Environmental Policy and Endogenous Market Structure[*]

Barbara Annicchiarico[†] Luca Correani[‡] Fabio Di Dio[§]

February 2018

Abstract

This paper presents a simple dynamic general equilibrium model with supply-side strategic interactions to study the economic effects of mitigating greenhouse gas emissions in an economy with an emission cap and oligopolistic firms competing on prices. With such endogenous market structure a gradual decarbonization policy is likely to induce higher markups, while the number of active firms displays a U-shaped behavior, first decreasing and then increasing. In the long run more firms are active, but they transfer a part of the compliance cost to households by charging a higher markup. The negative effects on the level of economic activity of this anti-competitive outcome are strongly mitigated by recycling policies.

Keywords: *Environmental Policy, Dynamic General Equilibrium Model, Endogenous Market Structure.*
JEL codes: E60, Q54, Q58.

---

[*] This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. We are very grateful to two anonymous referees and to the Associate Editor, Knut Einar Rosendahl, for their excellent comments and suggestions. We also thank an anonymous referee of the CEIS Research Paper Series, Claudio Cesaroni, Francesca Diluiso, Pierfrancesco Molina, Simone Valente and Pietro Zoppoli for useful comments and discussions. The views expressed herein are those of the authors and not necessarily reflect those of Sogei S.p.A.

[†] *Corresponding author*: Dipartimento di Economia e Finanza, Università degli Studi di Roma Tor Vergata, Via Columbia 2, 00133 Roma - Italy; e-mail: barbara.annicchiarico@uniroma2.it.

[‡] Dipartimento di Economia e Impresa, Università degli Studi della Tuscia; e-mail: correani@unitus.it.

[§] Sogei S.p.a. - IT Economia - Modelli di Previsione ed Analisi Statistiche; e-mail: fdidio@sogei.it.

1 Introduction

This paper provides a fresh look at the relationship between emission limitation policy and economic activity by presenting a simple dynamic general equilibrium model including endogenous market structure and environmental policy. These features allow us to shed light on the relationship between environmental policy and the main macroeconomic variables, and to study how the gradual reduction of the emission target might feed back into the dynamic adjustment of the aggregate economy, thus affecting output, consumption and the price markup. In particular, we aim at analyzing the effects of mitigation policy in a model with endogenous firm entry, where firms interact in a oligopolistic market and, by virtue of their market power, manage to react to environmental regulation by transferring the burden of the abatement costs to households. Furthermore, the endogenous market structure of the economy allows us to identify the contribution of the extensive margin, as opposed to the intensive margin, to the price markup dynamics. This is a central issue in the recent heated debate over market-based greenhouse gas mitigation (GHG) policies. In this regard a principal concern is the potential impact of a strong climate action on production costs, employment and, ultimately, on the entry rate of firms. In the European Union (EU) member states are indeed divided over the 2030 climate and energy policy. Half of the EU countries fully support the 40 per cent GHG emission reduction target and the remaining half fear that a more ambitious action may endanger their competitiveness and frustrate their efforts to attain more rapid growth.[1]

The model we present in this paper has two key-features. First, it embeds oligopolistic competition *à la* Bertrand with endogenous firm entry, where entry into the goods market is subject to a sunk cost measured in units of labor. The entry of new firms is thus determined endogenously by equating the present discounted value of expected profits to such a sunk cost.[2]

---

[1] On the implications for international competitiveness of climate actions, see e.g. Aldy and Pizer (2015) and Alexeeva-Talebi et al. (2012).

[2] The use of the Bertrand model, as opposed to the Cournot oligopoly, is motivated by the fact that in Bertrand prices are strategic complements entailing two main methodological advantages. First, the existence of the model's equilibrium is guaranteed; second, games with strategic complements exhibit unambiguous comparative cross-policy properties, even if we do not obtain closed-form solutions for the equilibrium value (for more details, see Belleflamme and Peitz 2015). Some examples of Bertrand oligopoly are in Anderson and Wilson (2015), dealing with market power in the transportation industry, and Delbono and Lambertini (2016) who apply Bertrand competition to the wholesale electricity market.

Second, the model incorporates pollutant emissions which are a by-product of output, and the stock of pollution negatively affects the production possibilities of the economy. The government is assumed to set the aggregate level of emissions (namely the emission cap) and to sell emission permits to pollutant oligopolistic firms which, in turn, are induced to limit the environmental impact of their production activity by undertaking abatement measures, and to adjust their pricing decision in response to changes in the production cost. While the goods market is characterized by imperfect competition and endogenous firm entry, the rest of the economy is described by a simple flexible price model with endogenous labor supply. However, as a robustness check, we also carry out further analysis on the economy response to the mitigation policy under different hypotheses about the parametrization of the model, the available abatement technology, price adjustment costs and the utilization of revenues from permit sales. We argue that the toy model we present in this paper can be extended along several dimensions to be fruitfully used in environmental policy analysis.

Our analysis provides several interesting results. First, we find that in response to a mitigation policy envisaging a 30 per cent reduction of GHG emissions, the absence of perfect competition is likely to induce higher markups, while the number of active firms initially declines and then increases. In other words, we observe how the implementation of a mitigation plan tends to exacerbate the preexisting distortions caused by the lack of competition. The higher abatement effort required by the decarbonization process induces an increase in the cost sustained by firms, thus reducing the firm value. Furthermore market power allows producers to shift the abatement burden to households by charging a higher markup. At the earlier stages of the mitigation process the first force prevails and induces a decline of the number of firms. At later stages, however, the second force dominates the former and the number of active firms in the economy increases. Initially the policy pushes profits down, deters firms from entering the market and weakens competition, thus increasing markups and, through general equilibrium effects, decreasing wages. The permanent increase in markups and the reduction of wages induce a stronger intertemporal substitution effect on consumption and labor, which magnifies the effect of this policy shock compared to a model with perfect competition. At later stages, by virtue of the higher markup, the number of active firms in the economy starts to increase. Therefore, when the decarbonization plan is entirely implemented there are more firms that produce less individually. Second, the dynamic reaction of the economy along with the long-run effects are shown to crucially depend on several parameters, such as the exogenous exit rate of firms and their number, the available abatement technology, the intensity of the negative pollution externality on production, the size of the sunk entry costs, the Frisch elasticity of labor supply and the elasticity of substitution between goods. Third, the introduction of strong price stickiness gives rise to a major reaction of the markups already at earlier stages of the mitigation plan, thus immediately inducing the entry of new firms. Lastly, the negative effects on the level of economic activity of this less competitive allocation are strongly mitigated by recycling schemes, where the extra fiscal revenues generated by the environmental policy are used to mitigate labor income taxes or consumption taxes. Further, recycling schemes are shown to reduce the impact of environmental policy on the markup, thus diminishing its detrimental effects on competition. In this respect we show how the returns to revenue recycling are higher under imperfect competition.

The remainder of the paper is organized as follows. Section 2 presents a short overview of the literature related to the paper. Section 3 develops the model with endogenous market structure and environmental variables. Section 4 describes the baseline parametrization and the model solution. Section 5 illustrates the potential impact on competition of a policy action aimed at limiting pollutant emissions. Section 6 conducts the analysis under a wide range of possible parametrizations and allowing for different degrees of price stickiness. Section 7 presents two alternative policy scenarios in which the revenues of the environmental policy are recycled back into the economy through reductions of distortionary taxes. Section 8 summarizes the main results of the paper and concludes.

2 Related Literature

Global warming is one of the major policy issues at stake and is raising the attention of a growing body of academic literature. Given the extensive effects of climate actions on the economy, it is natural that this issue has been attracting the interest of an increasing number of researchers, also in the field of macroeconomics.[3] In particular, a recent macroeconomic literature investigates the short-run effect of such environmental regulation, exploring the associated economic trade-offs stemming from the presence of uncertainty and elucidating how temporary fluctuations, due to idiosyncratic shocks, interact with environmental policies in the achievement of climate-energy targets. In this respect, see the contributions by Fischer and Springborn (2011), Angelopoulos et al. (2013), Heutel (2012), Bosetti and Maffezzoli (2014), who conduct their analysis in real business cycle type models to study environmental regulation and optimal policy, and by Ganelli and Tervala (2011) and Annicchiarico and Di Dio (2015), who conduct similar analyses in New Keynesian models, where the interaction between uncertainty and environmental policies is further complicated by the existence of nominal rigidities and by the stabilizing role of monetary policy.

Our paper sits at the intersection of the literature combining environmental economics and macroeconomics in a general equilibrium model, aiming at assessing the impact of emission mitigation policies on economic activity. Given the close interrelationship between macroeconomic performance and environmental policies, this growing strand of literature includes some relevant aspects that are at the heart of the question, such as agents' expectations, lack of perfect competition and an intertemporal dimension. While our contribution embodies all these features, the introduction of an endogenous market structure allows us to single out the relationship between competition and mitigation measures through endogenous firm entry and a variable markup.

To the best of our knowledge we are the first to investigate the dynamic effects of a gradual mitigation policy in a framework where the existence of supply side strategic interaction, arising from oligopolistic producers competing on prices, is likely to amplify the response of the economy.[4]

---

[3] This is particularly the case for the relationship between economic growth and the environment. Pioneering works on such relationship include Nordhaus (1974, 1977) and Grossman and Krueger (1995), while for a political economy perspective, see Jones and Manuelli (2001), who study the relationship between pollution and growth in a model in which environmental regulation is set endogenously via voting. For exhaustive reviews of this literature, see Brock and Taylor (2005) and Xepapadeas (2005). More recently, a new strand in the growth literature emphasizes the importance of endogenous technological change for environmental policy. See Peretto (2008, 2009) and Acemoglu et al. (2012). In addition, the literature on the distributional and welfare aspects of environmental regulation and of public abatement, on the the macroeconomic implications of environmental externalities and on optimal taxation is very vast. See Bovenberg and van der Ploeg (1994), Bovenberg and Goulder (1996), Bovenberg and Heijdra (1998), Bovenberg and Heijdra (2002), Economides and Philippopoulos (2008), Heijdra and Heijnen (2013) and John et al. (1995). Yet environmental aspects are usually neglected by the so called "New Consensus Macroeconomics". On this point, see Arestis and González-Martínez (2015).

[4] For the importance of accounting for endogenous entry and strategic interaction among firms for the business cycle properties of an economy, see Bilbiie et al. (2012), Bilbiie et al. (2014), Faia (2012), Etro and Colciago (2010)

In this respect, we seek to contribute to the debate over environment policy and economic activity by pointing out the role of non-competitive markets in the transmission of the effects and in the transitional dynamics. First contributions in this direction are given by Peretto (2008, 2009), who studies the effects of environmental policy and energy taxes on technical change in models with endogenous firm entry.

Some recent contributions employ large scale dynamic general equilibrium models embodying a cap on pollutant emissions to analyze specific climate-energy policies for some EU countries. See Annicchiarico et al. (2017), Bartocci and Pisani (2013) and Conte et al. (2010). Aspects related to the market structure of the economy are however overlooked in these works.

Nonetheless, the mechanism for recycling mitigation-related revenues allows us to delve into distributional issues aimed at overcoming the emerging trade-off between mitigation policies and economic activity. Our paper is thus related to the literature exploring the implications of combining pollution taxes with revenue recycling. In this respect some relevant examples include Parry (1995), Bovenberg and Goulder (1996) and Goulder and Hafstead (2013) among others. In particular, Parry (1995) examines the interaction of environmental taxes with the labor market emphasizing the existence of an *interdependency effect*. The main result of the study is that the gains from using pollution tax revenues to substitute for labor tax revenue tend to be offset by the cost of exacerbating the preexisting distortion in the labor market. Bovenberg and Goulder (1996) extend earlier analytical works on optimal environmental taxation in a general equilibrium setting by considering pollution taxes levied on intermediate inputs. They show that even when revenues from environmental taxes are used to cut distortionary taxes, the optimal environmental tax rate is in general below the Pigouvian rate. Moreover, the numerical simulations show that with policy constraints, the optimal carbon tax rate is far below the marginal environmental damage and may even be negative, suggesting that estimates of optimal carbon taxes in integrated climate-economy models are biased upward.[5] In a recent paper Goulder and Hafstead (2013) examine the impacts of alternative revenue recycling options comparing lump-sum rebates, cuts in personal and/or corporate income taxes, and a tradable exemption option for carbon-intensive industries. Precisely,

---

and Etro and Rossi (2015).

[5] See, e.g., Nordhaus (1993).

using a CGE model, they simulate the economic impacts of a U.S. carbon tax under alternative methods of recycling the tax revenues, and show that using carbon tax revenues to finance marginal tax rate cuts can significantly lower the cost of carbon tax relative to lump-sum rebate. In this paper, we complement these findings by showing how the preexisting distortions of the economy related to the lack of competition are likely to alter the performance of recycling policies.

3 The Setup

The economy is populated by a continuum of identical households who consume, supply labor and hold shares of firms. On the supply side, perfectly competitive final goods producers assemble differentiated intermediate goods produced by oligopolistic firms, competing *à la* Bertrand, which face sunk entry costs. The existence of such entry costs thus allows us to endogenize the entry of firms along with their stock market value. In addition, pollutant emissions are costly to intermediate-goods producers and their level depends on the environmental policy and on the available abatement technology. The presence of endogenous market structure generates a time-varying price markup which depends on the number of firms, on the elasticity of substitution between goods and on the emission mitigation policy. Finally, the government runs a balance budget jointly deciding on fiscal and environmental policy.

3.1 Final Goods-Producing Firms

We assume that firms producing the final good are symmetric and act under perfect competition. In each period the representative firm producing the final good y_t^c combines a bundle of differentiated intermediate goods $y_{j,t}$ indexed by $j = 0, 1, 2... N_t$ according to a constant elasticity of substitution technology of the type, $y_t^c = \left(\sum_{j=1}^{N_t} y_{j,t}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}}$, where $\theta > 1$ denotes the elasticity of substitution between differentiated intermediate goods. Let p_t^c denote the price of this final good. Taking the price of each generic variety $p_{j,t}$ as given, the typical final goods firm chooses intermediate goods quantities $y_{j,t}$ to minimize its costs, resulting in the usual demand schedule: $y_{j,t} = \left(p_{j,t}/p_t^c\right)^{-\theta} y_t^c$. Perfect competition and free entry drive the final goods-producing firms profits to zero, so that from the zero-profit condition we obtain:

$$p_t^c = \left(\sum_{j=1}^{N_t} p_{j,t}^{1-\theta} \right)^{\frac{1}{1-\theta}}, \tag{1}$$

which defines the consumption price index of our economy.

3.2 Intermediate Goods-Producing Firms

The intermediate goods sector is made up of N_t oligopolistic polluting producers indexed by j. Notably, the lack of competition is a source of inefficiency. Oligopolistic markets, in fact, generate an average markup, which lowers the level of economic activity. Here we assume that firms compete in prices (i.e. Bertrand competition).

Following Bilbiie et al. (2012) new entrants in period $t-1$ will start producing at time t, so that the number of existing firms N_t evolves according to the following law of motion:

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

where N_{t-1}^e is the number of new entrants and $\delta \in (0,1)$ is an exogenous parameter denoting the fraction of both the existing and new firms which exit the market. This parameter δ can be interpreted as the probability for producers of incurring an exogenous-exit shock. It should be noted that the number of producing firms at time t is an endogenous state variable.

The typical firm j hires $l_{j,t}$ labor inputs to produce intermediate goods $y_{j,t}$, according to the constant-return to scale technology:

$$y_{j,t} = a_t l_{j,t}, \tag{3}$$

where the term a_t represents total factor productivity and is assumed to be negatively affected by pollution. To capture this negative externality we adopt a simple specification of the form:

$$a_t = \bar{a} \exp[-\chi(M_t - \overline{M})], \tag{4}$$

where $\bar{a} > 0$, M_t is the global stock of pollutant in period t, $\overline{M}$ is the pre-industrial atmospheric concentration of GHG, and χ is a positive scale parameter measuring the intensity of the negative externality on total factor productivity.[6]

As in Annicchiarico and Di Dio (2015) pollutant emissions at firm level, $z_{j,t}$, are assumed to be linearly related to output.[7] However, this relationship is affected by the abatement effort $u_{j,t}$. In particular, we assume

$$z_{j,t} = (1 - u_{j,t})\, \varphi y_{j,t}, \tag{5}$$

where $\varphi > 0$ measures emissions per unit of output in the absence of any abatement effort. The cost of abating a fraction of emissions, $\mathcal{C}_A$, is, in turn, a function of the abatement effort and output, namely:

$$\mathcal{C}_A(u_{j,t}, y_{j,t}) = \phi_1 u_{j,t}^{\phi_2} y_{j,t},\ \ \phi_1 > 0, \quad \phi_2 > 1, \tag{6}$$

where ϕ_1 and ϕ_2 are technological parameters. The term $\phi_1 u_{j,t}^{\phi_2}$ can then be interpreted as the fraction of individual output used for abatement purposes. Emissions are assumed to be costly for producers and the unit cost of emission $p_{z,t}$ depends, in turn, on the emission mitigation target.

