*, 156, 304–321.

LYUBICH, E., J. S. SHAPIRO, AND R. WALKER (2018): “Regulating Mismeasured Pollution: Implications of Firm Heterogeneity for Environmental Policy,” *AEA Papers and Proceedings*, 108, 136–42.

MIAO, J. AND P. WANG (2014): “Lumpy Investment and Corporate Tax Policy,” *Journal of Money, Credit and Banking*, 46, 1171–1203.

NELSON, R. A., T. TIETENBERG, AND M. R. DONIHUE (1993): “Differential Environmental Regulation: Effects on Electric Utility Capital Turnover and Emissions,” *The Review of Economics and Statistics*, 75, 368–373.

NORDHAUS, W. D. (1994): *Managing the Global Commons: The Economics of Climate Change*, MIT Press.

——— (2008): *A Question of Blance: Weighing the Options on Global Warming Policies*, Yale University Press.

NORDHAUS, W. D. AND J. BOYER (2000): *Warming the World: Economic Models of Global Warming*, MIT Press.

PORTER, M. (1991): "America's Green Strategy," *Scientific American*, 264, 168.

QI, J., X. TANG, AND X. XI (2014): "The Size Distribution of Firms and Industrial Pollution," Arizona State University manuscript.

RAUSCH, S., G. METCALF, J. REILLY, AND S. PALTSEV (2010): "Distributional Implications of Alternative U.S. Greenhouse Gas Control Measures," *The B.E. Journal of Economic Analysis & Policy*, 10, Symposium.

RESTUCCIA, D. AND R. ROGERSON (2008): "Policy Distortions and Aggregate Productivity with Heterogeneous Establishments," *Review of Economic Dynamics*, 11, 707–720.

SANDMO, A. (1975): "Optimal Taxation in the Presence of Externalities," *The Swedish Journal of Economics*, 77, 86–98.

SHAPIRO, J. S. AND R. WALKER (2018): "Why is Pollution from U.S. Manufacturing Declining? The Roles of Environmental Regulation, Productivity and Trade," *Americaon Economic Review*, forthcoming.

STAVINS, R. N. (2006): "Vintage Differentiated Environmental Regulation," *Stanford Environmental Law Journal*, 25, 29–66.

THOMAS, J. K. (2002): “Is Lumpy Investment Relevant for the Business Cylce?” *Journal of Political Economy*, 110, 508–534.

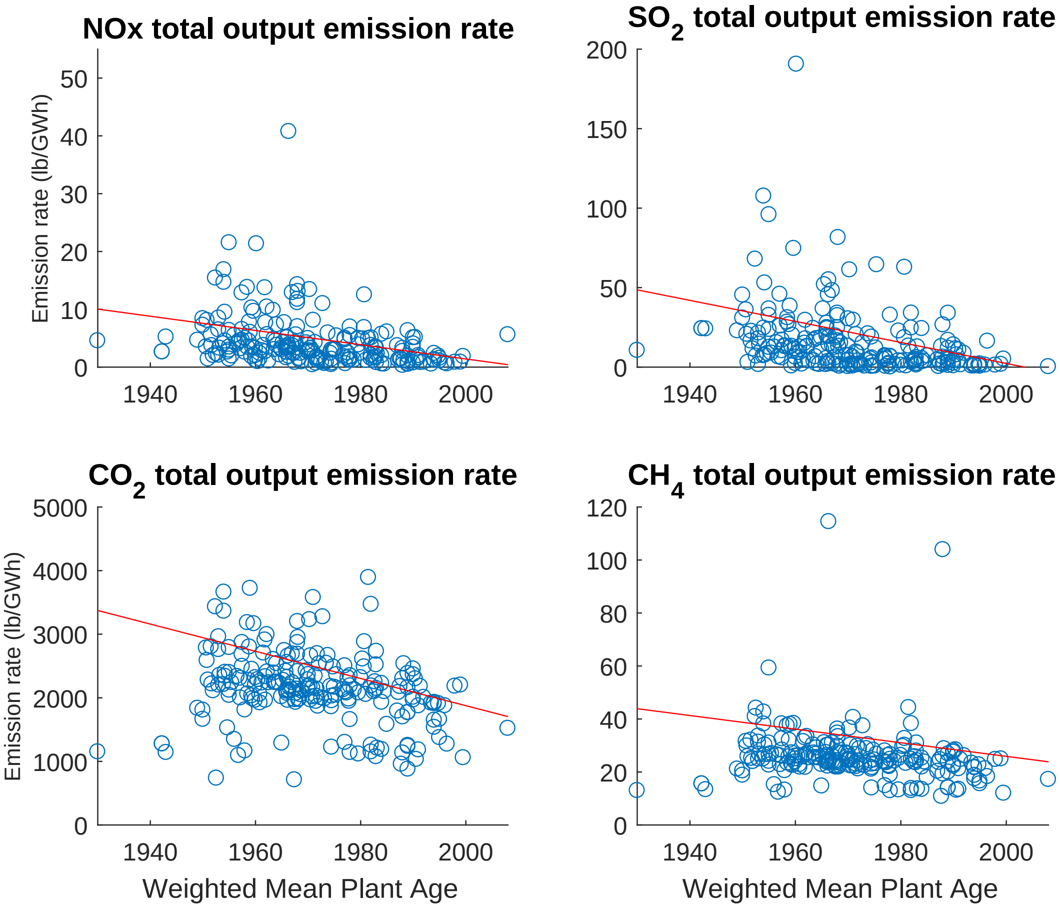

Figure 1: Emission Rates for coal power plants in the U.S by plant age for 2010. The plant age is constructed as the weighted mean of the plant's generators' age, weighted by each generators net electricity generation. Each scatter plot is accompanied by its linear fit.

