Research Papers

ISSN 2610-931X

CEIS Tor Vergata

RESEARCH PAPER SERIES

Vol. 20, Issue 2, No. 535 – March 2022

Climate Actions, Market Beliefs, and Monetary Policy

Barbara Annicchiarico, Fabio Di Dio and Francesca Diluiso

Climate Actions, Market Beliefs, and Monetary Policy*

Barbara Annicchiarico† Fabio Di Dio‡ Francesca Diluiso§

March 2022

Abstract

This paper studies the role of expectations and monetary policy on the economy's response to climate actions. We show that in a stochastic environment and without the standard assumption of perfect rationality of agents, there is more uncertainty regarding the path and the economic impact of a climate policy, with a potential threat to the ability of central banks to maintain price stability. Market beliefs and behavioral agents increase the trade-offs inherent to the chosen mitigation tool, with a carbon tax entailing more emissions uncertainty than in a rational expectations model and a cap-and-trade scheme implying a more pronounced pressure on allowances prices and inflation. The impact on price stability is worsened by delays in the implementation of stringent climate policies, by the lack of confidence in the ability of central banks to keep inflation under control, and by the adoption of monetary rules tied to expectations rather than current macroeconomic conditions. Central banks can implement successful stabilization policies that reduce the uncertainty surrounding the impact of climate actions and support the greening process while staying within their mandate.

Keywords: Climate policy; monetary policy; expectations; inflation; market sentiments; business cycle.
JEL Codes: D83, Q50, E32, E71.

*We thank all the participants to presentations at the Banque de France's workshop on "Advances in Macro and Finance Modelling of Climate Change", the 62nd Annual Conference of the Italian Economic Association, the 26th EAERE Annual Conference, the 3rd International Conference on European Studies, the University of Venice Ca' Foscari, the University of Naples Federico II, and the 9th IAERE Annual Conference for helpful comments. We are also grateful to Alkis Blanz, Stefano Colonnello, Pietro Dindo, Lorenzo Frattarolo, Francesco Giovanardi, Matthias Kalkuhl, Richard Jaimes, Loriana Pelizzon, Alessandro Spiganti and Guido Traficante for useful suggestions and discussions. B.A. acknowledges funding from the University of Rome "Tor Vergata" within the Beyond Borders project (grant reference: E89C20000530005). F.D. acknowledges funding from the German Federal Ministry of Education and Research within the PEGASOS project (grant reference: 01LA1826A).

†University of Rome "Tor Vergata", Department of Economics and Finance, Via Columbia 2, 00133 Rome, Italy. Email: barbara.annicchiarico@uniroma2.it

‡Institute for Globally Distributed Open Research and Education (IGDORE). Email: fabio.didio@igdore.org

§Mercator Research Institute on Global Commons and Climate Change, Torgauer Strasse 12-15, D-10829 Berlin, Germany. Email: diluiso@mcc-berlin.net

1 Introduction

In analyzing the economic impact of climate policies in a stochastic environment, the following questions may arise. Suppose that a mitigation plan is implemented through a quantity or a price regulation on emissions. How will the economy's response change if we remove the standard assumption of rational expectations? What is the role of market beliefs in driving or hindering the mitigation process? Finally, on a policy level, can monetary policy tame the irrational exuberance or the doom and gloom of the markets rendering the greening policy put in place more effective, while maintaining price stability?

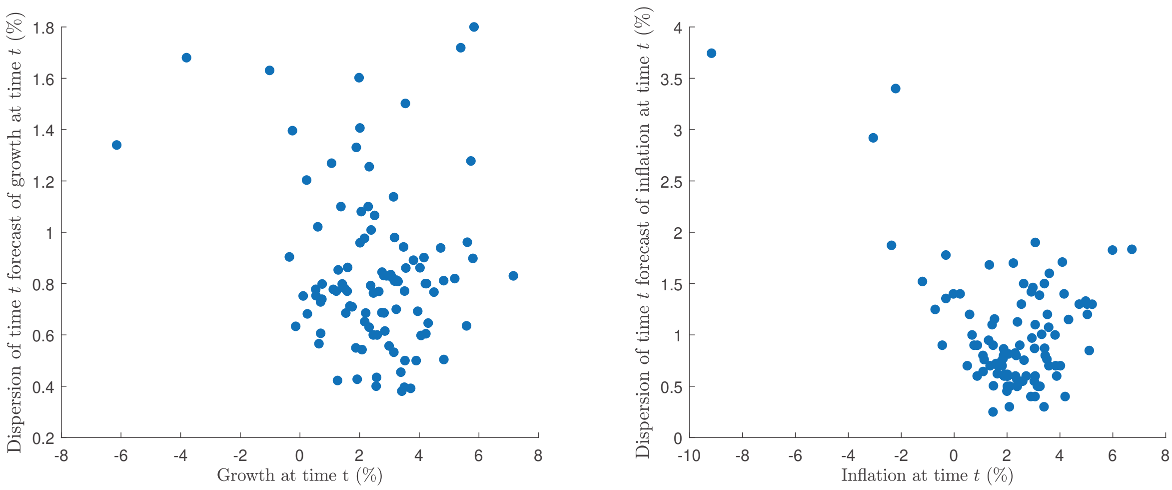
To address these issues, we start our analysis from the simplest version of the canonical New Keynesian model augmented to include a negative environmental externality and agents who lack the cognitive abilities necessary to form rational expectations. The paper highlights the role of expectations in the transmission of climate policies along the business cycle and studies how monetary policy can facilitate the achievement of a predetermined mitigation target while keeping inflation under control.