Given the above assumptions and using (3), profits for firm j are defined as

$$D_{j,t} = p_{j,t} y_{j,t} - \frac{W_t}{a_t} y_{j,t} - p_{j,t} \phi_1 u_{j,t}^{\phi_2} y_{j,t} - p_{z,t} z_{j,t}, \tag{7}$$

where W_t is the wage. The typical firm j will then choose the set of sequences $\{u_{j,t}, p_{j,t}\}_{t=0}^{\infty}$ to maximize the expected discounted value of expected future profits (i.e. the firm value):

$$E_0 \left\{ \sum_{t=0}^{\infty} (1-\delta)^t Q_{0,t} D_{j,t} \right\}, \tag{8}$$

given the demand schedule $y_{j,t} = \left(p_{j,t}/p_t^c\right)^{-\theta} y_t^c$ and the price index (1). In (8) E_0 represents the

---

[6] A similar specification is adopted by Annicchiarico and Di Dio (2017), who simplifies that of Golosov et al. (2014). Notably, an alternative way of introducing the negative externalities of pollution into the economy is that of including it directly into the utility function. This is the strategy commonly adopted when studying the effects of pollutants that may directly harm health. Since here our focus is on GHG pollutants, we work under the assumption that climate change affects the production possibilities of the economy. See also Heutel (2012) and Nordhaus and Boyer (2003).

[7] This specification, in turn, simplifies the one adopted by Nordhaus and Boyer (2003) and Heutel (2012).

rational expectations operator, while the term $Q_{0,t}$ denotes the stochastic discount factor used at time 0 by shareholders to value date t profits, and is related to the household's discount factor $\beta \in (0,1)$ and to the their marginal utility of wealth λ_t (i.e. $Q_{0,t} = \beta^t \frac{\lambda_t}{\lambda_0}$).[8]

It should be noted that, contrary to the traditional Dixit-Stiglitz monopolistic competition approach, that neglects strategic interactions among firms, here under Bertrand competition, each firm sets the price of its own variety taking as given the price of the other firms, but taking into account the effects that its own pricing decision will have on the overall production price index. Therefore, at the optimum, the following first-order conditions must hold:

$$\phi_1 \phi_2 u_{j,t}^{\phi_2 - 1} = \frac{p_{z,t}}{p_{j,t}} \varphi, \tag{9}$$

$$p_{j,t} = \mu_{j,t} \left[\frac{W_t}{a_t} + p_{z,t} \left(1 - u_{j,t}\right) \varphi \right], \tag{10}$$

where $\mu_{j,t}$ is the firm's markup defined as

$$\mu_{j,t} = \frac{\theta \left(1 - x_j\right)}{\left[\theta \left(1 - x_j\right) - 1\right] \left(1 - \phi_1 u_{j,t}^{\phi_2}\right)}, \tag{11}$$

where $x_j = \frac{p_{j,t} y_{j,t}}{p_t^c y_t^c}$ represents the firm's j market share. Condition (9) equates the marginal value of abatement (i.e. the cost saving related to lower emissions, $\frac{p_{z,t}}{p_{j,t}} \varphi y_{j,t}$) to its marginal cost (i.e. $\phi_1 \phi_2 u_{j,t}^{\phi_2 - 1} y_{j,t}$). Condition (10) determines the optimal price as a markup $\mu_{j,t}$ over the marginal cost $\frac{W_t}{a_t} + p_{z,t} \left(1 - u_{j,t}\right) \varphi$. From equation (11), it is clear that the markup charged by producer j, $\mu_{j,t}$, is increasing in its market share x_j and in its abatement effort, while is decreasing in the degree of substitutability between products, θ. The lack of perfect competition allows firms to transfer the burden of the abatement to households by charging higher markups. For $x_{j,t} \to 0$ and in the absence of environmental policy, equation (11) collapses to the familiar condition $\mu_{j,t} = \frac{\theta}{\theta - 1}$ prevailing under monopolistic competition *à la* Dixit-Stiglitz.

In the symmetric equilibrium all oligopolistic firms charge the same price and choose the same abatement effort, therefore $p_{j,t} = p_t$, $u_{j,t} = u_t$, $\mu_{j,t} = \mu_t$, $y_{j,t} = y_t$, $z_{j,t} = z_t$, $D_{j,t} = D_t$, $x_j = \frac{1}{N_t}$,

---

[8] See Appendix A for details.

$p_t^c = N_t^{\frac{1}{1-\theta}} p_t$ and $y_t^c = y_t N_t^{\frac{\theta}{\theta-1}}$. The price p_t defines the production price index. Under symmetry (11) boils down to

$$\mu_t = \frac{\theta\left(1 - \frac{1}{N_t}\right)}{\left[\theta\left(1 - \frac{1}{N_t}\right) - 1\right]\left(1 - \phi_1 u_t^{\phi_2}\right)}, \tag{12}$$

which clearly shows how the markup is decreasing in the number of firms.

Since the number of firms evolves over time we have to determine the number of firms that each period enter the oligopolistic market, N^e, through an entry condition. To enter the market, firms must pay a fixed entry cost, η, which, following Bilbiie et al. (2012), corresponds to labor inputs necessary to set up a new business l_t^e, given the productivity level a_t: $\eta = a_t l_t^e$. The sunk entry cost is thus equal to $\eta W_t / a_t$. Let v_t indicate the value of a firm which is measured as the present discounted value of its future expected profits (8) expressed in units of the consumption good. Entry will occur until the firm value is equalized to the entry cost, therefore, under symmetric equilibrium, we can write the following free-entry condition:

$$v_t = \eta \frac{W_t}{p_t^c a_t}. \tag{13}$$

3.3 Households

The economy is populated by a continuum of identical households of mass one which maximize the following expected lifetime utility:

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left(\log c_t - \mu_L \frac{L_t^{1+\psi}}{1+\psi} \right), \quad \mu_L > 0,\ \psi \geq 0, \tag{14}$$

where c_t represents consumption of the final good, L_t denotes labor, μ_L weights the disutility of working and ψ is the inverse of the Frisch elasticity of labor supply.

The typical household supplies labor earning a wage W_t, pays taxes on consumption and on labor income at rates τ_t^c and τ_t^l, and holds shares of firms. Let s_t denote the shares carried over from the previous period. In each period holding shares yields a profit which is equal to the total dividends of all oligopolistic firms that produce in that period, namely $N_t D_t$. The period-by-period budget constraint for the typical household reads as:

$$p_t^c c_t(1+\tau_t^c) + p_t^c v_t(N_t + N_t^e)s_{t+1} = W_t L_t(1-\tau_t^l) + N_t\left(D_t + p_t^c v_t\right)s_t + p_t^c T_t, \tag{15}$$

where T_t are real fiscal transfers. The typical household will choose the set of processes $\{c_t,\ L_t,\ s_{t+1}\}_{t=0}^{\infty}$ to maximize (14), subject to (15) and to the usual transversality condition. First-order conditions to the above problem are then found to be

$$\lambda_t = \frac{1}{p_t^c c_t(1+\tau_t^c)}, \tag{16}$$

$$L_t^{\psi}\mu_L = \lambda_t\left(1-\tau_t^l\right)W_t, \tag{17}$$

$$\beta\left(1-\delta\right)E_t\left\{\frac{\lambda_{t+1}}{\lambda_t}\left[\left(D_{t+1} + p_{t+1}^c v_{t+1}\right)\right]\right\} - p_t^c v_t = 0, \tag{18}$$

where λ_t denotes the Lagrange multiplier attached to the household's budget constraint (15). Equation (17) describes the optimal condition with respect to labor, and (18) is the optimal investment condition with respect to firms' shares and describes the time path of their value v_t.

The solution to the typical household's problem is fully described in Appendix A.

3.4 Public Sector and Environmental Policy

We assume that the government budget is always balanced, therefore the flow budget constraint of the public sector reads as

$$p_t^c T_t = p_t^c c_t \tau_t^c + W_t L_t \tau_t^l + p_{z,t} Z_t, \tag{19}$$

where T_t, τ_t^c, τ_t^l are adjusted, in turn, to ensure the equilibrium, the term $p_{z,t}Z_t$ reflects total revenues from the government sale of emission permits $Z_t = N_t z_t$. In what follows we will consider an environmental policy characterized by an emission cap in which the overall emission target (i.e. Z_t) is set by the government according to an exogenously set mitigation scheme.

3.5 Aggregation, Resource Constraint and Stock of Pollution

In equilibrium all markets must clear, therefore labor demand and supply are equal:

$$L_t = N_t^e l_t^e + N_t l_t. \tag{20}$$

By combining the budget constraint of the households (15) with the flow budget constraint of the public sector (19) and profits under symmetry (7), and imposing the equilibrium condition $s_{t+1} = s_t = 1$, we obtain the resource constraint of the economy:

$$N_t \frac{p_t}{p_t^c} y_t = c_t + N_t \frac{p_t}{p_t^c} \phi_1 u_t^{\phi_2} y_t. \tag{21}$$

Recalling that $p_t^c = N_t^{\frac{1}{1-\theta}} p_t$ and $y_t^c = y_t N_t^{\frac{\theta}{\theta-1}}$, the resource constraint of the economy can be expressed in terms of the final consumption good as

$$y_t^c = c_t + \phi_1 u_t^{\phi_2} y_t^c. \tag{22}$$

Finally, the stock of pollution M_t accumulates as follows:

$$M_t = \kappa M_{t-1} + N_t z_t + Z_t^{RoW} + Z_t^{NI}. \tag{23}$$

where $1 - \kappa \in (0, 1)$ is the natural decay rate of GHG in the atmosphere, Z_t^{RoW} denotes emissions of the rest of the world and Z_t^{NI} non-industrial emissions.

Before tuning to the solution of the model and to the mitigation exercise, two remarks are needed. The first regards the fact that the economy under study has three sources of inefficiencies, namely: (i) the existence of an entry sunk cost, (ii) the oligopolistic market structure, and (iii) the negative externality of pollution which reduces the production possibilities of the economy. We will see how these features of the model shape the dynamic response of the economy to the decarbonization process. The second remark regards the absence of physical capital. In our simplified setup firms produce output only by means of labor. Of course in this way the model does not reflect a further source of inertial adjustment to the policy shift. Nonetheless, it is worth noticing that the presence of the stock of firms might be seen as a sort of capital stock of the economy. Indeed, we make use of a different notion of investment, fully relying on the extensive margin (firm-capital to manufacture new varieties of goods), as opposed to the intensive margin (physical capital to produce more of the same good).[9]

In Appendix A we summarize the equations of the model.

4 Parametrization and Model Solution

In this Section we present the benchmark parametrization used to assess the quantitative implications of an emission reduction plan. The parametrization is summarized in Table 1. The model frequency is quarterly. Some parameters are calibrated using data for EU15 countries, while others are set in line with the existing literature.

The discount factor β is set to 0.99, so that the steady-state annualized real interest rate is equal to 4%. We set the rate of business destruction δ equals to 0.025 as in Bilbiie et al. (2012), so as to imply an annual exit rate equal to 10%. Following Smets and Wouters (2003), we assign a value of 3.8 to the elasticity of substitution between differentiated intermediate goods θ. The calibration of the parameter governing the labor elasticity ψ (the inverse of the Frisch elasticity) is more delicate, given the important role played by this parameter in shaping the dynamic response of an economy to shocks and policy changes. Notably, there is a wide variety of estimates available for the Frisch elasticity (i.e. the elasticity of labor supply with respect to wages at constant marginal utility), ranging from 0.2-0.5 to 2-4 depending on whether the econometric investigation is based on microeconomic or macroeconomic data.[10] Given the great uncertainty surrounding the estimates of the Frisch elasticity of labor supply, we set the relevant parameter ψ so as to match the observed relative standard deviation of hours with respect to GDP for the EU15 for the period 2000-2015. According to OECD HP filtered annual data the relative standard deviation of hours is 0.7, while the standard deviation of GDP is 0.0119, corresponding to a quarterly value by about 0.006. To

---

[9] In this sense, as explained by Bilbiie et al. (2012), the decision of households to invest resources for the entry of new firms is equivalent to the decision to invest in physical capital as in a standard model.

[10] On this, see Rogerson and Wallenius (2009), Chetty (2012) and Peterman (2016).

match such variability, we have extended the model to allow for productivity shocks. Therefore, only for calibration purposes, equation (4) is replaced by $a_t = (\bar{a} \exp \varepsilon_t) \exp[-\chi(M_t - \overline{M})]$, where $\varepsilon_t = \rho\varepsilon_{t-1} + \xi_t$, $0 < \rho < 1$ and $\xi_t \sim i.i.d.N(0, \sigma^2)$. Setting $\sigma = 0.009975$, $\rho = 0.9$, with an inverse of the Frisch elasticity, ψ, set at 2, we obtain a quarterly standard deviation for output 0.006 and a relative standard deviation of hours close to 0.7. Hence, with a Frisch elasticity of 0.5, our model is able to match the observed amount of volatility in aggregate hours.[11]

The scale parameter μ_L, measuring labor disutility, is calibrated to 0.4897 in order to induce the steady-state level of labor L equal to 1. The level of technology a and the baseline value for the entry cost η are set such that the final output y^c is equal to 1 and so the number of new firms entering the market N^e. Clearly, alternative combinations of the level of technology a and of the entry cost η affect the endogenous level of market power since a low (high) entry cost, compared to the size of the market, leads to a larger (smaller) number of competitors and thus to less (more) market power and lower (higher) markups. Finally, we set the consumption tax rate τ^c to 0.2, and the labor income tax rate τ_t^l to 0.36. The rates reflect the average implicit rates observed in the EU15 countries in 2015 consumption taxes and for labor income. See OECD (2016a) and the OECD Tax Database.

Turning to the parametrization regarding the environmental part of the model, our calibration strategy starts with matching the observed average emission intensity for EU15. According to the World Bank Indicators we set the initial level of Nz/y^c at 0.1763, which corresponds to the mean of the CO_2 kilos per GDP (constant 2010 US$) observed for the years 2010-2014. Having normalized the level of output to 1, with this restriction we pin down total emissions of the economy in model units. The scale parameter φ is then determined so that the level of abatement effort is consistent with the observed reduction of CO_2 in the period 1990-2014 according to World Bank Data for EU15 (i.e. 18.84%).

The parameter ϕ_2 is set at 2.8, consistently with the RICE-2010 model of Nordhaus.[12] To

---

[11] Only for calibration purposes the model has been initially solved relying on a first-order perturbation method, which is a solution method commonly used for running stochastic simulations. The relevant statistics are computed on simulated series for 10,000 quarters, dropping the first 200 periods. Stochastic simulations have been carried in Dynare, a software platform for handling dynamic general equilibrium models. See Adjemian et al. (2011).

[12] The RICE-2010 model is available for download at http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm. For a detailed description of the model, see Nordhaus and Boyer (2003).

circumvent the great uncertainty surrounding the estimates of the abatement costs (see Fischer and Morgenstern 2006), we anchor the scale parameter determining their size, $\phi_{1,}$ to the effective carbon rate (ECR) observed for EU15 in 2016. According to OECD (2016b) , the weighted average ECR is equal to 22.7466 euros per tonne of CO_2. We then use the observed ECR to calibrate the initial steady state for $\hat{p}_z$. Using the optimal condition $\phi_1\phi_2 u^{\phi_2-1} = \frac{\hat{p}_z}{\hat{p}}\varphi$, the scale parameter ϕ_1 immediately follows.

To calibrate $\bar{a}$ and χ and pin down an initial steady state level for M we proceed as follows. We start by observing that according to World Bank Data in 2015, the share of EU15 on total world emissions of CO_2 is 0.07186. In this way we obtain total industrial emissions in modelling units $Nz + Z^{RoW}$. From the RICE model projections, non-industrial emissions amount to 11.312% of total industrial emissions of CO_2 in 2015, therefore $Z^{NI} = 0.11312(Z^{RoW} + Nz)$. By setting a decay rate $1-\kappa$ of the carbon dioxide to 0.0021 as in Reilly and Richards (1993), from (23) these results deliver the stock of pollutant in modelling units M. According to the United States Environmental Protection Agency carbon dioxide concentrations have increased substantially since the beginning of the industrial era, rising from an annual average of 280 ppm in the late 1700s to 401 ppm as measured in 2015. We are so able to express $\overline{M}$ in modelling units $\overline{M} = \frac{280}{401}M$. Finally, from the RICE model projections damage costs of pollution for Europe amount to 0.0026 of the GDP. By recalling that aggregate output is $y^c = yN^{\frac{\theta}{\theta-1}} = \bar{a}lN^{\frac{\theta}{\theta-1}}\exp[-\chi(M-\overline{M})]$ and that the environmental damage is measured as $\bar{a}lN^{\frac{\theta}{\theta-1}}\left(1-\exp[-\chi(M-\overline{M})]\right)$ the parameter χ immediately follows.[13] The scale parameter $\bar{a}$ immediately follows from $a = \bar{a}\exp[-\chi(M-\overline{M})]$.