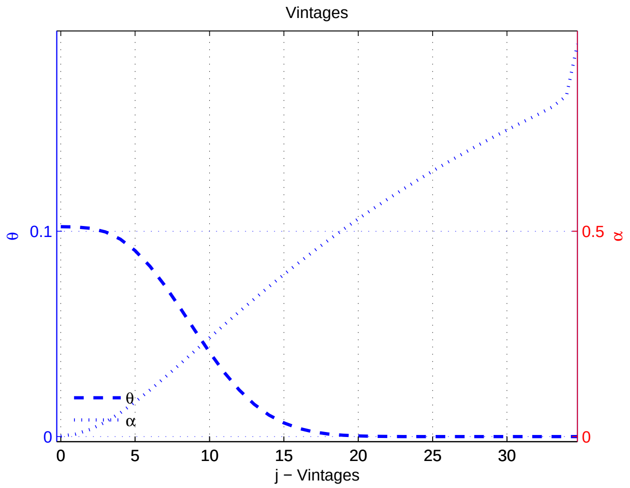

Figure 2: The initial steady state distribution of firms (θ_j) and hazard rates (α_j).

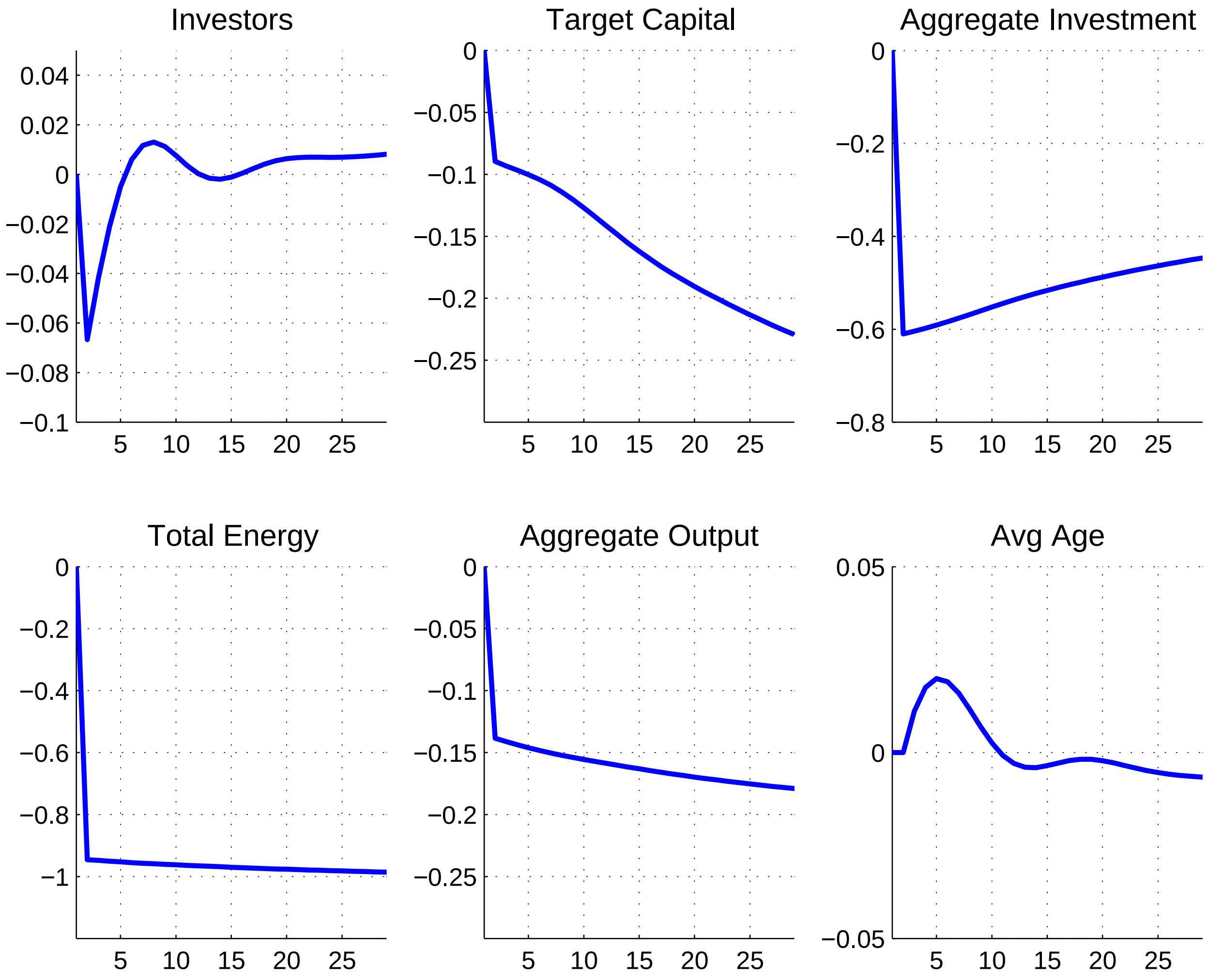

Figure 3: Responses when $\Omega_j = 1$ to a permanent carbon tax set to achieve a long term reduction in energy usage of 1%. X-axis denotes quarters while y-axis measures percentage deviation from initial steady state.