According to the standard economic theory, when economic agents make their decisions, they consider all the options available to them, anticipate the possible outcome,and know how the economy works and the probability distributions of future events. Put another way, agents formulate rational expectations. However, do agents do that? Do agents have a sufficient ability to understand economic variables and formulate fully-model consistent expectations? Since the seminal contributions of Tversky and Kahneman (1974), Grether and Plott (1979), and Thaler (1980), an increasing number of studies have accounted for the fact that agents are not perfectly rational when making their choices and that their actions are subject to errors and cognitive biases. Moreover, in a world where knowledge is bounded and time is pressing, the decision process can be extremely complicated and costly.[1] To overcome these cognitive limits and to the extent that economic forecasting is costly, agents, in need of making quick choices, formulate expectations and take decisions based on simple rules, the so-called heuristics or rules of thumb.[2] However, agents using heuristics learn from their mistakes and stand ready to choose the rule that exhibits the best performance, generating endogenous dynamics that, in turn, may give rise to short-term macroeconomic fluctuations. There is quite an extensive literature, based on survey data, rejecting the rational expectations hypothesis and emphasizing the considerable heterogeneity of private-sector forecasts of macroeconomic variables. For a comprehensive survey, see Pesaran and Weale (2006). Figure 1 shows some evidence of substantial heterogeneity in expectations formation by displaying the dispersion of expected GDP growth and CPI inflation in the US Survey of Professional Forecasters. Data

[1] On this issue see the early paper of Evans and Ramey (1992).

[2] Forming rational expectations can be expensive (one needs to do research and be very smart), while observing just current data/variables is cheaper. On the notion of heuristics see e.g. Gigerenzer and Selten (2002) and Gigerenzer and Gaissmaier (2011).

Figure 1: Cross-Sectional Dispersion of Growth and Inflation Expectations



Note: the figure plots the cross-sectional difference between the 75th percentile and the 25th percentile of projections of real GDP growth and CPI inflation against actual data. All variables are expressed in annualized percentage points. Data are from the US Survey of Professional Forecasters for the period 1995Q1-2019Q4.

refer to forecasts made in the relevant quarter for the period 1995Q1-2019Q4. The figure documents substantial disagreement among professional economists about both variables. The disagreement tends to be more prominent when the growth and inflation are away from long-run averages.

It is then reasonable to deduce that the presence of heterogeneous agents who change the way they formulate expectations and, therefore, their behavior along the business cycle, adds a further complication and an additional layer of uncertainty also for the analysis of the macroeconomic impact of carbon pricing policies.[3] In the context of climate policy, agents also operate under the uncertainty inherent to the selected environmental regulatory instrument. While a carbon tax (i.e., price regulation) entails emission uncertainty, a cap-and-trade mechanism (i.e., quantity regulation) introduces short-term volatility of allowance prices. Climate policy-induced uncertainty directly reflects in output and inflation dynamics. Assuming agents formulate expectations on these two variables we are implicitly considering climate policy uncertainty and how agents react to it.[4] Via the expectation channel, agents shape the dynamics in response to mitigation policies and may play an enabling or a hampering role in the transition process, depending on how they forecast future economic variables.

[3]Along this line, see Alessi et al. (2021), who study the reaction of financial investors to the Paris Agreement and then to the subsequent withdrawal of the US from it, finding evidence of a strong heterogeneity of reactions across different categories of investors. In particular, following the US withdrawal the behavior of households is shown to be more sentiment-driven, in contrast to that of regulated financial institutions.

[4]Note that in this context formulating expectations directly on emission dynamics or on the time path of the permits price would be redundant.

The economy's response to climate policies and the effects on macroeconomic stability, particularly on inflation dynamics, are at the center of the current policy debate. While there is a broad consensus on the necessity of policy actions to comply with the goals set by the Paris Agreement and meet climate targets (e.g. IPCC, 2018), the short-medium-run macroeconomic implications of climate policies are not yet very well understood. This poses a challenge in particular for the conduct of monetary policy, whose conventional policy horizon is typically from three to five years. The process of reducing emissions is likely to have a significant impact on the economy, with potential repercussions on macroeconomic and price stability, conditioning the environment in which central banks operate and, thus, the conduct of their policies (e.g. NGFS, 2019 and Schoenmaker, 2021).

Several central banks around the world have joined the Network for Greening the Financial System (NGFS) and are currently evaluating how climate policies can influence their mandates and what role they can play in the fight against climate change (e.g. Carney, 2015, Rudebusch et al., 2019, Lagarde, 2021, Villeroy de Galhau, 2021). Last year the European Central Bank presented an action plan to include climate change considerations in its monetary policy strategy (see ECB 2021). We can expect climate and monetary policy to walk closer in the future. Even if governments remain primarily responsible for facilitating an orderly low-carbon transition and undertaking the main policy interventions, there are several areas in which central banks can contribute to support climate actions, simply acting in the perimeter of their mandates.