In our simulation exercise aimed at assessing the potential macroeconomic impact of an emission mitigation plan, we examine the response of the economy to a permanent and gradual reduction process of the aggregate emission target, starting at the beginning of our simulation time horizon. In what follows we abstract from the presence of uncertainty,[14] focusing our analysis on deterministic simulations. Therefore, any possible source of uncertainty about the parameters or the underlying path of policy changes is ruled out. In particular, the model is solved using a Newton-type algo-

---

[13] Parameter χ solves equation $0.0026 = \frac{1-\exp[-\chi(M-\overline{M})]}{\exp[-\chi(M-\overline{M})]}$.

[14] However, given the uncertainty surrounding the structural parameters of the model, in Section 6 we check how our results are affected by an alternative parametrization through some sensitivity analysis.

rithm. To conduct our simulation exercise, we treat total emissions Z_t as an exogenous variable and examine the deterministic response of the economy to permanent changes in this variable.

Deterministic simulations are carried out when studying the effects of structural reforms and/or policy interventions involving permanent changes (see e.g. Conte et al. 2010 and Annicchiarico et al. 2017). The economy is assumed to be initially in a state of equilibrium before a period '1' when the mitigation plan is learned by agents. With the simulations we are able to describe the dynamic response of the economy in reaction to both current and future emission cuts. Clearly, the analysis of the effects of permanent policy shifts requires solving a two-point boundary problem, specifying the initial conditions for the predetermined variables and the terminal conditions for the forward looking variables. To solve this problem we have derived the new steady state of the model implied by the environmental policy put in place and used the theoretical equilibrium values as terminal conditions.[15]

5 Environmental Policy and Market Structure

In this Section we present the main simulation results. In particular, we analyze how a 30-per-cent reduction in GHG overall emissions may interplay with the economy and how it may affect price markups and firm entry. The reduction is assumed to be permanent, but it is modeled as a gradual change, phased in over 15 years. In this way we account for the slow pace of convergence toward the European Union climate targets, requiring member states to cut their carbon dioxide emissions over a comparable time frame. We also assume that the policy action is fully credible and anticipated by agents. We initially consider the simple case where revenues from the emission permits are earmarked for households through a lump-sum transfer. Section 7 will consider different recycling hypotheses, so as to appreciate the possible distributional implications of this scenario.

The GHG mitigation policy is evaluated along two dimensions: first, we look at the transitional dynamics on a quarterly basis, then we analyze the medium-long run effects. Figure 1 reports the adjustment dynamics during the transition toward the new steady state for 9 key macro-variables,

---

[15] The model has been solved using Dynare. For more details on the algorithm used for deterministic simulations, see Adjemian et al. (2011).

namely aggregate output y_t^c, output per firm y_t, consumption c_t, labor L_t, the number of firms N_t, the price markup μ_t, the overall emissions $N_t z_t$, the abatement effort u_t and the permit price $p_{Z,t}$. All the variables are expressed as percentage deviations from the initial steady state level, with the exception of the abatement effort u_t that is expressed as percentage point (p.p.) deviation. Time on the horizontal axis is in quarters. Table 2 shows the effects of this mitigation policy for different time horizons up to the long run. For the sake of completeness, Table 2 also reports labor inputs l_t and dividends per firm d_t, the value of firm v_t and the real wage w_t.

We start by discussing the impact of this mitigation policy on the economy, then we delve into the subsequent dynamics in a long-term perspective. In order to understand the economic forces behind the results, it is instructive to take a close look at the chain of events triggered by the policy under consideration and then at how the variables gradually adjust toward the new equilibrium.

First consider the response of incumbent firms. As expected, this gradual policy of emission reduction entails a higher abatement effort and a boost in the permit price. Note that the abatement effort increases less than proportionally relatively to the permit price as a consequence of the convexity of the abatement technology (see in particular equation 9). Intuitively, since abatement costs are now higher, firms are induced to resort to an alternative option for complying with environmental regulation, namely buying emission permits, so as to bring about an increase in their price. Despite these higher costs, at the earlier stages the decarbonization process yields a positive, albeit small, effect on aggregate output, on output per firm and on consumption. The higher costs for permits and abatement do not prevent incumbent firms from expanding their production. Indeed market power allows producers to shift a part of the compliance cost to consumers by charging a higher markup, which in fact is shown to leap up immediately. However, despite the higher markup, consumption slightly increases as a result of the initially higher current profits which contribute positively to the budget constraint of households. Also, this initial positive effect on consumption is amplified by the decreasing value of firms that further pushes households to increase consumption through a reduction in savings.

Now analyze the response of potential entrants to the mitigation plan. As a result of the higher current and expected compliance costs, the firm value immediately decreases thus discouraging entry. It is worth highlighting that, while the cost of the environmental policy is fully borne by the incumbent firms, it nonetheless reduces the value of potential entrants so as to discourage entry, at least initially. We observe, in fact, that on impact the number of new entrants, N^e, moves down. Therefore, the demand for labor inputs necessary to set up a new firm decreases, thus yielding a drop in the wage. The free entry condition is met when the firm value and the wage reduce proportionally. The reduction of the wage, in turn, contributes to the initial expansion of the output of incumbent firms. It is worth noting that the entry of new firms is subject to a one period time-to-build lag, as equation (2) reads, implying that on impact the number of active firms, N, remains unchanged.[16]

The subsequent dynamics of the model substantially change. After the initial positive jump, we observe a reduction of output and consumption, while labor continues to inch down along with the wage, while the markup steadily increases. The number of active firms, instead, declines up to the first 10 quarters, and then starts to increase converging toward a higher value. With the gradual reduction of the overall emissions, Nz, the abatement effort increases accordingly. However, since in the long run the number of firms is higher, the percentage reduction of emissions at firm level must be larger than that observed at aggregate level.

As the mitigation policy becomes increasingly implemented, it imposes a higher permit price and abatement costs on firms. In response to this increase in their costs, producers will reduce their emissions not only by increasing their abatement effort, but also by decreasing production. As a consequence, firms will reduce the demand for labor and so the wage will trend down. A fraction of this extra cost is transferred to consumers, through a higher markup, which in fact is shown to increase steadily along all the adjustment path. In these circumstances it comes as no surprise that in the long run consumption reduces by more than aggregate output. On the one hand, we observe a sort of crowding out mechanism, due to the fact that a higher amount of resources is devoted to emission abatement and so less resources are now available for consumption. On the other hand, the higher markup charged by firms further reduces consumption possibilities. It should be noted that, while this crowding out effect is quite common to models adopting this kind of formalization

---

[16] This also explains why initially the positive effect on aggregate output and on output per firm is of the same size.

for abatement costs, the markup effect is instead specific of this model, where the oligopolistic market structure introduces further complications.[17] In other words, the effect of this policy on consumption is magnified in the presence of an endogenous market structure.

To conclude our discussion we now have to explain why, after an initial downturn, the number of active firms increases, displaying a U-shaped adjustment path. Despite the steady reduction of the firm value, it can be shown that the entry rate becomes positive already after 3 years. This result is due to the sharp decline of the wage rate, which makes it possible for the potential new firms to bear a lower cost to start up their business and thus facilitating their entry notwithstanding that the higher costs, needed to comply with the emission reduction, trigger a deterioration of profit opportunities. Clearly, the dynamic response of incumbents and entrants is driven by related mechanisms. On the one hand, incumbent firms respond to the mitigation policy by increasing abatement effort, by boosting markups and by reducing production. This downsizing of incumbents leaves room for the entry of new firms in the market. Despite the deterioration of the market conditions, the higher markups and the lower wage are such to induce the entry of new firms explaining the observed dynamics. This key mechanism explaining the relationship between incumbents and potential entrants determines the quantitative response of the environmental policy on the main macroeconomic variables. Besides this interesting dynamics, our results clearly show that at least in the short-run the bulk of the implementation-related effects of the policy are about production at intensive margin, rather then the number of firms which changes only moderately.[18]

The consequent higher number of firms operating in the economy, eventually, tend to mitigate the markup increase delivered by the higher abatement cost. All in all, as a result of the policy aimed at reducing the overall level of emissions, a large number of less polluting firms will be active in the economy.[19]

---

[17] See, e.g., Heutel (2012) and Annicchiarico and Di Dio (2015). It should be noted that in Annicchiarico and Di Dio (2015) abatement costs consist in units of final output, while here they represent a fraction of firm intermediate-good production.

[18] This result depends on the timing of the implementation. See Appendix B, where we show that under the assumption of a faster implementation of the mitigation process the number of firms changes at a greater extent already in the short run.

[19] This result is consistent with the findings of Peretto (2008) who shows that an exogenous-rate effluent tax reduces the scale of activity of each firm, but has positive effect on the number of firms. In Appendix B we show that results are very similar if we assume an emission reduction target set at firm level. However, as a result of the higher number of active firms, already in the medium run, we observe that the percentage reduction of overall emissions is lower

6 Sensitivity Analysis

This Section discusses sensitivity analysis. In particular, we carry out a series of checks to assess the robustness of the previous results against changes in the values of some key-parameters that might be surrounded by uncertainty and that might be particularly relevant in shaping the response of the economy to a gradual decarbonization process. The parameters of this analysis include the firm exit rate δ, the elasticity of substitution between goods θ, the abatement technology parameter ϕ_2, the intensity of the negative externality of pollution on productivity χ and the inverse of the Frisch elasticity of labor supply ψ. For completeness we also check how the results change when we assume different values for the parameter η, reflecting higher or lower entry sunk costs.

We conclude our analysis by exploring the possible role of nominal rigidities, by introducing adjustment costs *à la* Rotemberg (1982) into the model. To better appreciate the effects of changing parameters on the entry of firms and, therefore, on the market structure we plot the firm value, instead of aggregate emissions, which in all cases follows the same linear decreasing path as in Figure 1.

6.1 Exit Rate, Elasticity of Substitution between Goods and Entry Sunk Costs

Figure 2 shows the short-run response of the economy to a gradual cut of emissions for three different values of the exit rate δ, while Table 3 reports the long-run effects. Compared to the benchmark scenario, we observe that a higher firm exit rate is shown to induce a sharper reduction of output. The reduced level of output, in turn, implies a lower demand of labor from active firms, whose reduction is now more pronounced relatively to the benchmark. Also, at the earlier stages of emission reduction a higher exit rate improves the profit opportunities for the existing firms since the markup will decline slightly less. The combination of lower wages with higher firm value turns out to attract a higher number of new firms, so as to partially counterbalance the effect stemming from the higher exit rate. This is why we observe a higher number of active firms relatively to the benchmark case and the effect of changing δ on N and y^c has a different sign. Overall, the major

---

than that envisaged by the emission reduction target set at aggregate level. In Appendix B we also explore different speeds of implementation. We show that the higher the speed of the mitigation plan, the sharper the initial drop in the number of firms.

qualitatively changes regard the number of firms whose dynamics is directly affected by changes in δ from equation (2). Furthermore, the sharp decline of wages and labor affects household income, so as to reduce consumption accordingly. However, at later stages of the decarbonization process, the incentive to entry will ultimately taper off and the relationship will be reverted. To sum up, in the long run for a higher exit rate the environmental policy would deliver lower output and consumption. Similar considerations hold for the case of relatively lower values of firm exit rate, but in the opposite direction.

Figure 3 presents the response of the economy to the mitigation policy for three different values of θ, while Table 3 shows the long-run impact on the main macroeconomic variables. A lower elasticity of substitution between goods θ confers more market power to firms, which, therefore, will be able to set a higher markup. By virtue of their higher market power, oligopolistic firms will be able to transfer a major portion of the abatement cost to households. As a result, the level of economic activity will reduce by more, while the number of firms will diminish by less during the early stages of the GHG mitigation process. In the later stages, the major profit prospects will tend to attract more firms than in the benchmark parametrization, therefore at the end of the adjustment process there will be more active firms, producing less and charging a higher markup. On the contrary, for a higher θ, the ability of firms to transfer the burden of the abatement cost to households is diminished. As a result, the effect on the markup will be lower than in the benchmark case so as the number of active firms.

By increasing indefinitely the elasticity of substitution θ goods become perfect substitute. In this circumstance the elasticity of demand faced by a firm increases without bound and the economy will tend toward a more competitive market structure. However, the existence of sunk entry costs would prevent firms from entering the market in the case of too low expected profits. In order to have a useful benchmark of what would be the dynamics under perfect competition we have also solved the model assuming no barriers to entry (and exit), homogeneity of goods and price-taking firms. The results are reported in Appendix C. Consistently with the findings obtained in our sensitivity exercise for a higher θ, the detrimental effects on the level of economic activity of the decarbonization process are strongly lower than those obtained in oligopoly where mitigation policy is found to further exacerbate the existing distortions related to the lack of competition.[20]

Figure 4 shows the effects of the mitigation policy for different values of the scale parameters η that determines the size of the sunk entry costs. In this case assuming a higher value for η entails that the mitigation plan is implemented under an initial lower degree of competition among firms (e.g. higher entry sunk costs imply a higher markup). Besides, we carry out a simulation when η is lower than the benchmark. To be sure, the results with a higher η are qualitatively similar to the case of a lower elasticity of substitution between goods θ discussed above, although the mechanism that lies behind the short-term adjustment might be interpreted differently. Indeed, when η is higher there is a lower number of new entrants N^e, the competitive pressure on the active firms is more feeble, so that they are able to operate with a higher markup. Households will thus bear the higher cost of the mitigation policy compliance, so that consumption will reduce by more than in the benchmark case. Production, labor and wages will adjust accordingly. It is worth noticing that while, on the one hand, the profit prospects are more favorable as a result of a lower level of new entrants, on the other hand a higher markup will amplify the drop in output, so as to reduce the profitability of incumbents. Since this second effect tends to prevail over the first, we observe that the value of firms will be slightly lower relatively to the benchmark case. As for the case of a lower elasticity of substitution, in the long run we will observe more firms producing a lower level of aggregate output and setting a higher markup. The opposite is true for a lower level of the entry sunk costs. Clearly, the higher the number of firms in the economy, the less price setting firms will perceive the effects that their decisions will have on the general price level. The economy will thus tend toward a monopolistic competitive structure.[21]

---

[20] Under perfect competition, at the earlier stages output does not increase as in oligopoly, where instead incumbent firms find it optimal to initially increase production to support the higher abatement. See Appendix C.

[21] It should be noted from (2) that the number of incumbent firms N is increasing in N^e. In the Appendix C we solve the model under the assumption of monopolistic competitive market *à la* Dixit-Stiglitz and show the results of our mitigation exercise. In particular, the positive effects on the level of economic activity are initially slightly lower than in the benchmark case. In the long run, instead, the number of active firms is higher, overall production is higher, while production per firm is lower than in oligopoly. Intuitively, while the markup is increasing in the abatement effort, it does not change in response to the number of firms. The initial decrease and the later increase in the number of incumbent firms observed during the adjustment process affect the markup in oligopoly and is able to explain the different quantitative response.

6.2 Abatement Technology and Environmental Damage

Figure 5 considers different abatement technology by changing the value of ϕ_2. As usual in Table 3 we report the long-run implications of the carbonization process under a different parametrization. We start by discussing the short-run implications of having a less favorable abatement technology and notice what follows. First, when abatement is more costly the price on emission permit consistent with a declining level of emissions will be higher. Second, the higher ϕ_2, the larger the amount of resources needed to comply with the environmental regulation. In this case, the markup will increase by less, therefore the level of output will reduce by less. Consistently, labor will diminish by less and so the number of active firms. In the long run the higher abatement cost implies a lower decline of output than in the benchmark case, consistently with the fact that the compliance with a 30 per cent cut of emissions requires more resources, while the number of active firms will be lower since the higher compliance cost reduces the entry of new firms.

Now consider what happens when a more favorable abatement technology is available. We notice, as expected, that the price of emission permit will increase by less and that, more interestingly, the markup will now increase by more, since less resources are now required to comply with the environmental regulation. The possibility of charging a higher markup, however, makes entry relatively more attractive than in the benchmark case, inducing a lower initial decline of the number of active firms, that in fact starts trending upward already after the first 9 quarters. In the long run the lower abatement cost induces a much lower decrease of output, while the number of active firms increases by less than in the benchmark case, as a result of the relatively lower profitability. It should be noted that two effects are at work here. On the one hand, a lower abatement cost is consistent with a higher level of economic activity than that observed in the benchmark case. On the other hand, since less resources are now needed for complying with environmental regulations, in equilibrium the markup charged by firms will be higher. This effect is induced by the lower number of active firms in the new steady state. As a result of a lower abatement cost we have less firms and less competition than in the benchmark case. On the contrary, when the abatement cost is higher, we will have less firms (because of the less favorable technology), but more competition than in the benchmark case.