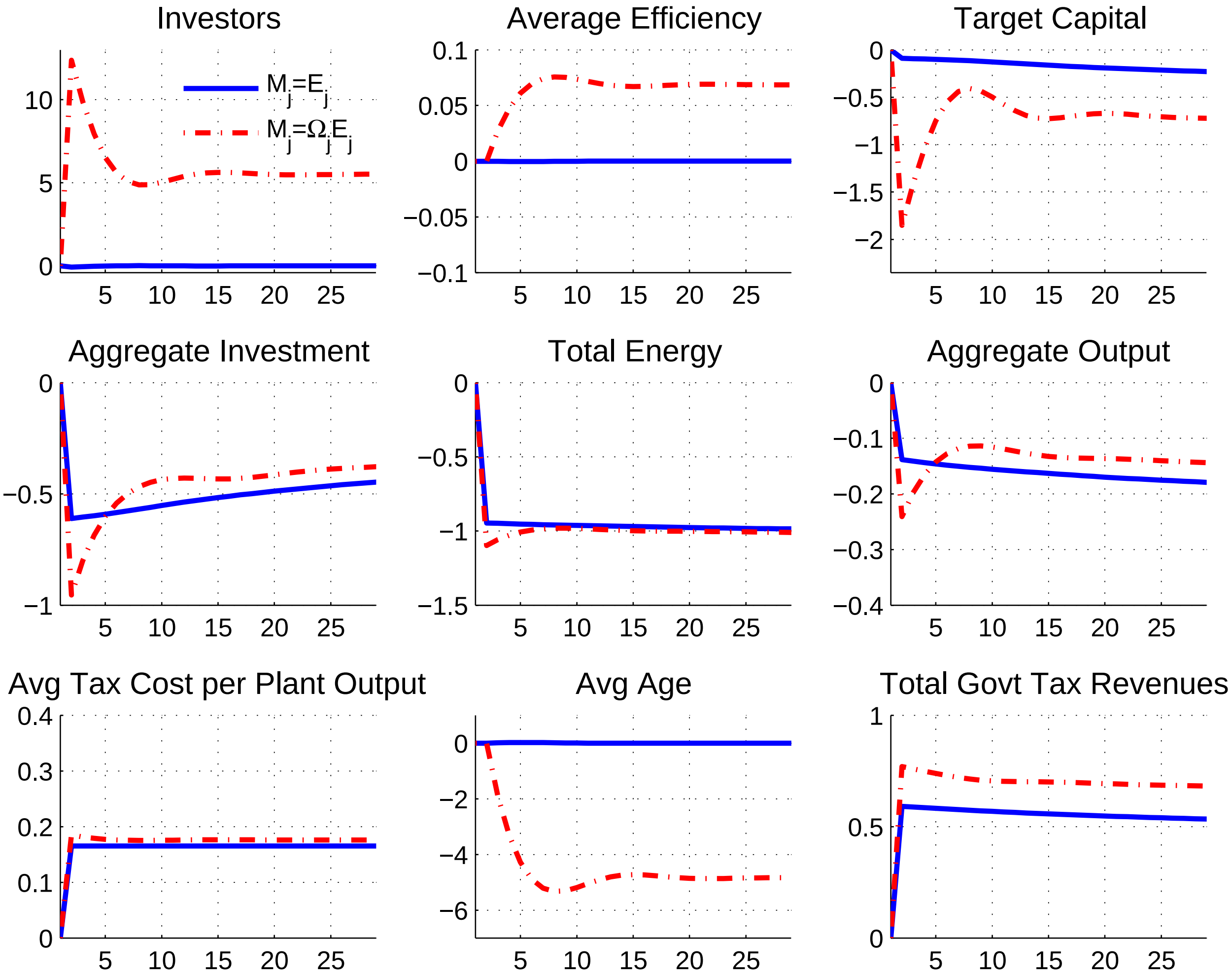

Figure 4: Responses to a permanent carbon tax set to achieve a long term reduction in energy usage of 1%. Solid blue lines: $\Omega_j = 1$; dashed red lines: $\Omega_j = j + 1$. X-axis denotes quarters while y-axis measures percentage deviation from initial steady state.