This paper explicitly contributes to this debate by discussing the role of monetary policy in the face of climate actions when considering (i) short-run uncertainty and (ii) agents that are not-fully rational.[5] This allows us to evaluate the performance of climate policy and its interaction with monetary policy in an economy hit by shocks and subject to market beliefs. Bounded rationality and behavioral biases, coupled with business cycle fluctuations, can prevent agents from fully internalizing the impact of climate policies, conditioning the policy effectiveness and the achievement of climate targets. In this context, an active monetary policy can anchor expectations and support the greening process of the economy.

The underlying view of our approach is that it is crucial to understand how the stabilization of the price levels by central banks affects the nature of the business cycle whose fluctuations are dominated by movements of 'animal spirits', and to understand if the stabilization efforts, aimed at reducing the intensity of booms and busts, might be beneficial also in reducing the uncertainty surrounding the underlying climate policy and in mitigating its short-run costs.

Our results show that without the standard assumption of perfect rationality, there is more uncertainty surrounding the time path, the effectiveness, and the impact of climate policies, opening up to a non-trivial interplay between climate and monetary policies. Specifically, our key findings are as follows. First, the presence of market beliefs and behavioral agents drives

[5]Note that the models usually adopted to evaluate climate policy scenarios are deterministic (Cai and Lontzek, 2019 is one of the laudable exceptions), adopt a long-run perspective, and do not include neither monetary policy nor inflation dynamics (e.g. Nordhaus, 2007).

and amplifies business cycle fluctuations, making the adjustment dynamics during the transition highly unpredictable. Second, under price regulation, the time needed to achieve an emission-reduction target can be longer in a behavioral model, while under a cap-and-trade scheme, there may be a severe threat to price stability. Third, a monetary policy sufficiently reactive to the output gap or inflation can dampen emission volatility, reducing the uncertainty surrounding the achievement of climate targets and stabilizing inflation, thus reducing the pressure on prices introduced by an increasingly stringent climate policy, regardless of the environmental regime adopted. Fourth, delays in the implementation of the mitigation plan, lack of credibility regarding the ability of the central bank to keep inflation under control, and the adoption of monetary policy rules reacting to market expectations, rather than to fundamentals, are all factors that may amplify fluctuations and worsen the impact of climate actions on price stability. Overall, our results suggest central banks' critical role in the fight against climate change within the remit of their mandates.

To the best of our knowledge, this paper is the first attempt to study the transmission of climate actions and the role of monetary policy in the low-carbon transition in a behavioral New Keynesian model, where agents are not fully rational and subject to market beliefs. For the formalization of behavioral agents in the context of the canonical New Keynesian model, this work follows quite closely the contributions by De Grauwe (2011, 2012b,a), Kurz et al. (2013), De Grauwe and Macchiarelli (2015), De Grauwe and Gerba (2018), De Grauwe and Ji (2020), Hommes and Lustenhouwer (2019) and Hommes et al. (2019).[6] Several authors have also considered New Keynesian model variants deviating from the rational expectations hypothesis and introducing heterogeneous market beliefs. These include Branch (2009), Branch and McGough (2010), Levine et al. (2012), Kurz et al. (2013), Massaro (2013), and Annicchiarico et al. (2019), among others.

The interactions between monetary and climate policy in New Keynesian models have been explicitly investigated by Annicchiarico and Di Dio (2015, 2017), Economides and Xepapadeas (2018) and Chan (2020) in closed economy, and by Annicchiarico and Diluiso (2019), Economides and Xepapadeas (2019) and Ferrari and Pagliari (2021), in open economy.[7] Recently, in a New Keynesian model with financial frictions Diluiso et al. (2021) explore the monetary policy's role during a credible and gradual medium-term mitigation plan, showing that a monetary policy targeting inflation can limit output losses, while jointly safeguarding financial and price stability. However, in that analysis, the economy is not perturbed by any shocks during the greening process, and agents are assumed to be fully rational. Dietrich et al. (2021) focus on the implications that climate-change-related disaster expectations can have for the conduct

[6]Other variants with non-rational agents include the near rationality hypothesis as in Woodford (2010), the learning mechanism as in Bullard and Mitra (2002) and Evans and Honkapohja (2012), and the approach of Gabaix (2020) who introduces the notion of *cognitive discounting* by which non-rational agents discount future events relatively more than rational agents when the forecasting horizon is more distant in the future.

[7]For an overview of the literature on business cycles and environmental policy, see e.g. Annicchiarico et al. (2021).

of monetary policy and the emergence of cyclical fluctuations. Our paper contributes to this literature and provides a different perspective to the heated debate on the role that central banks can play during the transition to a low-carbon economy and the impact that the fight against climate change may have on the price stability objectives (see e.g. NGFS, 2020a,b).