To better illustrate the non-linearity of the relationship between long-run output and the convexity of the abatement function, see Figure 6, where we plot the long-run variation for aggregate output and the number of active firms for different values of ϕ_2. We also plot the long-run effect of the mitigation policy on the markup for different abatement technologies. The vertical lines correspond to the benchmark case. Notice that for lower values of ϕ_2 the more advantageous abatement technology induces a lower drop of output, despite the fact that the markup is higher. Clearly, a more favorable technology requires less resources to comply with the regulation. By increasing ϕ_2 the long run impact on output becomes more negative, while more firms find it optimal to enter the market, but will produce less. However, when the abatement technology becomes more convex and thus less favorable, firms cannot charge too much higher markups and have to produce more than in the benchmark case in order to support the very costly abatement and the higher permit price. As a result, the new steady state value of output will curve upward, while the long-run number of active firms will decrease.

Consider now the effects of the mitigation policy for higher values of the damage intensity factor χ. See Figure 7 for the short run and Table 3 for the long-run effects. A higher χ implies that the mitigation policy has stronger positive effects on productivity inducing a fall of firms' marginal costs. As expected, output and consumption will be higher than in the benchmark, while labor will display a negative reaction. Then, wages will steadily decline less than in the benchmark case making the entry of new firms more costly and thus provoking an outflow of firms. This is why we observe a more pronounced reduction in the number of firms. No noticeable change instead is observable for abatement effort, emission price and markup. Overall, in the short run results are relatively invariant to the choices on damage parameter χ, since the mitigation process is slowly implemented and regards only one area of the world (the EU15).

In the long term, when the mitigation plan is fully implemented, the beneficial effects from the higher productivity may more than compensate the cost of compliance with the mitigation policy, thus inducing firms to expand the production and creating larger profit opportunities.[22] This, in turn, attracts new firms, so that in the long term the number of firms will be higher than in the

---

[22] This is particularly evident under the assumption of a very high χ, where the beneficial effects ascribed to the reduced negative externality more than overcome the costs of the policy.

benchmark. Part of the increase in output is invested in firm creation, that on the one hand pushes output up, on the other hand strengthens the feedback effect on consumption, yet fuelled by the increase in labor supply associated with higher wages.

6.3 Frisch Elasticity and Nominal Rigidities

In Figure 8 we report the effects of varying the inverse of the Frisch elasticity of labor supply ψ from 0.5 to 5 (in the benchmark calibration it is set to 2). A higher elasticity of labor supply (i.e. a lower ψ) entails a stronger reduction of labor, implying a diminished positive effects of output on impact and a stronger decline in transition. The reduction of output of incumbent firms, which starts already in the second quarter, implies lower emissions per firm and so lower abatement cost. As a result, the present discounted value of profits (i.e. the firm value) reduces by less, the higher the elasticity of labor supply, thus inducing a lower decrease of the number of active firms, at least in transition. In the long run the effects are reverted. In the long run equilibrium, in fact, the diminished response of wages necessary to clear the labor market, will imply a lower firm value and so a lower number of active firms.

We conclude this Section by studying the implications of having costly price adjustment in the model.[23] We assume that intermediate goods oligopolistic producers face quadratic adjustment costs when resetting their price in the spirit of Rotemberg (1982), $\frac{\gamma_p}{2}\left(\frac{p_{j,t}}{p_{j,t-1}}-1\right)^2 y_{j,t}$, where $\gamma_p > 0$ measures the degree of sluggishness in the price adjustment process. The introduction of nominal rigidities shapes the transitional dynamics, but it does not affect the long run response of the economy to the mitigation policy. Put it differently, setting nominal rigidities to different levels alters only the speed of adjustment toward the new steady state. In Figure 9 we increase the parameter measuring the degree of price rigidities, γ_p, from zero, which represents the benchmark case with flexible prices, to 25 and then to 50. With costly price adjustment firms will have to reduce production by more in order to comply with the required cut of emissions. This will induce inevitably to higher markups, which in turn, will attract more firms into the market already during the earlier stages of the decarbonization process. It should be noted that the effects induced

---

[23] See Appendix D for details.

by sluggish price adjustments are completely absorbed after 10 years for aggregate production, consumption and labor, while persist on markups (which drive the different dynamics), the number of firms and production at firm level.

7 Mitigation with Redistributive Policies

All previous scenarios are designed in a way that fiscal revenues generated by government sale of emission permits are earmarked for transfers T_t to households, so as to keep public budget balanced. In this Section, instead, we consider two alternative scenarios which specifically differ in recycling the emission permit revenues. An alternative mechanism for recycling mitigation-related revenues allows us to seek the effects of growth-enhancing distributional policies. In particular, we carry out two additional simulations in which the fiscal revenues from the sale of emission permits serve either for the reduction of consumption taxes or of labor income taxes. In other words, we endogenize, in turn, the tax rates τ_t^c and τ_t^l, keeping the amount of lump-sum transfers constant.[24]

By and large, reductions in either consumption or labor taxes have a number of positive effects on rendering the mitigation policy less painful. In this respect our simulation results are broadly consistent with the relevant literature discussed in Section 2, showing that carbon revenues recycled for consumption or labor taxes is less harmful for the economic activity than recycled through lump-sum transfers. Although differences between recycling rules is very small in the short run, it is still possible to appreciate considerable differences in the medium-long run.

Taking a closer look at these scenarios (see Figure 10 and Tables 4 and 5), we note that in the short term the two policy options slightly differ from to the benchmark case, whereas significant effects on aggregate output, consumption, labor and the number of active firms materialize in the medium-long run, especially when the fiscal revenues of the environmental policy are used to reduce labor income taxes. In this case, in fact, compared to the baseline, the long-run negative impact on aggregate output and consumption is about 27 basis points lower, while the impact on labor is softened by respectively 24 basis points. The benefits from reducing consumption taxes, are,

---

[24] Of course other recycling schemes could be considered. For instance revenues from the mitigation policy could be used to subsidize firms to sustain their abatement cost. For various policy experiments in the context of dynamic general equilibrium model, see Conte et al. (2010) and Annicchiarico et al. (2017).

in turn, more modest hovering around 10 basis points for output and consumption, and about 7 basis points for labor. Moreover, the higher relative benefits from labor tax cuts with respect to consumption tend to spread out over time, reaching a substantial difference in 20 years. It is worth noting that the impact on price markup is significantly reduced when these recycling schemes are at work, so that policies designed to address distributional concerns could also relieve the cost of climate change mitigation by granting more competition among firms relatively to the benchmark. Also in the long term, under both recycling schemes, the effect on the markup will be around 11 basis points lower than in the baseline case.

In order to understand the importance of market structure in determining the benefits of recycling, we conclude our analysis by comparing the long-run effects of mitigation obtained in oligopoly with the ones that would stem out in perfect competition.[25] The results are shown in Table 6. Clearly, the benefits of recycling, intended as the lower loss in terms of economic activity, are larger in oligopoly than in perfect competition. That is because in oligopoly the final outcome is distorted by the lack of competition and the marginal benefits of distortionary tax reductions are larger. When we look at the welfare cost, measured in terms of consumption equivalent units,[26] we also notice how the benefits of recycling are larger in oligopoly than under perfect competition. Recycling revenues to cut consumption taxes, rather than lump-sum taxes, reduces the welfare loss by 5.6 basis points in oligopoly and by 3.31 basis points under perfect competition. In the case of labor income tax cuts, we observe a reduction of the welfare cost by 17.58 basis points in oligopoly and by 7.5 basis points in perfect competition.[27]

Two major policy messages emerge from this analysis. First, the choice of the recycling schemes affects both the size of the related economic benefits and the degree of competition. As a result, the

---

[25] See Appendix C for the alternative model specification.

[26] The welfare cost is defined as the permanent change in consumption that leaves households indifferent between the utility derived by remaining in a no-policy equilibrium and the utility implied by the implementation of the emission mitigation plan.

[27] By comparing the welfare costs under the two different market structures we notice that these are larger in oligopoly than under perfect competition when the revenues from the environmental policy are recycled to reduce lump-sum or consumption taxes. On the contrary, when the revenues are recycled to reduce labor income taxes the detrimental effects on welfare the policy are slightly lower in oligopoly. These results show how the preexisting distortions of the economy are likely to alter the performance of recycling policies. From this perspective an *interdependency effect*, as meant by Parry (1995), would affect the optimal design of environmental policy. We leave this aspect to future research.

range of options of these rules should be carefully evaluated as they could significantly magnify the economic benefits and, to some extent, alleviate the trade-offs arising between mitigation actions and the degree of competition. Second, the farther the market from a competitive outcome, the higher the benefits of coupling a decarbonization process with a redistributive policy reducing the level of economic distortions.

8 Conclusions

In this paper we analyze the impact of an emission mitigation process on economic activity and competition in a dynamic general equilibrium model embodying endogenous firm entry and environmental policy. In particular we construct a model featuring Bertrand oligopolistic competition with differentiated goods and endogenous firm entry, where pollutant emissions are a by-product of output. We show that in response to a gradual emission mitigation policy producers tend to transfer the higher abatement cost to households by charging a higher markup. The number of firms displays a U-shaped behavior, first decreasing and then increasing, so that in the long run we observe a lower market concentration. The dynamic response of the economy as well as the long-run implications of environmental policy are crucially affected by the abatement technology, the elasticity of substitution between goods produced by oligopolistic firms, the size of sunk costs, the intensity of the negative externality of pollution, the existence of nominal adjustment cost and the firm exit rate.

Overall, we find that models with endogenous market structure may be extremely useful to shed light on the distributional implications of environmental policy. In this context, in fact, recycling schemes, according to which the extra fiscal revenues generated by the environmental policy are used to diminish distortionary taxation, are shown not only to mitigate the detrimental effects on the main macroeconomic variables generated by the decarbonization process but also to reduce the positive effects on markups. In this sense, a carefully designed recycling scheme is shown to reduce the potential anti-competitive effect of a pollution mitigation policy.

In interpreting our results some words of caution are needed, since quantifying the impact on the main macrovariables of an ambitious emission mitigation plan is an extremely difficult exercise.

The tight theoretical assumptions of the model used for our simulations and the length of the time horizon considered suggest reading our results as heuristic and not as a full counterfactual prediction.

Yet, despite its simple structure, we argue that the model we present in this paper is flexible enough to allow for a variety of alternative and plausible extensions. For the sake of parsimony, we have opted to keep the model as simple as possible in order to single out the role of market structure and endogenous firm entry in determining the response to a mitigation process from other economic factors. A natural extension of our model would be the incorporation of physical capital along with real adjustment costs that would allow to add other more realistic sources of dynamics. An interesting extension of the model would be the introduction of R&D in the abatement technology. In this case the technology would allow firms to reduce both abatement costs and permits price in order to comply with the mitigation policy through an R&D investment. This, in turn, might reduce the entry costs so as to make room for new entrants. Future research should also explore the effects of GHG emission mitigation policy under alternative oligopolistic settings and characterize the optimal environmental policy. Further, we argue that the insights obtained from this simple model prepare the ground for more complex explorations on the implications of environmental policies on external competitiveness. An important extensions in this direction could be the study of the problem in an open economy model, where the effects of environmental policy on external imbalances could be fully assessed.

Acknowledgments

We are very grateful to two anonymous referees and to the Associate Editor, Knut Einar Rosendahl, for their excellent comments and suggestions.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *The American Economic Review*, 102(1):131–166.

Adjemian, S., Bastani, H., Juillard, M., Mihoubi, F., Perendia, G., Ratto, M., and Villemot, S. (2011). Dynare: Reference manual, version 4. *Dynare Working Papers - CEPREMAP*, no. 1.

Aldy, J. E. and Pizer, W. A. (2015). The competitiveness impacts of climate change mitigation policies. *Journal of the Association of Environmental and Resource Economists*, 2(4):565–595.

Alexeeva-Talebi, V., Böhringer, C., Löschel, A., and Voigt, S. (2012). The value-added of sectoral disaggregation: Implications on competitive consequences of climate change policies. *Energy Economics*, 34:S127–S142.

Anderson, S. P. and Wilson, W. W. (2015). Market power in transportation: Spatial equilibrium under Bertrand competition. *Economics of Transportation*, 4(1):7–15.

Angelopoulos, K., Economides, G., and Philippopoulos, A. (2013). First-and second-best allocations under economic and environmental uncertainty. *International Tax and Public Finance*, 20(3):360–380.

Annicchiarico, B., Battles, S., Di Dio, F., Molina, P., and Zoppoli, P. (2017). GHG mitigation schemes and energy policies: A model-based assessment for the Italian economy. *Economic Modelling*, 61:495–509.

Annicchiarico, B. and Di Dio, F. (2015). Environmental policy and macroeconomic dynamics in a new Keynesian model. *Journal of Environmental Economics and Management*, 69:1–21.

Annicchiarico, B. and Di Dio, F. (2017). GHG emissions control and monetary policy. *Environmental and Resource Economics*, 67(4):823–851.

Arestis, P. and González-Martínez, A. R. (2015). The absence of environmental issues in the New Consensus Macroeconomics is only one of numerous criticisms. In Arestis, P. and Sawyer, M., editors, *Finance and the Macroeconomics of Environmental Policies*, pages 1–36. Springer.

Bartocci, A. and Pisani, M. (2013). Green fuel tax on private transportation services and subsidies to electric energy. A model-based assessment for the main European countries. *Energy Economics*, 40:S32–S57.

Belleflamme, P. and Peitz, M. (2015). *Industrial organization: markets and strategies.* Cambridge University Press.

Bilbiie, F. O., Fujiwara, I., and Ghironi, F. (2014). Optimal monetary policy with endogenous entry and product variety. *Journal of Monetary Economics*, 64(C):1–20.

Bilbiie, F. O., Ghironi, F., and Melitz, M. J. (2012). Endogenous entry, product variety, and business cycles. *Journal of Political Economy*, 120(2).

Bosetti, V. and Maffezzoli, M. (2014). Occasionally binding emission caps and real business cycles. *IGIER Working Paper*, 523.

Bovenberg, A. and Goulder, L. H. (1996). Optimal environmental taxation in the presence of other taxes: general-equilibrium analyses. *The American Economic Review*, 86(4):985–1000.

Bovenberg, A. and Heijdra, B. J. (1998). Environmental tax policy and intergenerational distribution. *Journal of Public Economics*, 67(1):1 – 24.

Bovenberg, A. and Heijdra, B. J. (2002). Environmental abatement and intergenerational distribution. *Environmental and Resource Economics*, 23(1):45–84.

Bovenberg, A. L. and van der Ploeg, F. (1994). Environmental policy, public finance and the labour market in a second-best world. *Journal of Public Economics*, 55(3):349–390.

Brock, W. A. and Taylor, M. S. (2005). Economic growth and the environment: A review of theory and empirics. In Aghion, P. and Durlauf, S., editors, *Handbook of Economic Growth*, volume 1, pages 1749–1821. Elsevier.

Chetty, R. (2012). Bounds on elasticities with optimization frictions: A synthesis of micro and macro evidence on labor supply. *Econometrica*, 80(3):969–1018.

Conte, A., Labat, A., Varga, J., and Žarnić, Ž. (2010). *What is the growth potential of green innovation? An assessment of EU climate policy options*. European Economy - Economic Papers 413.

Delbono, F. and Lambertini, L. (2016). Ranking Bertrand, Cournot and supply function equilibria in oligopoly. *Energy Economics*, 60:73–78.

Economides, G. and Philippopoulos, A. (2008). Growth enhancing policy is the means to sustain the environment. *Review of Economic Dynamics*, 11(1):207–219.

Etro, F. and Colciago, A. (2010). Endogenous market structures and the business cycle. *Economic Journal*, 120(549):1201–1233.

Etro, F. and Rossi, L. (2015). New-Keynesian Phillips curve with Bertrand competition and endogenous entry. *Journal of Economic Dynamics and Control*, 51(C):318–340.

Faia, E. (2012). Oligopolistic competition and optimal monetary policy. *Journal of Economic Dynamics and Control*, 36(11):1760–1774.

Fischer, C. and Morgenstern, R. D. (2006). Carbon abatement costs: Why the wide range of estimates? *The Energy Journal*, 27(2):73.

Fischer, C. and Springborn, M. (2011). Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *Journal of Environmental Economics and Management*, 62(3):352–366.

Ganelli, G. and Tervala, J. (2011). International transmission of environmental policy: A New Keynesian perspective. *Ecological Economics*, 70(11):2070–2082.

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

Goulder, L. H. and Hafstead, M. A. (2013). Tax reform and environmental policy: options for recycling revenue from a tax on carbon dioxide. *Resources for the Future, DP 13-31.*

Grossman, G. M. and Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics*, 110(2):353–377.

Heijdra, B. J. and Heijnen, P. (2013). Environmental abatement and the macroeconomy in the presence of ecological thresholds. *Environmental and Resource Economics*, 55(1):47–70.

Heutel, G. (2012). How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Review of Economic Dynamics*, 15(2):244–264.