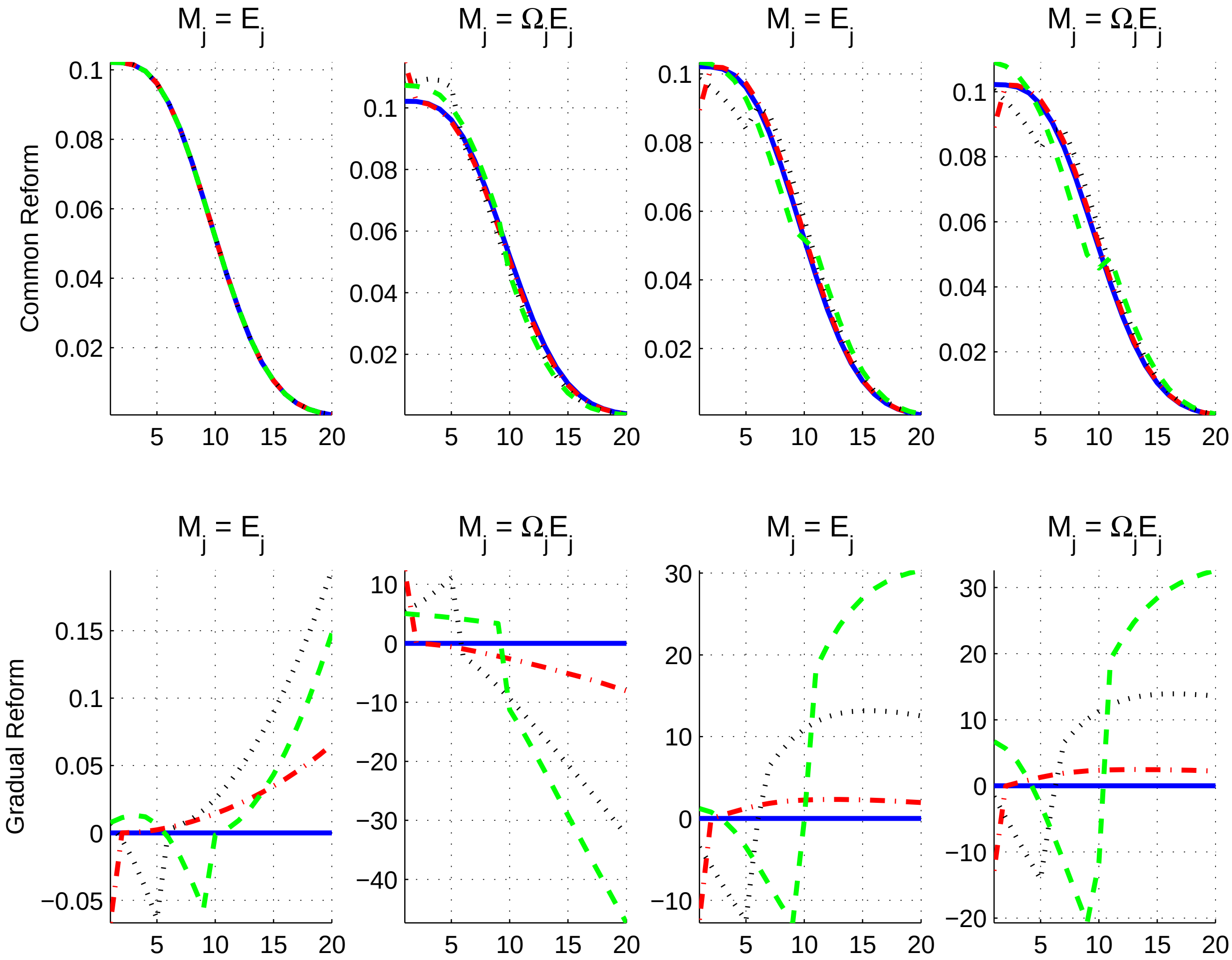

Figure 5: Dynamic evolution of the plant distribution. The top panel denotes the fraction of plants (y-axis) across vintages (x-axis). The bottom panel expresses this distribution in percentage deviations from the initial steady state distribution. Blue solid lines: initial steady state distribution; red dotted-dashed lines: on impact of carbon tax introduction; black dotted lines: 5 periods after carbon tax; green dashed lines: 10 periods after carbon tax.