Finally, by explicitly distinguishing between carbon taxes and cap-and-trade schemes, this paper also contributes to the literature on price versus quantity regulations that since the seminal contribution of Weitzman (1974) has animated the debate among economists, policy analysts and practitioners.[8] We show that in the presence of uncertainty and non-rational agents, the close connection between these two modes of environmental control becomes more problematic.

The paper is structured as follows. Section 2 presents the behavioral New Keynesian model with environmental externality. Section 3 describes the baseline calibration. Section 4 looks at the dynamic response of the economy to a mitigation policy and explores the role of monetary policy during the green transition. Section 5 undertakes some sensitivity analysis to examine the role of market beliefs, considers different hypotheses about how agents form their expectations, and studies the effects of the lack of credibility regarding the ability of the central bank to maintain inflation at its target. Section 6 concludes and draws some implications for monetary policy.

2 A Behavioral New Keynesian Environmental Model

We consider a behavioral variant of the prototypical New Keynesian dynamic stochastic general equilibrium model with imperfect price adjustment *à la* Calvo (1983), including pollutant emissions and climate policy. Private agents formulate expectations by endogenously selecting the forecasting rules based on their relative past performance. In what follows we present our setup where we adapt the microfoundations of the New Keynesian model with heterogeneous expectations of Kurz et al. (2013), also used in Hommes and Lustenhouwer (2019) and Hommes et al. (2019), among others.

The economy is populated by three types of agents: (i) a continuum of households who consume, supply labor, own firms, and formulate expectations according to simple heuristics; (ii) a continuum of monopolistically competitive polluting firms, facing nominal rigidities and using labor and a fossil resource as production inputs; (iii) a public sector conducting monetary policy through an interest rate rule of the Taylor-type and setting climate policy by either controlling the price of carbon or by setting a cap on emissions.

[8]See Karp and Traeger (2018) and Stavins (2020) for a comprehensive discussion on this debate and on the related policy implications.

2.1 Households

There is a continuum of mass one of infinitely lived households on the demand side. The representative household of type i has preferences represented by:

$$\tilde{E}_{i,0}\sum_{t=0}^{\infty}(\exp\mu_t)\,\beta^t\left[\frac{(C_{i,t}-hC_{t-1})^{1-\gamma}-1}{1-\gamma}-\chi\frac{N_{i,t}^{1+\varphi}}{1+\varphi}-\frac{\varrho}{2}\left(\frac{B_{i,t}}{P_t}\right)^2\right], \tag{1}$$

where $\tilde{E}_{i,0}$ denotes the subjective expectation operator in the period 0, the variable μ_t is an exogenous shock distorting the household discount factor (i.e., an intertemporal preference shock), $\beta \in (0,1)$ is the discount factor, $C_{i,t}$ is consumption, $\gamma > 0$ is the inverse of the intertemporal elasticity of substitution, $h \in [0,1)$ measures habit persistence[9], C_{t-1} is the lagged value of average aggregate consumption, taken as given by each atomistic household (external habit), $N_{i,t}$ denotes hours of work, χ measures the disutility of labor, and $\varphi > 0$ is the inverse of the Frisch elasticity of labor supply. Finally, P_t is the aggregate price level of the economy, $B_{i,t}$ denotes the quantity of one-period nominal bonds purchased in t and $\varrho > 0$. As in Kurz et al. (2013) the last term in (1) introduces a penalty on excessive lending at individual levels and replaces transversality conditions.[10] It should be noted that households are heterogeneous since they formulate different expectations about future income and inflation. In Section 2.4. we will see how expectations are formulated and how agents endogenously select their expectation rule.

Each household faces a flow budget constraint of the form:

$$P_tC_{i,t}+B_{i,t}=W_tN_{i,t}+R_{t-1}B_{i,t-1}+D_{i,t}, \tag{2}$$

where W_t is the nominal wage, R_{t-1} is the nominal (risk-free) interest factor and $D_{i,t}$ represents the lump-sum income component, including government transfers and dividends from the ownership of firms. The representative household of type i in period t chooses $C_{i,t}$, $B_{i,t}$ and $N_{i,t}$, so as to maximize (1), subject to (2).

2.2 Production

As in the baseline New Keynesian model, we assume there is a perfectly competitive final good sector assembling differentiated intermediate goods to produce a single final good, Y_t, according

[9] Habit persistence has been shown to improve the empirical performance of dynamic stochastic general equilibrium models. Habit formation, for instance, helps match the interest rate dynamics to several features of asset prices (as shown in Christiano et al. 2001), but also useful to have an empirical-relevant propagation of monetary shocks onto consumption (see Christiano et al. 2005).

[10] When the economy is out of its steady state, in fact, heterogeneous agents lend and borrow from each other. See Annicchiarico et al. (2019) where debt and wealth dynamics are made explicit.

to a constant elasticity of substitution (CES) technology:

$$Y_t = \left[\int_0^1 (Y_{i,t})^{(\sigma-1)/\sigma}\, di\right]^{\sigma/(\sigma-1)}, \tag{3}$$

where $\sigma > 1$ is the elasticity of substitution between intermediate goods and $Y_{i,t}$ is the intermediate good of generic type i. At the optimum, the demand equation for the generic variety i is $Y_{i,t} = (P_{i,t}/P_t)^{-\sigma}\, Y_t$, where $P_t = \int_0^1 \left(P_{i,t}^{1-\sigma}\right)^{1/(1-\sigma)} di$ is the aggregate price index of the economy, such that $P_t Y_t = \int_0^1 P_{i,t} Y_{i,t} di$.