John, A., Pecchenino, R., Schimmelpfennig, D., and Schreft, S. (1995). Short-lived agents and the long-lived environment. *Journal of Public Economics*, 58(1):127 – 141.

Jones, L. E. and Manuelli, R. E. (2001). Endogenous policy choice: The case of pollution and growth. *Review of Economic Dynamics*, 4(2):369 – 405.

Nordhaus, W. D. (1974). Resources as a constraint on growth. *The American Economic Review*, 64(2):22–26.

Nordhaus, W. D. (1977). Economic growth and climate: The carbon dioxide problem. *The American Economic Review*, 67(1):341–346.

Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the DICE model. *The American Economic Review*, 83(2):313–317.

Nordhaus, W. D. and Boyer, J. (2003). *Warming the world: Economic models of global warming.* The MIT Press.

OECD (2016a). *Consumption Tax Trends 2016 VAT/GST and excise rates, trends and policy issues: VAT/GST and excise rates, trends and policy issues.* OECD Publishing.

OECD (2016b). *Effective Carbon Rates - Pricing CO2 through Taxes and Emissions Trading Systems.* Paris, OECD.

Parry, I. W. (1995). Pollution taxes and revenue recycling. *Journal of Environmental Economics and Management*, 29(3):S64–S77.

Peretto, P. F. (2008). Effluent taxes, market structure, and the rate and direction of endogenous technological change. *Environmental and Resource Economics*, 39(2):113–138.

Peretto, P. F. (2009). Energy taxes and endogenous technological change. *Journal of Environmental Economics and Management*, 57(3):269–283.

Peterman, W. B. (2016). Reconciling micro and macro estimates of the Frisch labor supply elasticity. *Economic Inquiry*, 54(1):100–120.

Reilly, J. M. and Richards, K. R. (1993). Climate change damage and the trace gas index issue. *Environmental and Resource Economics*, 3(1):41–61.

Rogerson, R. and Wallenius, J. (2009). Micro and macro elasticities in a life cycle model with taxes. *Journal of Economic Theory*, 144(6):2277–2292.

Rotemberg, J. J. (1982). Monopolistic price adjustment and aggregate output. *The Review of Economic Studies*, 49(4):517–531.

Smets, F. and Wouters, R. (2003). An estimated dynamic stochastic general equilibrium model of the Euro Area. *Journal of the European Economic Association*, 1(5):1123–1175.

Xepapadeas, A. (2005). Economic growth and the environment. In Mäler, K.-G. and Vincent, J. R., editors, *Economywide and International Environmental Issues*, volume 3 of *Handbook of Environmental Economics*, pages 1219 – 1271. Elsevier.

Appendix A

Intermediate-Goods Producers' Problem

The problem of the typical oligopolistic firm

$$\underset{\{u_{j,t},p_{j,t}\}_{t=0}^{\infty}}{max} E_0 \sum_{t=0}^{\infty} (1-\delta)^t Q_{0,t} \left[p_{j,t} y_{j,t} - \frac{W_t}{a_t} y_{j,t} - p_{j,t} \phi_1 u_{j,t}^{\phi_2} y_{j,t} - p_{z,t} \left(1 - u_{j,t}\right) \varphi y_{j,t} \right],$$

where $y_{j,t} = \left(\frac{p_{j,t}}{p_t^c}\right)^{-\theta} y_t^c$, $p_t^c = \left(\sum_{j=1}^{N_t} p_{j,t}^{1-\theta}\right)^{\frac{1}{1-\theta}}$ and $Q_{0,t} = \beta \frac{\lambda_t}{\lambda_0}$. The first-order condition with respect to the abatement effort $u_{j,t}$ immediately follows

$$p_{j,t} \phi_1 \phi_2 u_{j,t}^{\phi_2 - 1} = p_{z,t} \varphi. \tag{A-1}$$

The first-order condition with respect to the price $p_{j,t}$ is found to be:

$$\begin{aligned} &\left(1 - \phi_1 u_{j,t}^{\phi_2}\right) y_{j,t} + \\ &+ \left[p_{j,t} - \frac{W_t}{a_t} - p_{j,t} \phi_1 u_{j,t}^{\phi_2} - p_{z,t} \left(1 - u_{j,t}\right) \varphi \right] \frac{\partial y_{j,t}}{\partial p_{j,t}} = 0, \end{aligned} \tag{A-2}$$

where $\frac{\partial y_{j,t}}{\partial p_{j,t}} = -\theta \frac{y_{j,t}}{p_{j,t}} \left(1 - x_{j,t}\right)$ with $x_j = \frac{p_{j,t} y_{j,t}}{p_t^c y_t^c}$ (i.e. the market share of firm j). Manipulating the above equation we have:

$$p_{j,t} \left[\theta \left(1 - x_{j,t}\right) - 1\right] \left(1 - \phi_1 u_{j,t}^{\phi_2}\right) = \theta \left(1 - x_{j,t}\right) \left[\frac{W_t}{a_t} + p_{z,t} \left(1 - u_{j,t}\right) \varphi \right]. \tag{A-3}$$

By solving for $p_{j,t}$ we have

$$p_{j,t} = \mu_{j,t} \left[\frac{W_t}{a_t} + p_{z,t} \left(1 - u_{j,t} \right) \varphi \right], \tag{A-4}$$

with $\mu_{j,t} = \frac{\theta(1-x_{j,t})}{[\theta(1-x_{j,t})-1]\left(1-\phi_1 u_{j,t}^{\phi_2}\right)}$.

In the symmetric equilibrium $p_{j,t} = p_t$, $y_t = y_{j,t}$ and $x_{j,t} = 1/N_t$, therefore (A-1) becomes

$$p_t \phi_1 \phi_2 u_{j,t}^{\phi_2 - 1} = p_{z,t} \varphi, \tag{A-5}$$

while (A-4) becomes

$$p_t = \mu_t \left[\frac{W_t}{a_t} + p_{z,t} \left(1 - u_t \right) \varphi \right], \tag{A-6}$$

where $\mu_t = \frac{\theta \frac{N_t - 1}{N_t}}{\left(\theta \frac{N_t-1}{N_t} - 1\right)\left(1-\phi_1 u_t^{\phi_2}\right)}$.

Households' Problem

The typical household will choose the set of processes $\{c_t,\, L_t,\, s_{t+1}\}_{t=0}^{\infty}$ to maximize (14) subject to (15). The Lagrangian associated to the household problem reads as

$$\mathcal{L}_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log c_t - \mu_L \frac{l_t^{1+\psi}}{1+\psi} + \lambda_t \left[\begin{array}{c} W_t L_t (1 - \tau_t^l) + \\ + \left(D_t + p_t v_t \right) N_t s_t + p_t T + \\ - \left(p_t c_t (1 + \tau_t^c) + p_t v_t (N_t + N_t^e) s_{t+1} \right) \end{array} \right] \right\}. \tag{A-7}$$

The first-order conditions to the above problem are then found to be:

$$\lambda_t = \frac{1}{p_t c_t (1 + \tau_t^c)}, \tag{A-8}$$

$$l_t^{\psi} \mu_L = \lambda_t \left(1 - \tau_t^l \right) W_t, \tag{A-9}$$

$$\beta E_t \left\{ \lambda_{t+1} \left[\left(N_{t+1} D_{t+1} + p_{t+1} v_{t+1} N_{t+1} \right) \right] \right\} - \lambda_t p_t v_t \left(N_t + N_t^e \right) = 0. \tag{A-10}$$

By recalling that $N_t = (1 - \delta) \left(N_{t-1} + N_{t-1}^e \right)$, we obtain (18) in the main text.

Resource Constraint of the Economy

In equilibrium $s_{t+1} = s_t = 1$, therefore the equation describing the budget constraint of the household (15) collapses to

$$p_t^c c_t (1 + \tau_t^c) + p_t^c v_t N_t^e = W_t L_t (1 - \tau_t^l) + N_t D_t + p_t^c T_t, \tag{A-11}$$

which combined with the budget constraint of the government becomes

$$p_t^c c_t + p_t^c v_t N_t^e = W_t L_t + N_t D_t + p_{z,t} N_t z_t. \tag{A-12}$$

By noticing that under symmetry (7) reads as

$$D_t = p_t y_t - W_t l_t - p_t \phi_1 u_t^{\phi_2} y_t - p_{z,t} z_t, \tag{A-13}$$

(A-12) can be written as

$$p_t^c c_t + p_t^c v_t N_t^e = W_t l_t^e N_t^e + N_t \left(1 - \phi_1 u_t^{\phi_2}\right) p_t y_t, \tag{A-14}$$

where we have used the labor market clearing condition $L_t = N_t^e l_t^e + N_t l_t$. Using the entry condition $v_t = \eta \frac{W_t}{p_t^c a_t}$, where $\eta = l_t^e / a_t$, we have that (A-14) fully simplifies to

$$N_t p_t y_t = p_t^c c_t + N_t \phi_1 u_t^{\phi_2} p_t y_t, \tag{A-15}$$

which corresponds to (21) in the main text. Using $p_t^c = N_t^{\frac{1}{1-\theta}} p_t$ and $y_t^c = y_t N_t^{\frac{\theta}{\theta-1}}$ the resource constraint of the economy can be written in real terms as (22).

Equilibrium Conditions of the Benchmark Model

Let $w_t = W_t / p_t^c$, $D_t / p_t^c = d_t$, $\hat{p}_{z,t} = p_{z,t} / p_t^c$, $\hat{p}_t = p_t / p_t^c$, then the equilibrium conditions describing the economy are the following:

$$y_t = a_t l_t, \tag{A-16}$$

$$y_t^c = y_t N_t^{\frac{\theta}{\theta-1}}, \tag{A-17}$$

$$N_t = (1-\delta)\left(N_{t-1} + N_{t-1}^e\right), \tag{A-18}$$

$$L_t = N_t^e l_t^e + N_t l_t, \tag{A-19}$$

$$\hat{p}_t = 1 / N_t^{\frac{1}{1-\theta}}, \tag{A-20}$$

$$\phi_1 \phi_2 u_t^{\phi_2 - 1} = \frac{\hat{p}_{z,t}}{\hat{p}_t} \varphi, \tag{A-21}$$

$$\hat{p}_t = \mu_t \left[\frac{w_t}{a_t} + \hat{p}_{z,t}(1-u_t)\varphi\right], \tag{A-22}$$

$$\mu_t = \frac{\theta\left(1 - \frac{1}{N_t}\right)}{\left[\theta\left(1 - \frac{1}{N_t}\right) - 1\right]\left(1 - \phi_1 u_t^{\phi_2}\right)}, \tag{A-23}$$

$$d_t = \hat{p}_t y_t - \frac{w_t}{a_t} y_t - \hat{p}_t \phi_1 u_t^{\phi_2} y_t - \hat{p}_{z,t}(1-u_t)\varphi y_t, \tag{A-24}$$

$$\eta = l_t^e a_t, \tag{A-25}$$

$$v_t = \eta \frac{w_t}{a_t}, \tag{A-26}$$

$$L_t^{\psi} \mu_L = \frac{\left(1 - \tau_t^l\right) w_t}{c_t (1 + \tau_t^c)}, \tag{A-27}$$

$$\beta(1-\delta) E_t \left\{\frac{c_t (1 + \tau_t^c)}{c_{t+1}(1 + \tau_{t+1}^c)} \left[(d_{t+1} + v_{t+1})\right]\right\} - v_t = 0, \tag{A-28}$$

$$y_t^c = c_t + \phi_1 u_t^{\phi_2} y_t^c, \tag{A-29}$$

$$z_t = (1-u_t)\varphi y_t, \tag{A-30}$$

$$T_t = c_t\tau_t^c + w_t L_t \tau_t^l + \hat{p}_{z,t} N_t z_t, \tag{A-31}$$

$$M_t = \kappa M_{t-1} + N_t z_t + Z_t^{RoW} + Z_t^{NI}, \tag{A-32}$$

$$a_t = \bar{a}\exp[-\chi(M_t - \overline{M})]. \tag{A-33}$$

The above equations, together with an environmental policy setting the time path for aggregate emissions $Z_t = N_t z_t$, constitute a system of 19 equations in 19 endogenous variables: a_t, c_t, d_t, L_t, l_t, l_t^e, M_t, N_t, N_t^e, $\hat{p}_t$, $\hat{p}_{z,t}$, T_t, u_t, v_t, w_t, y_t, y_t^c, z_t, μ_t. In the benchmark example, the tax rates τ_t^c and τ_t^l are exogenously set, while in Section 7 we will keep lump-sum transfers constant and the extra revenues derived from the sale of emission permits will be used to reduce the tax rates on labor income and consumption.

Appendix B

In this Appendix we report some extra results. In particular, Table (B-1) and Figure (B-1) show the results of a 30 per cent gradual reduction of emissions at firm level, diluted over a 15-year time horizon. Figure (B-2) presents the results of a 30 per cent gradual reduction of the overall level of emissions under different speeds of implementation.

Appendix C

Monopolistic Competition *à la* Dixit-Stiglitz

In this Appendix we show the results of a mitigation plan assuming that the firms operate under monopolistic competition, rather than under oligopoly. Given the constant elasticity of substitution production function, $y_t^c = \left(\sum_{j=1}^{N_t} y_{j,t}^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}}$, this is the case of monopolistic competition *à la* Dixit-Stiglitz.

Under monopolistic competition firms retain some monopoly power even if it is negligible with respect to the market, however they ignore the effects that their pricing decisions have on the general price level. As a result the markup is simply

$$\mu_t = \frac{\theta}{(\theta-1)\left(1-\phi_1 u_t^{\phi_2}\right)}, \tag{C-1}$$

which replaces equation (A-23) of the model of our stylized economy.[28] Under the same calibration, Table (C-1) reports the effects of the mitigation plan for different time horizons.

Perfect Competition

In this Appendix we present the simulation results under the assumption that firms operate in a perfectly competitive market, therefore there are neither barriers to entry nor to exit, firms produce homogenous goods and are price takers. We can then focus on the representative competitive firm

---

[28] In the absence of abatement the markup would be constant as usual.

and on the behavior of the representative consumer to derive the following equilibrium conditions of the model:

$$y_t^c = a_t L_t, \tag{C-2}$$

$$\phi_1 \phi_2 u_t^{\phi_2 - 1} = \hat{p}_{z,t} \varphi, \tag{C-3}$$

$$1 = \frac{w_t}{a_t} + \phi_1 u_t^{\phi_2} + \hat{p}_{z,t} \left(1 - u_t\right) \varphi, \tag{C-4}$$

$$L_t^{\psi} \mu_L = \frac{\left(1 - \tau_t^l\right) w_t}{c_t (1 + \tau_t^c)}, \tag{C-5}$$

$$y_t^c = c_t + \phi_1 u_t^{\phi_2} y_t^c, \tag{C-6}$$

$$Z_t = \left(1 - u_t\right) \varphi y_t^c, \tag{C-7}$$

$$T_t = c_t \tau_t^c + w_t L_t \tau_t^l + \hat{p}_{z,t} z_t, \tag{C-8}$$

$$M_t = \kappa M_{t-1} + Z_t + Z_t^{RoW} + Z_t^{NI}, \tag{C-9}$$

$$a_t = \bar{a} \exp[-\chi(M_t - \overline{M})]. \tag{C-10}$$

The above equations, together with an environmental policy setting the time path for aggregate emissions Z_t, constitute a system of 10 equations in 10 endogenous variables: a_t, c_t, L_t, M_t, $\hat{p}_{z,t}$, T_t, u_t, w_t, y_t^c, Z_t. To solve the model we have used the same calibration strategy adopted for the benchmark version. We have in fact normalized the overall output to 1, and so total labor input L and abatement cost and environmental damage have been determined in the same way. As a result, also the initial level of consumption is the same.

Figure (C-1) plots the response of the economy to a decarbonization process under perfect competition along with the results obtained for the corresponding macroeconomic variables in our benchmark case of oligopoly. Table (C-2) reports the impact of the same policy at different time horizons, while Table (6) reports the long-run effects of mitigation with recycling comparing the benefits in terms of economic activity obtained under perfect competition with the those observed in oligopoly.

Appendix D

The Model under Sticky Prices

The benchmark model can be easily augmented to account for sticky prices as follows. We assume that intermediate goods oligopolistic producers face quadratic adjustment costs when resetting their price in the spirit of Rotemberg (1982), $\frac{\gamma_p}{2}\left(\frac{p_{j,t}}{p_{j,t-1}} - 1\right)^2 y_{j,t}$, where $\gamma_p > 0$ measures the degree of sluggishness in the price adjustment process. In this case profits for firm j are defined as:

$$D_{j,t} = p_{j,t} y_{j,t} - \frac{W_t}{a_t} y_{j,t} - p_{j,t} \phi_1 u_{j,t}^{\phi_2} y_{j,t} - p_{z,t} \left(1 - u_{j,t}\right) \varphi y_{j,t} - p_{j,t} \frac{\gamma_p}{2} \left(\frac{p_{j,t}}{p_{j,t-1}} - 1\right)^2 y_{j,t}, \tag{D-1}$$

which replaces equation (7).