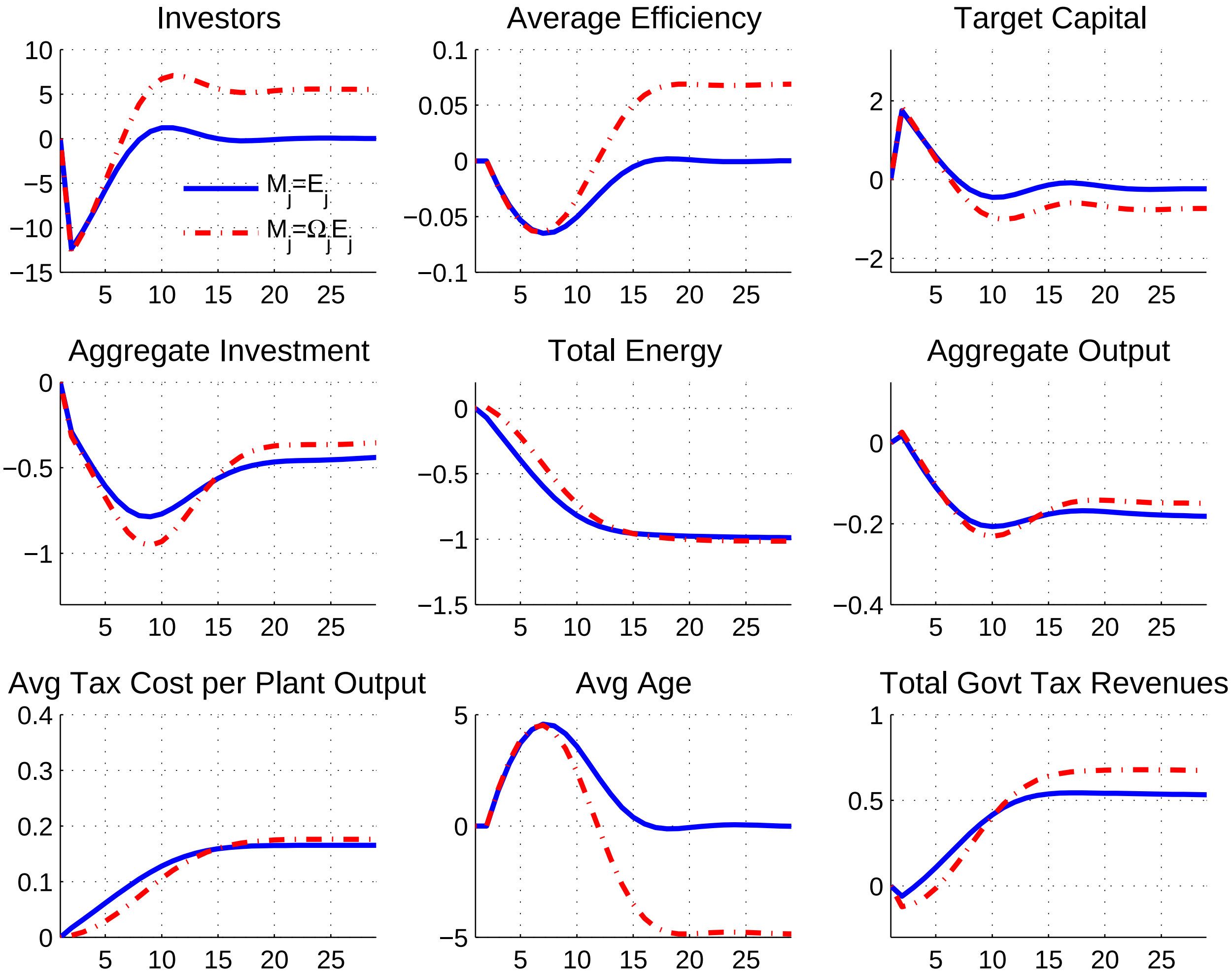

Figure 6: Responses to a permanent carbon tax that gradually affects plants, as they update their capital stock, and is set to achieve a long term reduction in energy usage of 1%. Solid blue lines: $\Omega_j = 1$; dashed red lines: $\Omega_j = j + 1$. X-axis denotes quarters while y-axis measures percentage deviation from initial steady state.