Monopolistic competitive firms produce intermediate goods. Households have equal ownership shares in all firms, but each household is assumed to manage only one firm. Note that we use the same index i used for types of households in indexing producers, given the assumption made regarding the management of firms.

The intermediate good producer i uses labor inputs $N_{i,t}$ and a fossil resource $Z_{i,t}$ as a polluting source of energy. The production function is a constant return to scale technology of the CES type:

$$Y_{i,t} = \Delta_t \left[\zeta Z_{i,t}^{\frac{\varkappa-1}{\varkappa}} + (1-\zeta)\left(A_t N_{i,t}\right)^{\frac{\varkappa-1}{\varkappa}}\right]^{\frac{\varkappa}{\varkappa-1}}, \tag{4}$$

where $Y_{i,t}$ is production, Δ_t, captures a negative environmental externality impacting all producers in the same way, A_t is an exogenous process measuring labor productivity, $\zeta \in (0,1)$ is the energy quasi-share parameter and $\varkappa > 0$ is the elasticity of substitution between energy and labor inputs. The CES structure of the production function implies that factor cost shares are allowed to vary along the business cycle. We assume $\varkappa \in (0,1)$, so to capture a certain complementarity between the two factor inputs.[11] Let $P_{Z,t}$ denote the nominal price of the fossil resource, then the real marginal cost of production can be written as:

$$MC_{i,t} = MC_t = \Delta_t^{-1}\left[\zeta^{\varkappa}\left(\frac{P_{Z,t}}{P_t}\right)^{1-\varkappa} + (1-\zeta)^{\varkappa} A_t^{\varkappa-1}\left(\frac{W_t}{P_t}\right)^{1-\varkappa}\right]^{\frac{1}{1-\varkappa}}, \tag{5}$$

where we have dropped the i subscript for the marginal costs since they are symmetric across firms.

Following Calvo (1983), each producer may reset its price only with probability $1-\varpi$. The typical firm able to re-optimize in period t will choose the *optimal* price, say $P_{i,t}^{*}$, to maximize the current market value of the expected profits generated while that price will stay put. We further assume that in the periods between price re-optimization, firms will be able to mechanically adjust their prices according to a simple indexation rule:

$$P_{i,t+s} = P_{i,t+s-1}\Pi^{\kappa}\Pi_{t+s-1}^{\kappa}, \qquad s = 1,...,n, \tag{6}$$

[11] On the implications of this assumption in an New Keynesian model, see Montoro (2012) who studies the monetary policy trade-off arising in a economy hit by oil price shocks.

where $\Pi_{t+1} = P_{t+1}/P_t$ is the gross inflation rate at the time $t+1$ and Π is steady-state value, while $\kappa \in [0,1]$ measures the degree of indexation to past inflation. Since there is a continuum of firms of mass one, in each period a fraction $1-\varpi$ of firms will be able to re-optimize and a fraction ϖ will increase their price according to the indexation rule (6). The solution to the price-setting problem is deferred to the Appendix.

2.3 Public Sector, Pollution Stock, and Equilibrium

We assume that the polluting energy input is extracted with no cost by the government, which sells it to the intermediate-goods producers and distributes the proceeds as lump-sum transfers to the households. The government's budget is then balanced at all times. We also assume that the emissions flow is equal to Z_t, so that by either setting the price or the supply of the fossil resource, the government can control emissions.[12] In the first case, the government sets the real price per emissions unit, and this price can be interpreted as a carbon tax; in the second case, the government sets a cap on the overall emissions generated by the economy. We limit our attention to these specific pollution policies since they are two instruments frequently contrasted in the literature and the policy debate.

Following Golosov et al. (2014), the cumulative emissions in the atmosphere, M_t, evolves as:

$$M_t - \overline{M} = \int_0^1 Z_{i,t} di + (1-\delta_M)\left(M_{t-1} - \overline{M}\right) + Z_t^{RoW}, \tag{7}$$

where $\overline{M}$ denotes the pre-industrial concentration of pollutant, $\delta_M \in (0,1)$ measures the natural rate at which the atmosphere recovers, and Z_t^{RoW} is an exogenous process capturing the rest-of-the-world emissions. In what follows, we will keep Z_t^{RoW} constant.

Finally, we include a damage channel in the model, namely a level impact channel affecting firms' productivity via the damage factor Δ_t. Following Golosov et al. (2014), who simplify the approach of Nordhaus (2008, 2017), the damage evolves as follows:

$$\Delta_t = \exp\left(-\eta\left(M_t - \overline{M}\right)\right), \tag{8}$$

where $\eta > 0$ is a scaling coefficient measuring the intensity of the negative externality on production. $1-\Delta_t$, is then the fraction of output lost due to climate change. This is a parsimonious way of introducing the negative environmental externality by which pollutant concentrations affect productivity.[13] From the climate system's functioning, it is easy to understand how changes in emissions in a limited period and implemented by one and only economy, do not

[12] Analogously one could assume that households own the fossil resource and that the public sector levies a tax on its use or imposes quantity restriction as a way to price carbon.