At the optimum, the first-order condition with respect to the price $p_{j,t}$ will now read

$$p_{j,t} = \mu_{j,t} \left[\frac{W_t}{a_t} + p_{z,t} \left(1 - u_{j,t}\right) \varphi\right], \tag{D-2}$$

where $\mu_{j,t}$ is the firm's markup defined as

$$\mu_{j,t} = \frac{\theta\left(1 - x_j\right)}{\left[\theta\left(1 - x_j\right) - 1\right]\left[1 - \phi_1 u_{j,t}^{\phi_2} - \frac{\gamma_p}{2}\left(\Pi_{j,t} - 1\right)^2\right] + \Psi_{j,t}}, \tag{D-3}$$

with $\Psi_{j,t} = \Pi_{j,t}\gamma_p\left(\Pi_{j,t} - 1\right) - \gamma_p(1-\delta)E_t Q_{t,t+1}\Pi_{j,t+1}^2\left(\Pi_{j,t+1} - 1\right)\frac{y_{j,t+1}}{y_{j,t}}$ and $\Pi_{j,t} = p_{j,t}/p_{j,t}$. Clearly, in the limiting case of fully flexible prices (i.e. $\gamma_p = 0$), this condition, collapses to $\mu_{j,t} = \frac{\theta(1-x_j)}{[\theta(1-x_j)-1]\left(1-\phi_1 u_{j,t}^{\phi_2}\right)}$ which is exactly (11).

On the demand side, we now assume that households hold two types of assets: shares of firms and risk-free bonds. In particular, the budget constraint of the typical household will now read as:

$$p_t^c c_t(1+\tau_t^c) + B_t + p_t^c v_t(N_t + N_t^e)s_{t+1} = W_t L_t(1-\tau_t^l) + R_{t-1}B_{t-1} + N_t\left(D_t + p_t^c v_t\right)s_t + p_t^c T_t, \tag{D-4}$$

where B_t denotes the quantity of one-period nominal riskless bonds purchased in period t, B_{t-1} the quantity of bonds carried over from period $t-1$ and R_{t-1} the nominal interest rate factor on these bonds. The typical household will choose the set of processes $\{c_t, L_t, B_t, s_{t+1}\}_{t=0}^{\infty}$ to maximize (14) subject to the above constraint. In this case an additional first-order condition will describe the solution to the household optimization problem, namely:

$$R_t^{-1} = \beta\frac{E_t\lambda_{t+1}}{\lambda_t}, \tag{D-5}$$

which is the Euler equation with respect to riskless bonds, governing the transmission mechanism from the monetary policy conduct, described by the behavior of R_t, and the real economy.

Given the existence of quadratic cost of price adjustment the resource constrain of the economy will now read as

$$y_t^c = c_t + \phi_1 u_t^{\phi_2} y_t^c + \frac{\gamma_p}{2}\left(\Pi_t - 1\right)^2 y_t^c, \tag{D-6}$$

which replaces (22).

Finally, we now assume that an independent monetary authority sets the one period nominal interest rate according to a standard Taylor rule of the form

$$\log\left(\frac{R_t}{R}\right) = \phi_R\log\left(\frac{R_{t-1}}{R}\right) + (1-\phi_R)\left[\phi_y\log\left(\frac{y_t^c}{y_{t-1}^c}\right) + \phi_\Pi\log\left(\frac{\Pi_t^c}{\Pi^c}\right)\right], \tag{D-7}$$

where $\Pi_t^c = p_t^c/p_{t-1}^c$ is the consumption price index inflation, R and Π^c are the steady-state values of the (gross) nominal interest rate and inflation, respectively, while ϕ_R, ϕ_{y^c}, ϕ_Π are policy parameters. According to (D-7), the monetary authority gradually adjusts the nominal interest rate in response to variations of output and inflation. In the simulation exercise we set $\phi_R = 0.8$, $\phi_{y^c} = 0.125$ and $\phi_\Pi = 1.5$ and vary the parameter γ_p, measuring the degree of price stickiness.

The equilibrium conditions describing the economy under sticky prices are the following:

$$y_t = a_t l_t, \tag{D-8}$$

$$y_t^c = y_t N_t^{\frac{\theta}{\theta-1}}, \tag{D-9}$$

$$N_t = (1-\delta)\left(N_{t-1} + N_{t-1}^e\right), \tag{D-10}$$

$$L_t = N_t^e l_t^e + N_t l_t, \tag{D-11}$$

$$\hat{p}_t = 1/N_t^{\frac{1}{1-\theta}}, \tag{D-12}$$

$$\phi_1 \phi_2 u_t^{\phi_2 - 1} = \frac{\hat{p}_{z,t}}{\hat{p}_t} \varphi, \tag{D-13}$$

$$\hat{p}_t = \mu_t \left[\frac{w_t}{a_t} + \hat{p}_{z,t} \left(1 - u_t\right) \varphi \right], \tag{D-14}$$

$$\mu_t = \frac{\theta \left(1 - \frac{1}{N_t}\right)}{\left[\theta \left(1 - \frac{1}{N_t}\right) - 1\right] \left[1 - \phi_1 u_t^{\phi_2} - \frac{\gamma_p}{2} \left(\Pi_t - 1\right)^2\right] + \Psi_t}, \tag{D-15}$$

with $\Psi_{j,t} = \Pi_t \gamma_p \left(\Pi_t - 1\right) - \gamma_p (1-\delta) \beta E_t \frac{c_t(1+\tau_t^c)}{c_{t+1}(1+\tau_{t+1}^c)} \frac{\Pi_{t+1}^2}{\Pi_{t+1}^c} \left(\Pi_{t+1} - 1\right) \frac{y_{t+1}}{y_t}$.

$$d_t = \hat{p}_t y_t - \frac{w_t}{a_t} y_t - \hat{p}_t \phi_1 u_t^{\phi_2} y_t - \hat{p}_{z,t} \left(1 - u_t\right) \varphi y_t - \hat{p}_t \frac{\gamma_p}{2} \left(\Pi_t - 1\right)^2 y_t, \tag{D-16}$$

$$\eta = l_t^e a_t, \tag{D-17}$$

$$v_t = \eta \frac{w_t}{a_t}, \tag{D-18}$$

$$L_t^{\psi} \mu_L = \frac{\left(1 - \tau_t^l\right) w_t}{c_t (1 + \tau_t^c)}, \tag{D-19}$$

$$R_t^{-1} = \beta E_t \frac{c_t (1 + \tau_t^c)}{\Pi_{t+1}^c c_{t+1} (1 + \tau_{t+1}^c)}, \tag{D-20}$$

$$\beta \left(1 - \delta\right) E_t \left\{ \frac{c_t (1 + \tau_t^c)}{c_{t+1} (1 + \tau_{t+1}^c)} \left[\left(d_{t+1} + v_{t+1}\right) \right] \right\} - v_t = 0, \tag{D-21}$$

$$y_t^c = c_t + \phi_1 u_t^{\phi_2} y_t^c + \frac{\gamma_p}{2} \left(\Pi_t - 1\right)^2 y_t^c, \tag{D-22}$$

$$z_t = \left(1 - u_t\right) \varphi y_t, \tag{D-23}$$

$$T_t = c_t \tau_t^c + w_t L_t \tau_t^l + \hat{p}_{z,t} N_t z_t, \tag{D-24}$$

$$M_t = \kappa M_{t-1} + N_t z_t + Z_t^{RoW} + Z_t^{NI}, \tag{D-25}$$

$$a_t = \bar{a} \exp[-\chi (M_t - \overline{M})]. \tag{D-26}$$

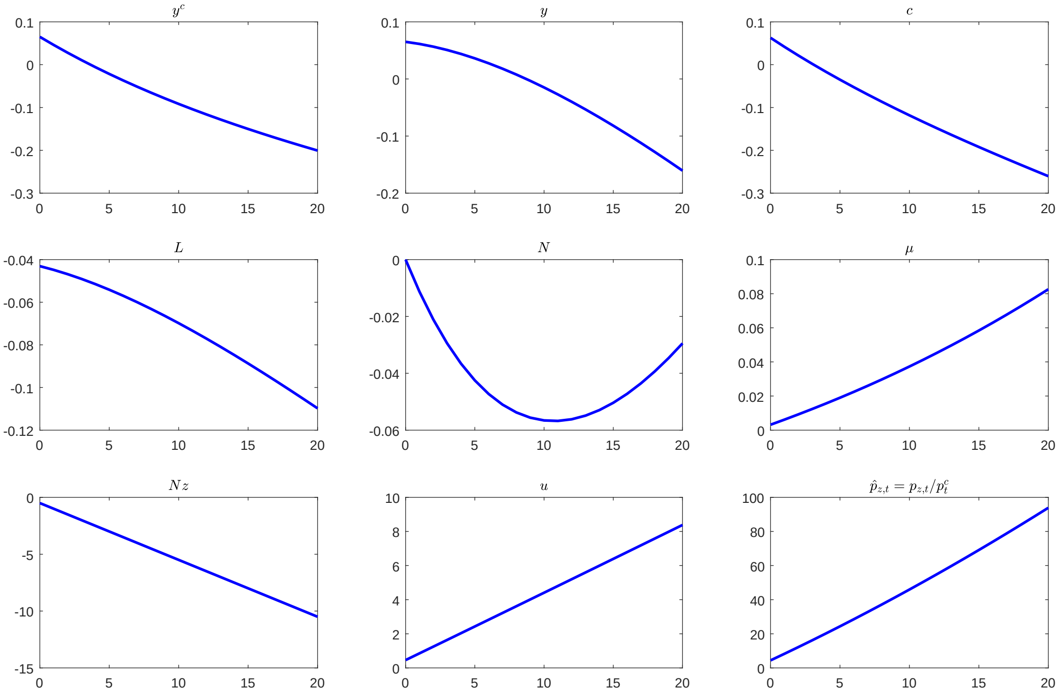
$$\Pi_t^c = \left(\frac{N_t}{N_{t-1}} \right)^{\frac{1}{1-\theta}} \Pi_t, \tag{D-27}$$

$$\log \left(\frac{R_t}{R} \right) = \phi_R \log \left(\frac{R_{t-1}}{R} \right) + (1 - \phi_R) \left[\phi_y \log \left(\frac{y_t^c}{y_{t-1}^c} \right) + \phi_\Pi \log \left(\frac{\Pi_t^c}{\Pi^c} \right) \right], \tag{D-28}$$

The above equations together with an environmental policy setting the time path for aggregate emissions $Z_t = N_t z_t$ constitute a system of 22 equations in 22 endogenous variables: a_t, c_t, d_t, L_t, l_t, l_t^e, M_t, N_t, N_t^e, $\hat{p}_t$, $\hat{p}_{z,t}$, R_t, T_t, u_t, v_t, w_t, y_t, y_t^c, z_t, Π_t, Π_t^c, μ_t.

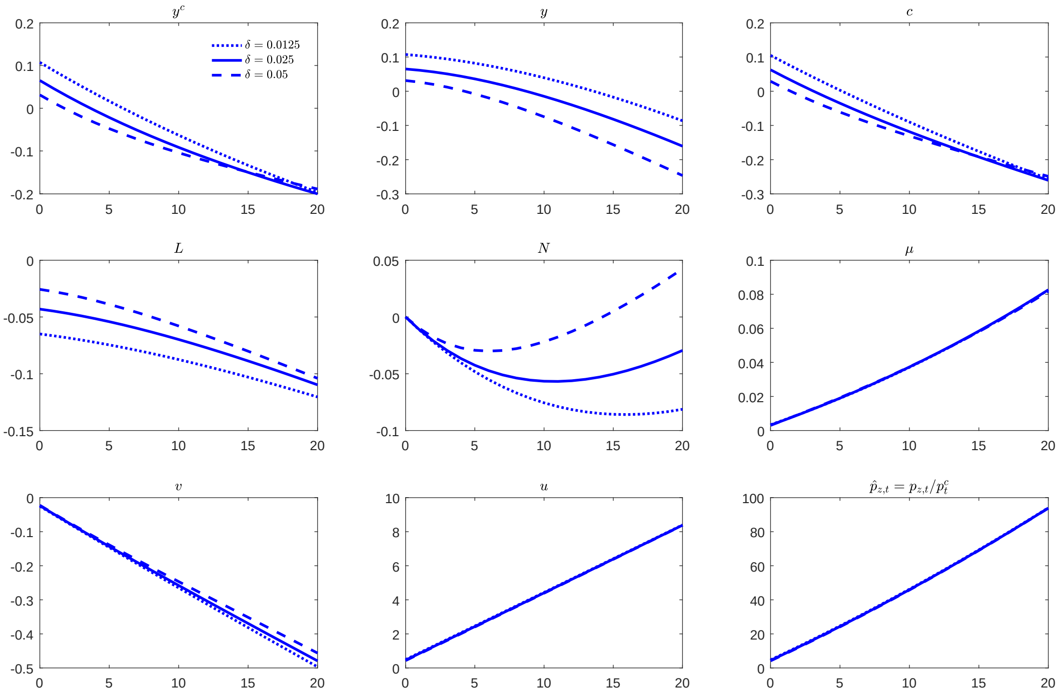
Notice that by setting $\gamma_p = 0$ the model described by the above equations boils down into the benchmark model with flexible prices, where monetary policy is neutral.

Figure 1: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Benchmark Model



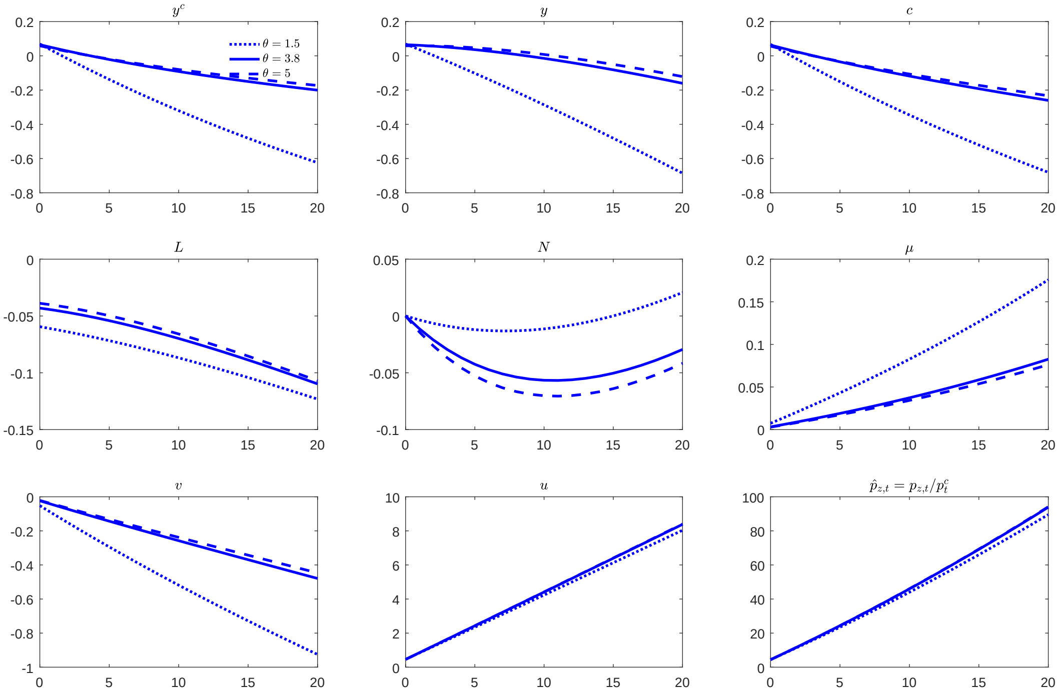
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 2: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Firms' Exit Rate



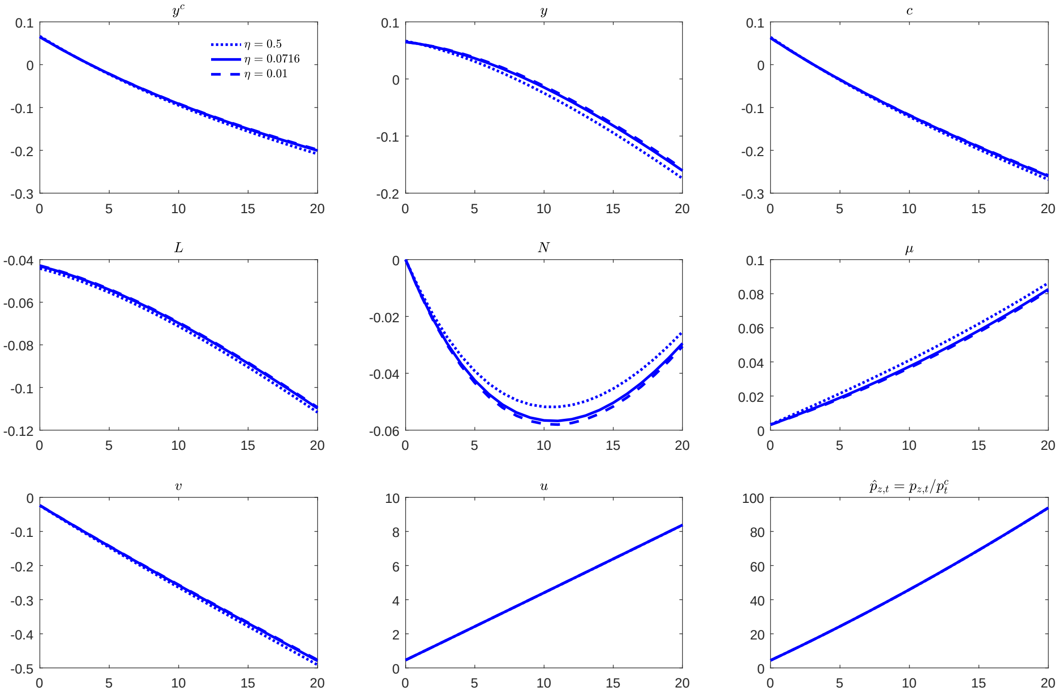
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for different firms exit rates δ. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 3: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Degree of Competition