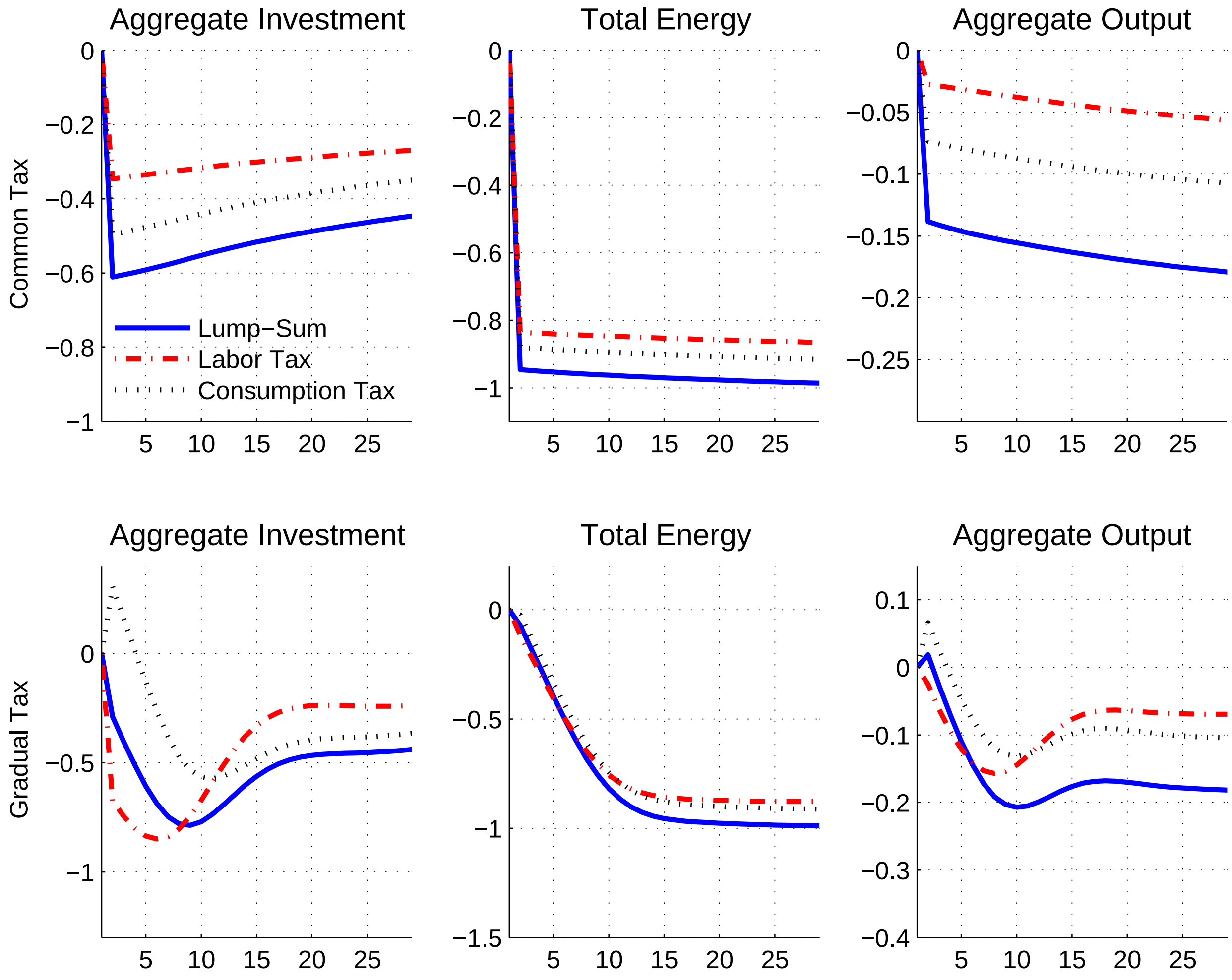

Figure 7: Various revenue recycling scenarios following a carbon tax introduction. Solid blue lines: rebating proceeds lump-sum to households; dashed red lines: reducing labor taxes. Black dotted lines: reducing consumption taxes. X-axis denotes quarters while y-axis measures percentage deviation from initial steady state.