[13] In fully fledged integrated assessment models carbon concentration affects global mean temperature, and then changes in temperature negatively impact productivity. See Golosov et al. (2014) for a discussion on how the exponential damage function specified here approximates the current state-of-the-art damage function given e.g. by Nordhaus (2007).

substantially change cumulative emissions in the atmosphere. This implies that the marginal benefits of unilateral mitigation policies are negligible at business cycle frequency, while the marginal costs are substantial.

Monetary policy is set according to a Taylor-type interest rate rule specified as follows:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\iota_R} \left[\left(\frac{\Pi_t}{\Pi}\right)^{\iota_\pi} \left(\frac{Y_t}{Y_t^*}\right)^{\iota_y}\right]^{1-\iota_R} \exp u_t, \tag{9}$$

where R denotes the steady-state value of the nominal interest rate, Π is the steady-state inflation, Y_t^* is the natural level of output (i.e., the output that would prevail if prices were fully flexible), $\iota_R \in [0,1)$ is the smoothing parameter, measuring the degree of persistence of the rule, $\iota_\pi > 0$ and $\iota_y > 0$ capture the responsiveness of nominal interest rate to movements in inflation and output, while u_t represents an exogenous monetary policy shock.

Finally, since we have assumed that the natural resource is produced at no cost, the resource constraint of the economy is given by:

$$Y_t = \int_0^1 C_{i,t} di. \tag{10}$$

2.4 The Aggregate Model and Expectations

In this section, we first summarize the aggregate equations of the model described in the previous section and then introduce the modeling of expectations. The equilibrium conditions describing the behavior of heterogeneous agents have been log-linearized around a zero-inflation steady state and then aggregated. The aggregate model is reported in Table 1, where y_t, mc_t, z_t, $p_{z,t}$, m_t, y_t^* and δ_t denote output, marginal costs, emissions flow, the relative price of carbon, stock of pollutant, natural output, and environmental damage. All these variables are expressed as natural log deviations from their steady-state values; in contrast the inflation rate, π_t, and the nominal interest rates, r_t, are expressed in deviations from their respective steady-state levels. In detail, the first equation of Table 1 describes the aggregate demand (IS curve); the second equation determines the time path of the marginal costs, where the last term measures the impact of the environmental damage on production; the third equation describes the dynamic of emissions that are decreasing in the carbon price; the fourth equation is the behavioral analog of the New Keynesian Phillips curve relating inflation to marginal costs and agents' beliefs about future inflation; the fifth equation describes the accumulation of the pollution stock; the sixth equation refers to the environmental damage factor; finally, the last equation is the interest rate rule, where we have set ι_r at zero. The equations of the aggregate model will come in handy in interpreting the results of our numerical experiments. For the complete derivation of these equations, see the Appendix.

We are now ready to describe how agents formulate expectations about future variables.

Table 1: The Aggregate Log-Linearized Model

Equation	Description
$y_t\,(1+h) = \tilde{E}_t y_{t+1} + h y_{t-1} - \frac{1-h}{\gamma}\left(r_t - \tilde{E}_t \pi_{t+1}\right) + v_t$	IS
$mc_t = mc_y y_t - mc_\delta \delta_t - \ mc_z z_t - mc_a a_t - mc_{y_{-1}} y_{t-1}$	Marginal Cost
$z_t = \varkappa mc_t + (\varkappa - 1)\,\delta_t + y_t - \varkappa p_{Z,t}$	Emissions
$\pi_t = \frac{1-\varpi\beta}{1+\beta\kappa}\frac{1-\varpi}{\varpi} mc_t + \frac{\beta}{1+\beta\kappa}\tilde{E}_t \pi_{t+1} + \frac{\kappa}{1+\beta\kappa}\pi_{t-1}$	New Keynesian Phillips Curve
$m_t = \delta_M \frac{Z}{Z+Z^{RoW}} z_t + (1-\delta_M) m_{t-1} + \delta_M \frac{Z^{RoW}}{Z+Z^{RoW}} z_t^{RoW}$	Pollution Stock
$\delta_t = -\eta\left(M - \overline{M}\right) m_t$	Environmental Damage
$r_t = \iota_\pi \pi_t + \iota_y (y_t - y_t^*) + u_t$	Taylor Rule

Note: the model is log-linearized around a zero steady-state inflation. In the second equation the coefficients are all positive and depend on a complex fashion on the deep parameters of the model. See the Appendix. Variables v_t, a_t and u_t are exogenous stochastic processes driving economic fluctuations.

As anticipated, agents are assumed to have cognitive limitations, therefore, they use simple rules (i.e., heuristics) to forecast future income and inflation. In the words of Gigerenzer and Gaissmaier (2011, p. 454), a heuristic is “a strategy that ignores part of the information to make decisions more quickly and frugally than more complex methods”. The assumption is that agents adopt precise rules of thumb in their decision-making to overcome their cognitive limitations.