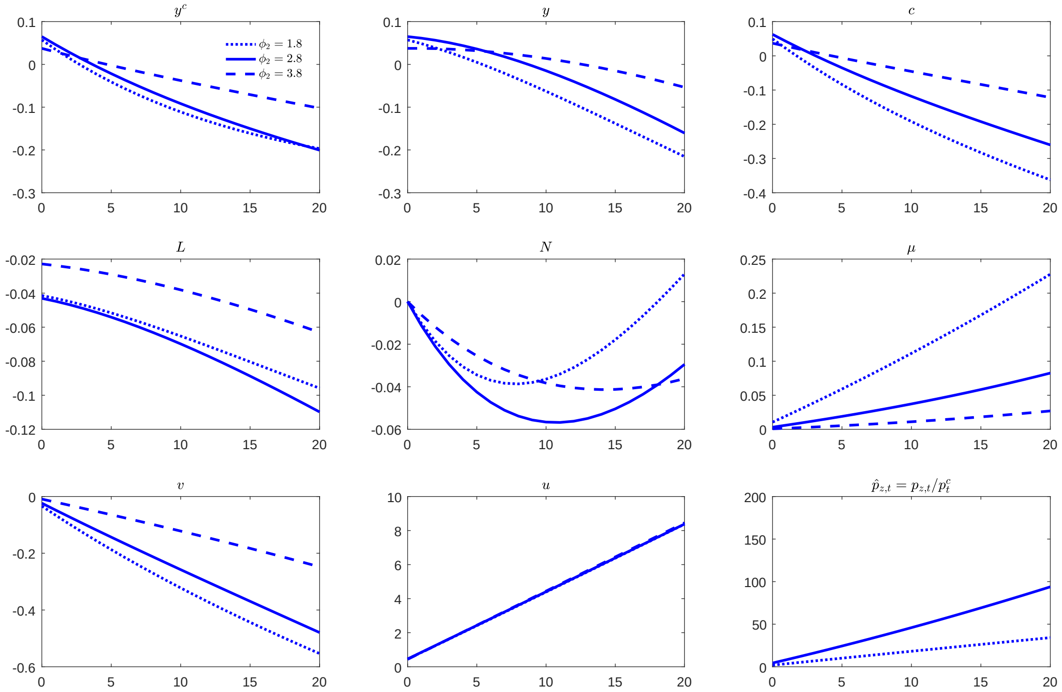
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for different degrees of competition measured by the elasticity of substitution between goods θ. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 4: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Sunk Entry Costs



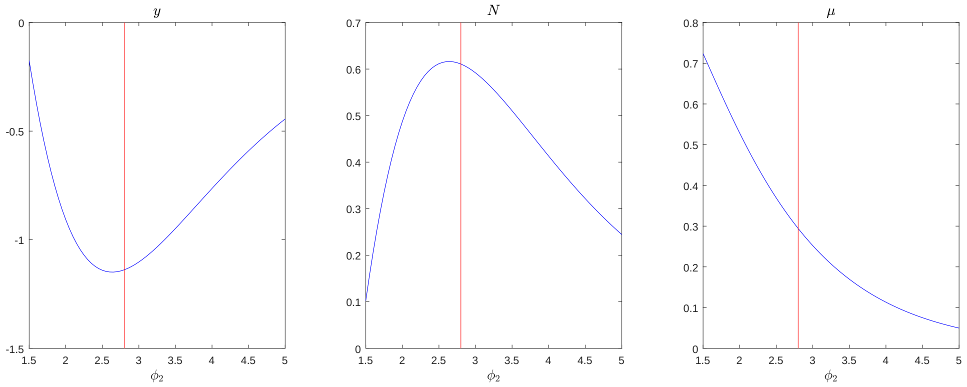
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for different values of the parameters η, reflecting higher or lower entry sunk costs. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 5: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Abatement Technology



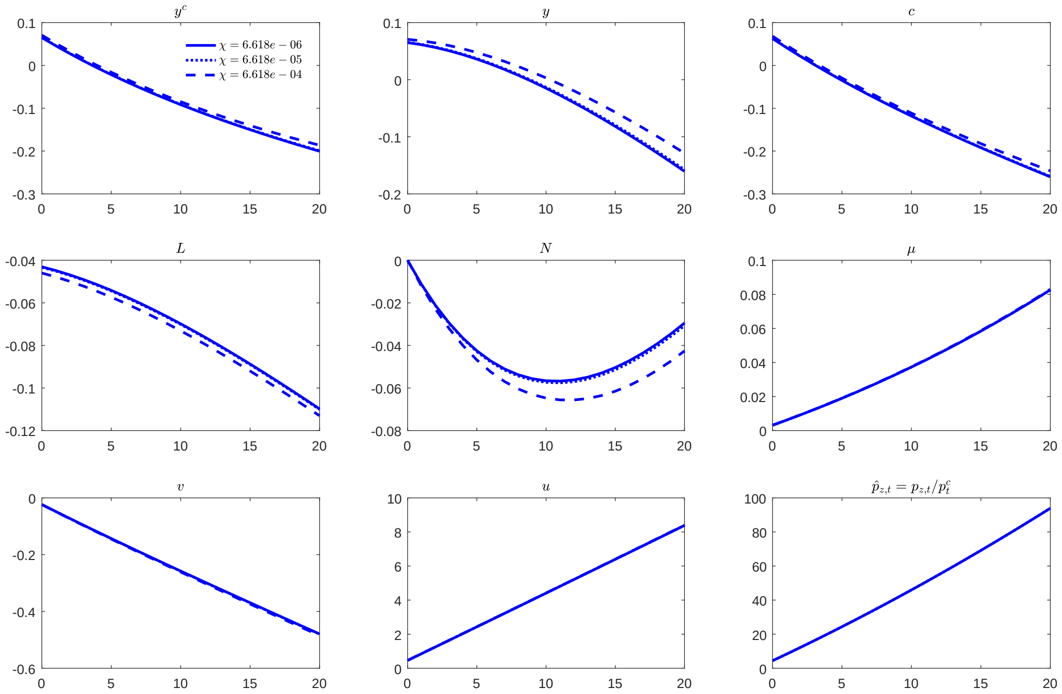
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for different values of the abatement cost parameter ϕ_2. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 6: Long-Run Macroeconomic Impact of Climate Change Mitigation Policy - The Role of the Abatement Technology



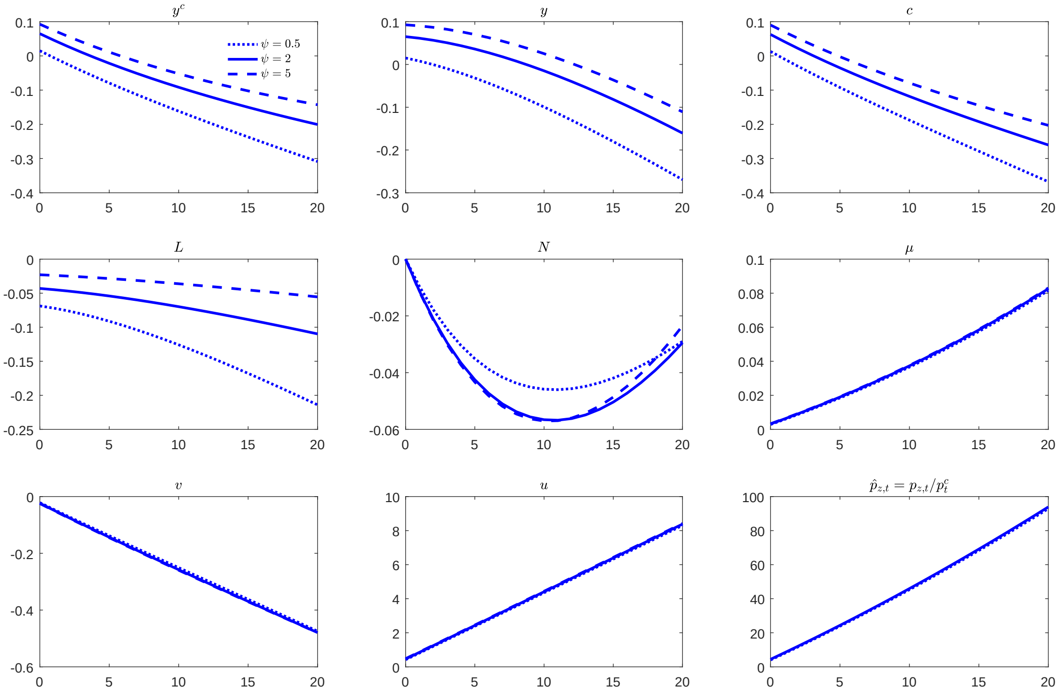
Note: The plot represents the long-run effects of a 30-per-cent reduction in GHG overall emissions for selected economic variables for different values of the abatement cost parameter ϕ_2. The vertical lines refer to the benchmark value of ϕ_2, 2.8. All variables are expressed in percentage deviations from their initial steady-state level.

Figure 7: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Damage Intensity



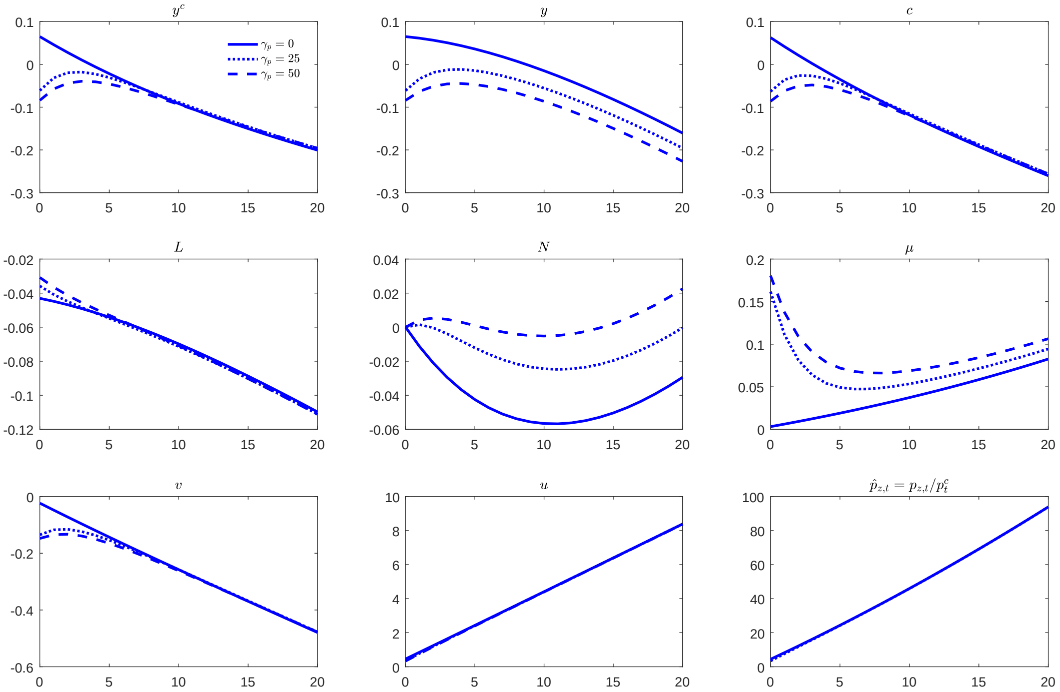
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for different values of the damage intensity parameter χ. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 8: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Inverse of the Frisch Elasticity



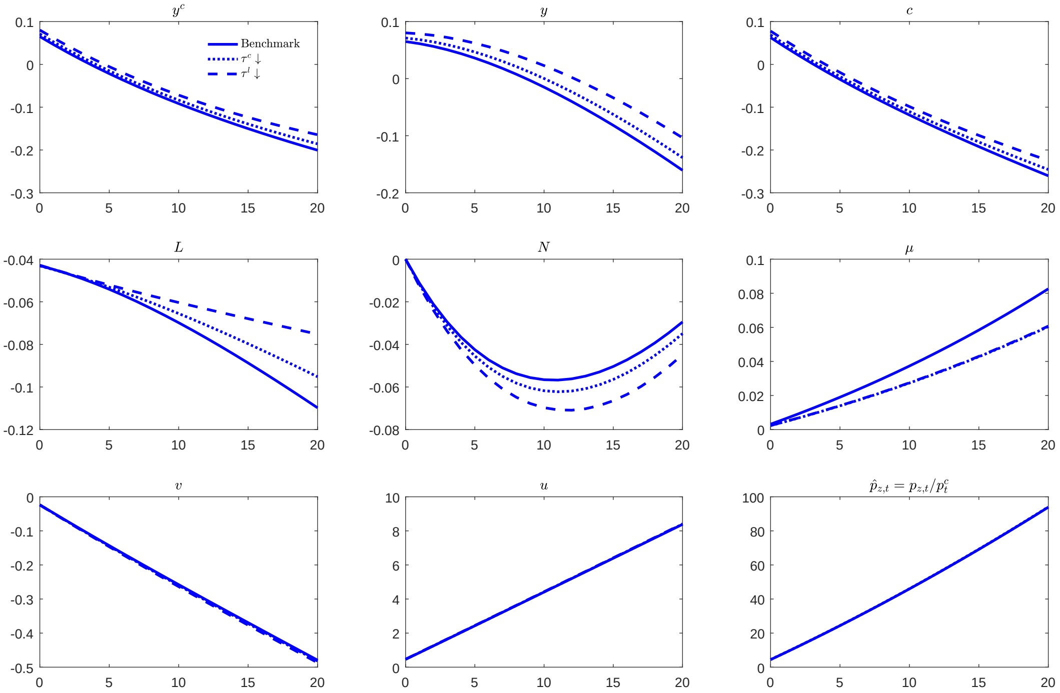
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for different values of the inverse of the Frisch elasticity ψ. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 9: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Role of Nominal Rigidities



Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years with ($\gamma_p > 0$) and without ($\gamma_p = 0$) nominal rigidities. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure 10: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy with Recycling



Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years combined with balance-budget cuts of distortionary taxes on consumption and labor income. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Table 1: Parametrization

Parameters	Value	Description
β	0.99	Discount factor
ψ	2	Inverse of the Frisch elasticity of labor supply
μ_L	0.48974	Disutility of labor
δ	0.025	Destruction rate of firms
θ	3.8	Elasticity of substitution
$\overline{a}$	0.3428	Productivity level
η	0.0716	Entry cost
φ	0.8039	Emission parameter
ϕ_1	0.0356	Multiplicative abatement cost parameter
ϕ_2	2.8	Abatement cost function parameter
$1-\kappa$	0.0021	Decay rate of the pollution stock
χ	$6.6177e-06$	Pollution damage parameter

Table 2: Macroeconomic Impact of Climate Change Mitigation Policy - Benchmark Model

	Impact	5 Years	10 Years	20 Years	Long Run
y	0.0650	-0.1440	-0.5243	-1.1064	-1.1386
y^c	0.0650	-0.1910	-0.3500	-0.3634	-0.3182
c	0.0627	-0.2470	-0.5017	-0.6613	-0.6166
l	0.0650	-0.1442	-0.5247	-1.1080	-1.1502
L	-0.0431	-0.1054	-0.1968	-0.2989	-0.3063
N	0.0000	-0.0346	0.1291	0.5530	0.6108
Ne	-0.4508	0.1713	0.5568	0.6924	0.6113
μ	0.0032	0.0775	0.2073	0.4036	0.4033
u	0.4582	7.9843	15.9720	24.0254	24.0396
z	-0.5000	-9.9688	-20.1031	-30.3850	-30.4250
Nz	-0.5	-10	-20	-30	-30
$\hat{p}_z = p_z/p^c$	4.4178	88.8116	201.9785	339.8145	340.1669
d	0.0627	-0.2116	-0.6333	-1.2220	-1.2357
v	-0.0235	-0.4574	-0.8933	-1.2559	-1.2360
$w = W/p^c$	-0.0235	-0.4573	-0.8929	-1.2543	-1.2245