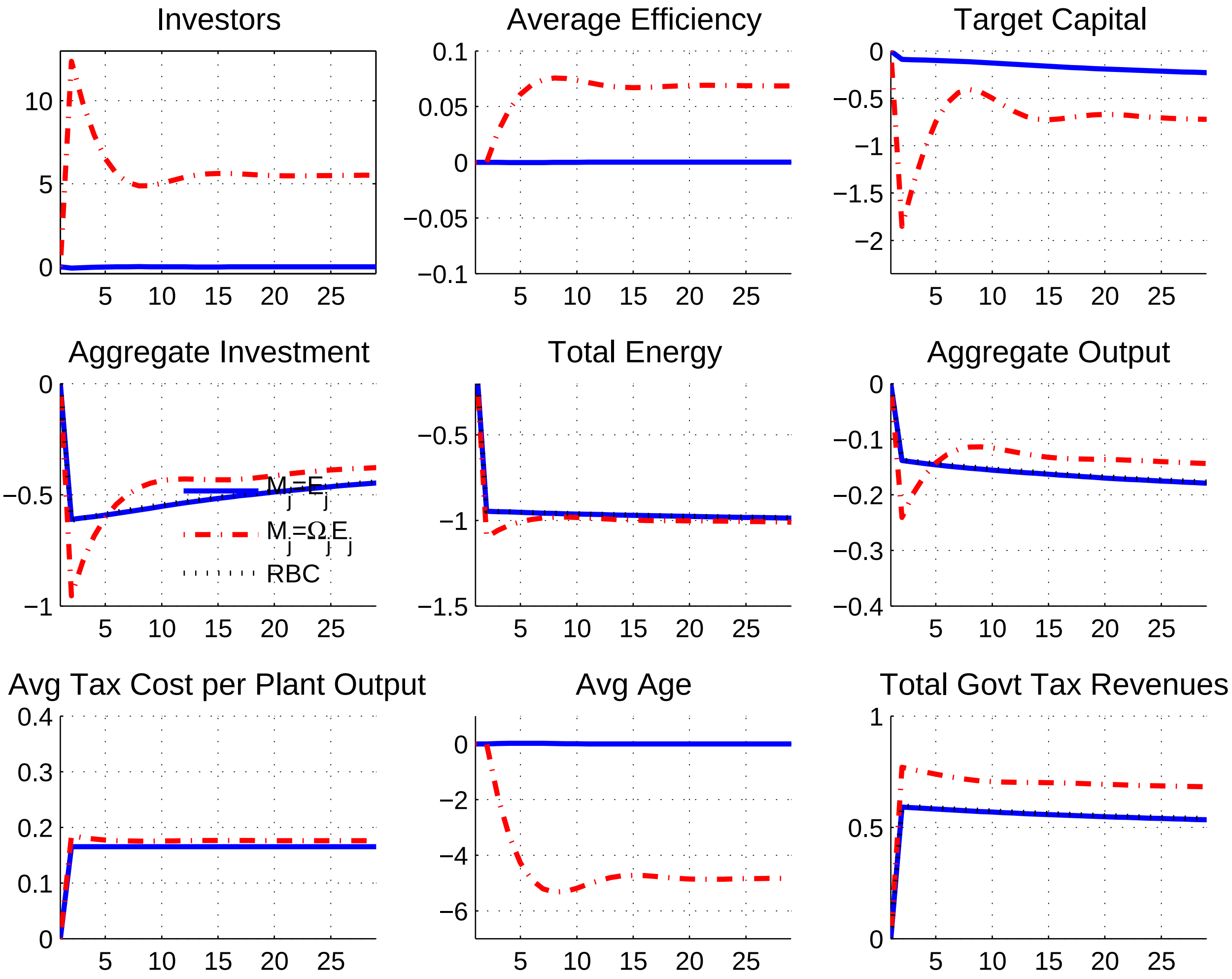

Figure 8: Comparison of heterogeneous firms and representative firm models. Solid blue lines: plants with homogenous emission rates ($\Omega_j = 1$); dashed red lines: plants with heterogenous emission rates ($\Omega_j = j + 1$). Black dotted lines: representative firm model. X-axis denotes quarters while y-axis measures percentage deviation from initial steady state.