Following the heterogeneous expectations framework of Brock and Hommes (1997), the forecasting rules are described by an endogenous selection mechanism by which agents switch from one rule to another based on their past forecasting performances. For simplicity, we assume only two types of forecasting rules. Consistently with the terminology of De Grauwe (2011, 2012a,b) we consider an ‘extrapolative’ rule and a ‘fundamentalist’ rule.

The extrapolative prediction rule, labeled e, is a random walk rule by which agents use the previously observed value of a variable as a forecast. This is a myopic rule according to which agents are insensitive to other information about the functioning of the economy. The fundamentalist rule, labeled f, is more sophisticated. Agents expect future output to be equal to the expected value of its fundamental level, natural output, while next period inflation is simply expected to return to its long-run value target set by the central bank. In formulating their expectation regarding the natural level of output, these agents use all the information set available at the time t, that is, they formulate rational expectations, but on the wrong variable since they neglect imperfect price adjustments. The judgment on future output is also based on the (wrong) belief that monetary policy is neutral. Put another way, fundamentalists expect that the next period’s output gap will be equal to zero.

According to these forecasting rules, expectations on output and inflation are such that:

$$\tilde{E}_{e,t}(y_{t+1}) = y_{t-1}, \qquad \tilde{E}_{e,t}(\pi_{t+1}) = \pi_{t-1}, \tag{11}$$

$$\tilde{E}_{f,t}(y_{t+1}) = E_t y^*_{t+1}, \qquad \tilde{E}_{f,t}(\pi_{t+1}) = 0, \tag{12}$$

where expectations are formulated at the beginning of the period t before the realization of the shocks. Let $\alpha^e_{y,t}$ ($\alpha^f_{y,t}$) denote the share of agents opting for an extrapolative (fundamentalist) rule for output forecast, and $\alpha^e_{\pi,t}$ ($\alpha^f_{\pi,t}$) the share of agents opting for an extrapolative (fundamentalist) rule for inflation forecast, the market forecasting rules for output and inflation immediately follow:

$$\tilde{E}_t(y_{t+1}) = \alpha^f_{y,t}\tilde{E}_{f,t}(y_{t+1}) + \alpha^e_{y,t}\tilde{E}_{e,t}(y_{t+1}), \tag{13}$$

$$\tilde{E}_t(\pi_{t+1}) = \alpha^f_{\pi,t}\tilde{E}_{f,t}(\pi_{t+1}) + \alpha^e_{\pi,t}\tilde{E}_{e,t}(\pi_{t+1}), \tag{14}$$

where $\alpha^f_{y,t} + \alpha^e_{y,t} = 1$ and $\alpha^f_{\pi,t} + \alpha^e_{\pi,t} = 1$.

Following Brock and Hommes (1997), agents can switch between these rules on the basis of their forecasting performances. Put it differently, agents are aware that their predictions may be biased, they then deliberately learn from their mistakes and switch to the best performing rule. From this point of view, agents can be seen as *rational* since they continuously evaluate the forecast performance of a given rule.[14]

Let U^i_x denote the fitness criterion of rule $i \in \{f, e\}$ for the generic variable $x \in \{y, \pi\}$. This criterion of success is simply defined as the negative of the weighted mean squared forecasting errors of the forecasting rule:

$$U^i_{x,t} = -\sum_{k=0}^{\infty} \gamma_k \left(x_{t-k-1} - \tilde{E}^i_{t-k-2}x_{t-k-1}\right)^2, \tag{15}$$

where γ_k denote geometrically declining weights measuring the weight attributed by agents to past forecast errors. We assume that agents tend to forget, so they attach relatively higher importance to recent errors than those made far in the past. To capture this tendency to forget in a parsimonious way, we assume $\gamma_k = (1-\rho)\rho^k$ with $0 \leq \rho \leq 1$, then (15) can be re-written as:

$$U^i_{x,t} = \rho U^i_{x,t-1} - (1-\rho)\left(x_{t-1} - \tilde{E}^i_{t-2}x_{t-1}\right)^2, \tag{16}$$

where the parameter ρ is a measure of agent memory. In particular, when $\rho = 1$ agents have infinite memory and assign the same weights to all past mistakes; when $\rho = 0$, instead, agents have no memory and only the last period forecasting error matters. In the latter case, we will see that the economy is more volatile.

Moreover, agents may be unpredictably affected by their state of mind when choosing between the two rules, or they may face a measurement error in calculating forecast errors. To

[14] Agents then spend some mental energy in evaluating the performance of a given heuristic.

capture these factors that may affect decisions, we assume that the comparison between the two values of the metrics chosen as fitness criterion of rules $i \in \{f, e\}$ is based on the following probability P :

$$\alpha^f_{x,t} = P[U^f_{x,t} + \epsilon^f_{x,t} > U^e_{x,t} + \epsilon^e_{x,t}], \tag{17}$$

where now $\alpha^f_{x,t}$ can be interpreted as the probability of opting for a fundamentalist rule, while $\epsilon^f_{x,t}$ and $\epsilon^e_{x,t}$ are random variables catching all the unpredictable factors that may affect agents when choosing between alternatives.