Table 3: Macroeconomic Impact of Climate Change Mitigation Policy - Sensitivity

	Benchmark	$\delta = 0.0125$	$\delta = 0.05$	$\theta = 1.5$	$\theta = 5$	$\eta = 0.01$	$\eta = 0.5$	$\phi_2 = 1.8$	$\phi_2 = 3.8$	$\chi = 6.6177e-05$	$\chi = 6.6177e-04$	$\psi = 0.5$	$\psi = 5$
y	-1.1386	-1.1441	-1.1287	-2.5665	-1.0474	-1.1468	-1.1094	-0.6883	-0.8381	-1.1348	-1.0967	-1.1420	-1.1369
y^c	-0.3182	-0.2734	-0.3572	-0.5692	-0.3047	-0.3105	-0.3494	-0.1871	-0.2292	-0.1784	1.2311	-0.7275	-0.1112
c	-0.6166	-0.5722	-0.6551	-0.8499	-0.6041	-0.6089	-0.6474	-0.7897	-0.3662	-0.4784	0.9136	-1.0209	-0.4121
l	-1.1502	-1.1556	-1.1402	-2.5779	-1.0590	-1.1583	-1.1210	-0.6998	-0.8496	-1.2500	-2.2423	-1.1535	-1.1485
L	-0.3063	-0.3211	-0.2960	-0.3408	-0.3008	-0.3062	-0.3069	-0.1845	-0.2255	-0.3068	-0.3118	-0.6083	-0.1537
N	0.6108	0.6483	0.5743	0.6787	0.6000	0.6227	0.5658	0.3716	0.4521	0.7119	1.7289	0.3088	0.7635
Ne	0.6113	0.6492	0.5746	0.6791	0.6005	0.6231	0.5662	0.3720	0.4525	0.7164	1.7739	0.3092	0.7639
μ	0.4033	0.4059	0.3984	0.7746	0.3740	0.4066	0.3878	0.8287	0.1825	0.4037	0.4085	0.4021	0.4039
u	24.0396	24.0577	24.0246	23.2417	24.0861	24.0416	24.0309	24.1631	24.1227	24.0991	24.6913	23.8657	24.1271
z	-30.4250	-30.4509	-30.3997	-30.4719	-30.4175	-30.4332	-30.3938	-30.2592	-30.3150	-30.4948	-31.1897	-30.2155	-30.5304
Nz	-30	-30	-30	-30	-30	-30	-30	-30	-30	-30	-30	-30	-30
$\hat{p}_z = p_z/p^c$	340.1669	340.5598	339.8339	330.3962	340.7271	340.2225	339.9356	93.7344	906.3937	341.4259	354.0672	336.4907	342.0238
d	-1.2357	-1.2208	-1.2538	-1.5357	-1.2124	-1.2278	-1.2675	-1.1666	-0.8264	-1.2003	-0.8458	-1.3335	-1.1863
v	-1.2360	-1.2213	-1.2539	-1.5360	-1.2127	-1.2281	-1.2678	-1.1670	-0.8267	-1.2034	-0.8763	-1.3338	-1.1866
$w = W/p^c$	-1.2245	-1.2098	-1.2424	-1.5246	-1.2012	-1.2166	-1.2563	-1.1554	-0.8151	-1.0882	0.2853	-1.3224	-1.1751

Table 4: Macroeconomic Impact of Climate Change Mitigation Policy with Consumption Tax Cut

	Impact	5 Years	10 Years	20 Years	Long Run
y	0.0712	-0.1224	-0.4990	-1.0942	-1.1378
y^c	0.0712	-0.1771	-0.3138	-0.2841	-0.2206
c	0.0688	-0.2333	-0.4659	-0.5830	-0.5202
l	0.0712	-0.1225	-0.4994	-1.0959	-1.1493
L	-0.0432	-0.0920	-0.1601	-0.2323	-0.2343
N	0.0000	-0.0403	0.1371	0.6029	0.6827
Ne	-0.4746	0.1753	0.6060	0.7778	0.6833
μ	0.0023	0.0567	0.1515	0.2948	0.2945
u	0.4632	7.9960	15.9938	24.0607	24.0809
z	-0.5000	-9.9637	-20.1096	-30.4195	-30.4747
Nz	-1	-10	-20	-30	-30
$\hat{p}_z = p_z/p^c$	4.4663	88.9556	202.3276	340.5454	341.0426
d	0.0688	-0.1920	-0.6058	-1.1944	-1.2124
v	-0.0237	-0.4602	-0.8918	-1.2402	-1.2127
$w = W/p^c$	-0.0237	-0.4601	-0.8913	-1.2386	-1.2012

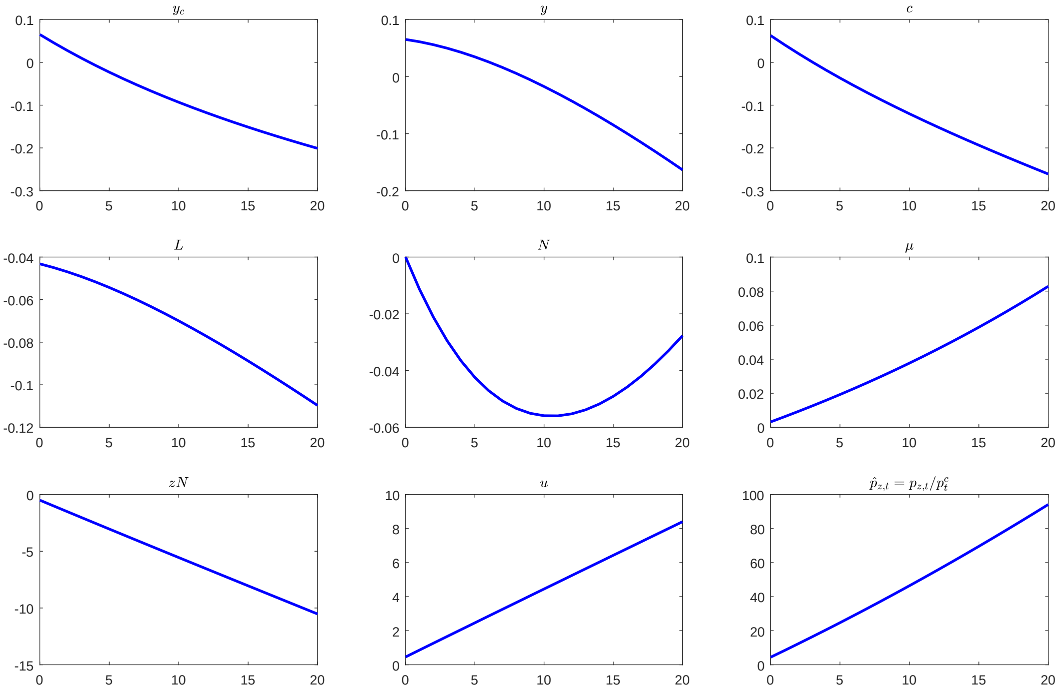
Table 5: Macroeconomic Impact of Climate Change Mitigation Policy with Labor Income Tax Cut

	Impact	5 Years	10 Years	20 Years	Long Run
y	0.0802	-0.0886	-0.4553	-1.0688	-1.1362
y^c	0.0802	-0.1570	-0.2582	-0.1502	-0.0445
c	0.0778	-0.2134	-0.4109	-0.4508	-0.3462
l	0.0802	-0.0887	-0.4558	-1.0704	-1.1477
L	-0.0428	-0.0738	-0.1036	-0.1183	-0.1045
N	0.0000	-0.0504	0.1458	0.6833	0.8125
Ne	-0.5071	0.1730	0.6779	0.9254	0.8132
μ	0.0024	0.0570	0.1519	0.2954	0.2949
u	0.4705	8.0133	16.0280	24.1210	24.1552
z	-0.5000	-9.9546	-20.1165	-30.4751	-30.5641
Nz	-0.5	-10	-20	-30	-30
$\hat{p}_z = p_z/p^c$	4.5373	89.1686	202.8722	341.7858	342.6221
d	0.0778	-0.1617	-0.5598	-1.1441	-1.1703
v	-0.0241	-0.4649	-0.8908	-1.2151	-1.1708
$w = W/p^c$	-0.0241	-0.4648	-0.8904	-1.2135	-1.1593

Table 6: Long-Run Macroeconomic Impact of Climate Change Mitigation Policy with Recycling - Oligopoly and Perfect Competition

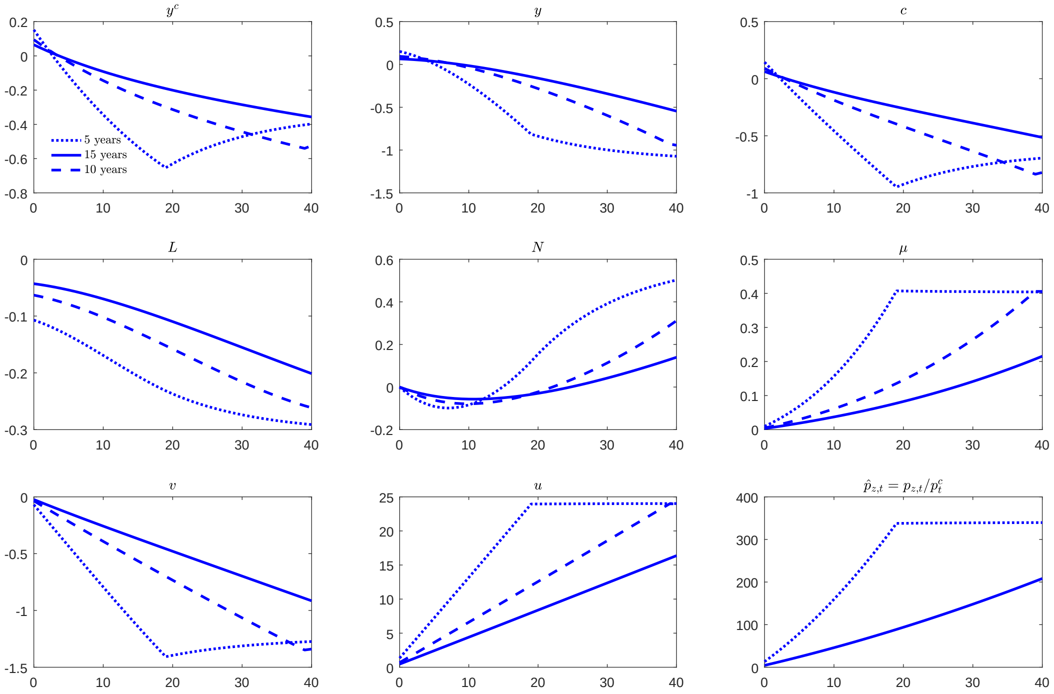
	Oligopoly			Perfect Competition		
with changes in	T	τ^c	τ^l	T	τ^c	τ^l
y^c	-0.3182	-0.2206	-0.0445	-0.2844	-0.1957	-0.1042
c	-0.6166	-0.5202	-0.3462	-0.5796	-0.4986	-0.4086
L	-0.3063	-0.2343	-0.1045	-0.2843	-0.2124	-0.1209
w	-1.2245	-1.2012	-1.1593	-1.1342	-1.1364	-1.1391
welfare cost	0.4610	0.4050	0.2852	0.4197	0.3866	0.3447

Figure B-1: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Reduction Target at Firm Level.



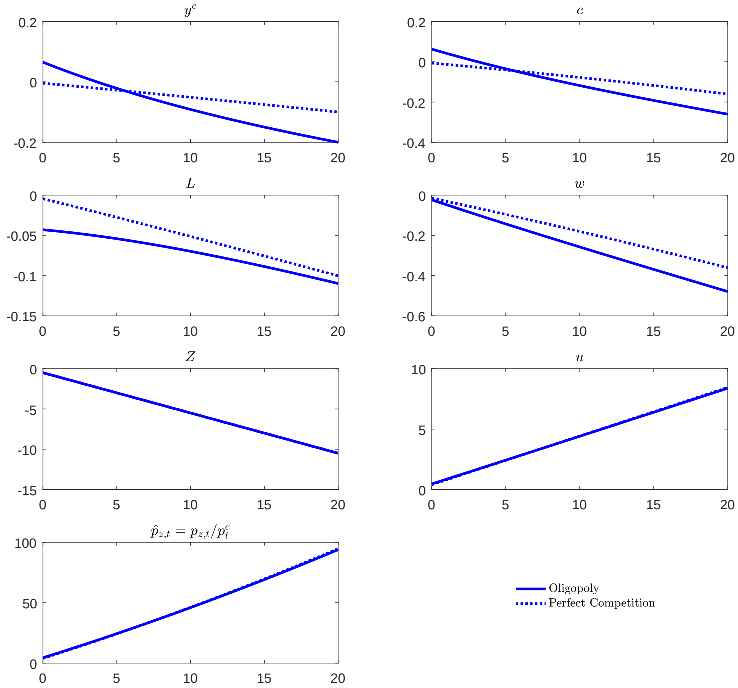
Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG emissions at firm level phased-in 15 years. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure B-2: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Different Implementation Speeds



Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 5, 10, 15 years. All variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Figure C-1: Short-Run Macroeconomic Impact of Climate Change Mitigation Policy - Market Structure



Note: The plot reports the short-run effects (up to 20 quarters) of a 30-per-cent reduction in GHG overall emissions phased-in 15 years for the benchmark model of oligopoly and under perfect competition; all variables are expressed in percentage deviations from their initial steady-state level, with the exception of the abatement effort u, expressed in p.p. deviations; in the horizontal axis time is in quarters.

Table B-1: Macroeconomic Impact of Climate Change Mitigation Policy - Reduction Target at Firm-Level

	Impact	5 Years	10 Years	20 Years	Long Run
y	0.0653	-0.1470	-0.5236	-1.0952	-1.1244
y^c	0.0653	-0.1916	-0.3474	-0.3583	-0.3142
c	0.0629	-0.2479	-0.4980	-0.6495	-0.6053
l	0.0652	-0.1471	-0.5241	-1.0969	-1.1358
L	-0.0432	-0.1054	-0.1957	-0.2957	-0.3025
N	0.0000	-0.0329	0.1305	0.5485	0.6031
Ne	-0.4525	0.1761	0.5542	0.6823	0.6036
μ	0.0032	0.0778	0.2056	0.3945	0.3933
u	0.4584	8.0075	15.8883	23.7160	23.6990
z	-0.5	-10	-20	-30	-30
Nz	-0.5000	-10.0296	-19.8956	-29.6161	-29.5778
$\hat{p}_z = p_z/p^c$	4.4198	89.1066	200.6743	334.1109	333.8833
d	0.0629	-0.2142	-0.6310	-1.2057	-1.2168
v	-0.0235	-0.4582	-0.8875	-1.2378	-1.2171
$w = W/p^c$	-0.0235	-0.4580	-0.8870	-1.2362	-1.2057

Table C-1: Macroeconomic Impact of Climate Change Mitigation Policy - Monopolistic Competition

	Impact	5 Years	10 Years	20 Years	Long Run
y	0.0645	-0.1398	-0.5215	-1.1148	-1.1495
y^c	0.0645	-0.1887	-0.3445	-0.3538	-0.3081
c	0.0622	-0.2448	-0.4963	-0.6518	-0.6065
l	0.0645	-0.1399	-0.5220	-1.1165	-1.1610
L	-0.0427	-0.1049	-0.1961	-0.2986	-0.3061
N	0.0000	-0.0361	0.1311	0.5665	0.6265
Ne	-0.4621	0.1734	0.5688	0.7109	0.6270
μ	0.0031	0.0763	0.2071	0.4072	0.4076
u	0.4578	7.9863	15.9751	24.0282	24.0422
z	-0.5000	-9.9675	-20.1047	-30.3943	-30.4358
Nz	-0.5	-10	-20	-30	-30
$\hat{p}_z = p_z/p^c$	4.4142	88.8362	202.0290	339.8869	340.2400
d	0.0622	-0.2088	-0.6266	-1.2114	-1.2253
v	-0.0233	-0.4540	-0.8866	-1.2458	-1.2257
$w = W/p^c$	-0.0233	-0.4539	-0.8862	-1.2442	-1.2141

Table C-2: Macroeconomic Impact of Climate Change Mitigation Policy - Perfect competition

	Impact	5 Years	10 Years	20 Years	Long Run
y^c	-0.0045	-0.0952	-0.1932	-0.2826	-0.2844
c	-0.0065	-0.1519	-0.3472	-0.5842	-0.5796
L	-0.0045	-0.0953	-0.1937	-0.2843	-0.2843
u	0.4021	8.0454	16.1043	24.1840	24.1897
Z	-0.5	-10	-20	-30	-30
$\hat{p}_z$	3.8725	89.6098	203.9074	341.876	342.0335
w	-0.0156	-0.3421	-0.7328	-1.1486	-1.1342