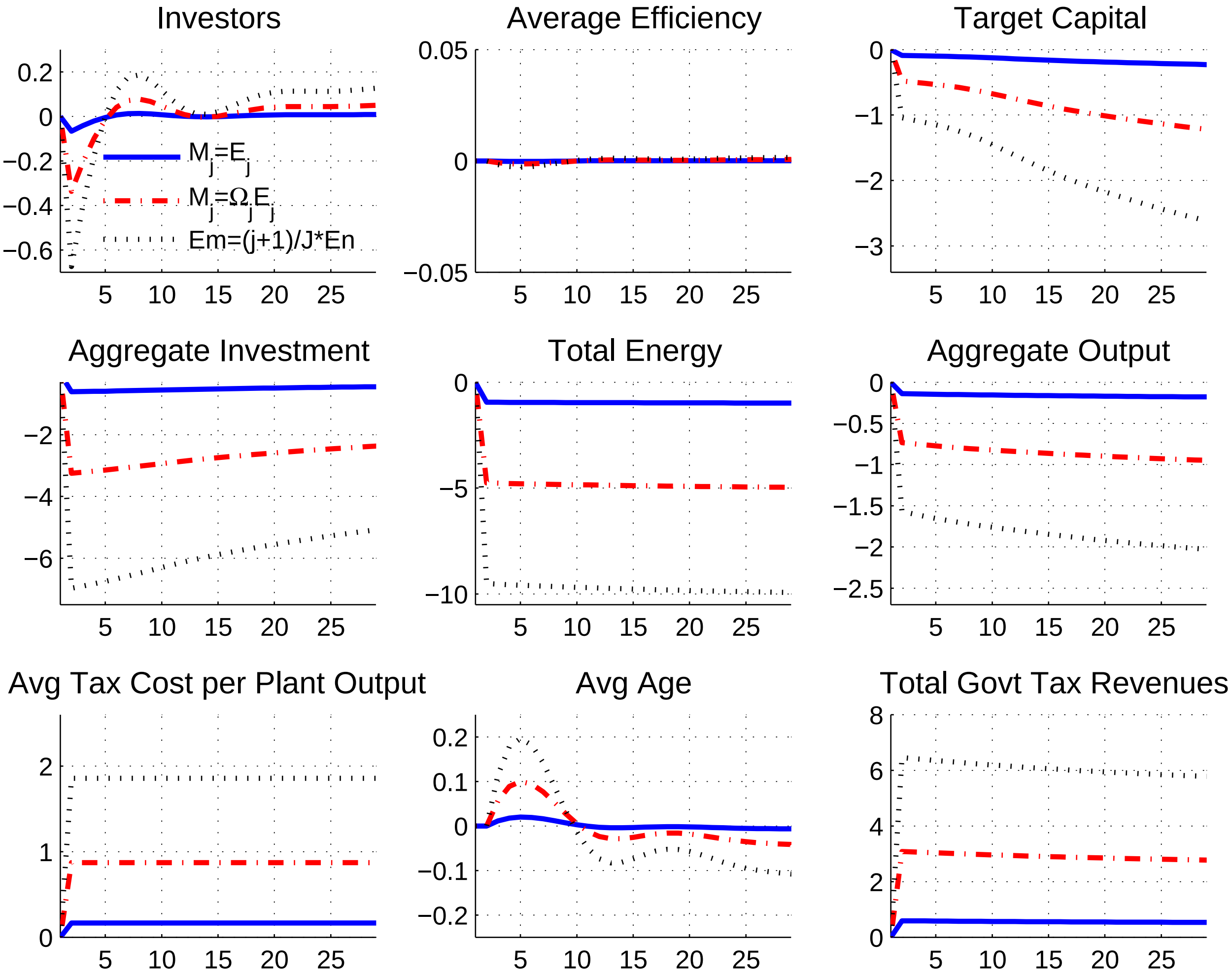

Figure 9: Various size carbon tax reforms. Solid blue lines: tax to give 1% long-run drop in energy; dashed red lines: tax to give 5% long-run drop in energy; Black dotted lines: tax to give 10% long-run drop in energy. X-axis denotes quarters while y-axis measures percentage deviation from initial steady state.

Table 1: Emissions Function Estimates

	Non-coal			
	SO_2 rate	NO_x rate	CH_4 rate	CO_2 rate
ln *age*	0.567***	0.574***	0.103***	0.107***
constant	-1.721***	1.170***	4.682***	6.698***
observations	10,559	12,165	9,384	11,423
Adj R-squared	0.71	0.57	0.65	0.45

	Coal			
	SO_2 rate	NO_x rate	CH_4 rate	CO_2 rate
ln *age*	0.907***	0.438***	0.045	0.059**
constant	-1.737***	-0.002	2.909***	7.154***
observations	2,809	2,809	2,193	2,809
Adj R-squared	0.28	0.22	0.40	0.44

Notes: Dependent variable is the plant's output emission rate (measured in pounds per megawatt), age is the weighted average of the plant generator's years online as of 2010. Each specification includes controls for the type of primary fuel input and state and year fixed effects. Asterisks denote (*) 10%, (**) 5% or (***) 1% significance. Each specification is estimated using ordinary least squares (OLS).

Table 2: Benchmark Calibration

Parameter		Target
Discount Factor	$\beta = 0.99$	Annual real interest rate = 4%
Disutility of Labor	$\psi = 21.3$	Steady state labor= 0.2
Inverse of Frisch elasticity	$\eta = 1$	Macro Literature
Production function parameter	$\gamma = 0.32$	Literature
Production function parameter	$\nu = 0.58$	Labor share
Energy price elasticity	$\epsilon = 0.25$	Kilian-Murphy (2014)
Production distribution parameter	$1 - \omega = 0.05$	Energy/Output = 5%
Depreciation Rate	$\delta = 0.015$	Literature
Capital obsolescence	$\delta_j^s = 0$	Authors' choice
Upper support adj. cost distribution	$B = 0.075$	Fraction of lumpy investors
Growth rate of productivity	$\Theta_{Z_0} = 1.0025$	Annual growth rate of output of 1.6%
Gov spending-output ratio	$G/Y = 0.2$	Data
Labor tax rate	$\tau^l = 0.20$	Data
Consumption tax rate	$\tau^c = 0.07$	Data

A EQUILIBRIUM CONDITIONS FOR REPRESENTATIVE FIRM MODEL

The stationary equilibrium conditions for the standard neoclassical growth version of the model are as follows:

$$
\begin{aligned}
y_t &= \left[\omega^{\frac{1}{\epsilon}}\left(\left(\frac{k_{t-1}}{\Theta_{K_t}}\right)^{\gamma} L_t^{\nu}\right)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}}(e_t)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} \\
p_t^e(1+\tau_t^E\Omega) &= (1-\omega)\frac{y_t}{e_t} \\
w_t &= \nu(\omega y_t)^{\frac{1}{\epsilon}}\left(\frac{k_{t-1}}{\Theta_{K_t}}\right)^{\frac{\gamma(\epsilon-1)}{\epsilon}} L_t^{\frac{\nu(\epsilon-1)}{\epsilon}-1} \\
\psi L_t^{\eta} &= \frac{(1-\tau_t^l)w_t}{(1+\tau_t^c)c_t} \\
\lambda_t &= \frac{c_t^{-1}}{1+\tau_t^c} \\
\lambda_t &= E_t\frac{\beta\lambda_{t+1}}{\Theta_{K_{t+1}}}\left(\gamma(\omega y_{t+1})^{\frac{1}{\epsilon}}\left(\frac{k_t}{\Theta_{K_{t+1}}}\right)^{\frac{\gamma(\epsilon-1)}{\epsilon}-1} L_{t+1}^{\frac{\nu(\epsilon-1)}{\epsilon}} + (1-\delta)\right) \\
y_t &= c_t + g_t + i_t + p_t^e e_t \\
k_t &= (1-\delta)\frac{k_{t-1}}{\Theta_{K_t}} + i_t \\
\Theta_{K_t} &= \Theta_{Z_t}^{\frac{1}{1-\gamma}}
\end{aligned}
$$