As in the discrete choice model of Brock and Hommes (1997) and hinging on the work of Manski and McFadden (1981) and Anderson et al. (1992), these random variables are assumed to be logistically distributed. Under the assumption that all agents can simultaneously update the forecasting rule they use, then the fraction of agents opting for rule i in each period will be given by:

$$\alpha^i_{x,t} = \frac{e^{\theta U^i_{x,t}}}{\sum_i e^{\theta U^i_{x,t}}}, \tag{18}$$

where the parameter θ referred to as 'learning parameter' or 'intensity of choice', reflects the tendency of agents to select the best-performing rule.[15] The size of this parameter is related to the variance of the random components $\epsilon^f_{x,t}$ and $\epsilon^e_{x,t}$ in (17). In particular, if this variance tends to infinity, then $\theta \to 0$ and agents cannot observe any difference in fitness between the two rules, or simply they do not exhibit any willingness to learn from past mistakes. In this case, agents flip a coin to make their choice, so that $\alpha^f_{x,t}$ and $\alpha^e_{x,t}$ will be equal to 0.5. When the variance of the random components tends to zero, $\theta \to \infty$ and agents select the best-performing rule, the probability of opting for one rule can be either 1 or 0. We will see that for a higher θ market beliefs tend to amplify disturbances.

Given these assumptions, the economy features four types of agents according to their way of formulating expectations: (i) agents who formulate expectations according to the extrapolative rule for both output and inflation, (ii) agents who formulate expectations according to the fundamentalist rule for both output and inflation, (iii) agents who opt for the extrapolative rule for output and the fundamentalist rule for inflation, (iv) agents who opt for the extrapolative rule for inflation and the fundamentalist rule for output.

3 Calibration

In this section we present the baseline calibration of the model. Each period corresponds to a quarter, and the model is calibrated to match key features of the US economy. Table 2 lists the choice of parameter values.

[15] According to (18) we are considering the case of synchronous updating, where all agents switch to better rules in each period. We will remove this assumption in Section 5, where will introduce the possibility of asynchronous updating.

Table 2: Calibration

Parameter	Value	Description
β	0.99	Discount rate
γ	1	Risk aversion coefficient
φ	1	Inverse Frisch elasticity
h	0.5	Habit parameter
θ	3050	Learning or intensity of choice parameter
ρ	0.4	Memory of agents
ζ	0.1724	Energy quasi-share parameter
$\varkappa$	0.3	Elasticity of substitution between energy and labor inputs
κ	0.5	Coefficient of price indexation
ω	0.75	Calvo's price parameter
δ_M	0.0021	Emissions decay rate
$\eta(M-\bar{M})$	0.0263	Impact damage coefficient
ι_r	0	Smoothing parameter of the Taylor rule
ι_y	0.125	Output gap coefficient of the Taylor rule
ι_π	1.5	Inflation coefficient of the Taylor rule
ρ_a	0.8	Technology shock persistence
ρ_v	0.8	Preference shock persistence
ρ_u	0.5	Monetary policy shock persistence
σ_a	0.009	Standard deviation of the technology shock
σ_v	0.005	Standard deviation of the preference shock
σ_u	0.005	Standard deviation of the monetary policy shock

The parameters related to the New Keynesian structure of the model are standard. Preferences in consumption are assumed to be logarithmic ($\gamma = 1$) and the inverse of the Frisch elasticity φ is set to 1, an intermediate value between micro and macro data estimates. The discount factor β is equal to 0.99, consistent with a real interest rate of 4% per year. The elasticity of substitution between energy and labor inputs, $\varkappa$, is fixed at 0.3, implying that the two production factors are imperfect complements. The quasi-share parameter measuring the contribution of the polluting input in the CES production, ζ, is calibrated starting from the share of income spent on energy in the US that in 2018 was around 6% of GDP according to EIA (2020). The parameters capturing habit persistence and past indexation of price settings, h and κ, are both set to 0.5, while the probability that prices stay unchanged in each quarter, ϖ, is fixed at 0.75. In the baseline calibration, the policy parameters of the Taylor rule are also standard, that is $\iota_\pi = 1.5$, $\iota_y = 0.125$ and $\iota_r = 0$. To calibrate the environmental part of the model, we proceed as follows. We start by considering the world's total emissions in 2020 according to the business-as-usual scenario of the DICE model, which is 41.685 giga-tons of

Table 3: Moments for Output y - Data and Model under the Baseline Calibration

	Standard Deviation	Autocorrelation	Kurtosis
Data	0.0103	0.8565	3.3057
Model	0.0105	0.8863	3.3239

Note: the table reports moments generated by the model under the baseline calibration for 100 replications of shock sequences of size 1,000 and those of the US data over the period 1990Q1-2019Q4, retrieved from FRED, Federal Reserve Bank of St.Louis. Series used: Real Gross Domestic Product - GDPC1 (HP Filtered series).

carbon dioxide per year.[16] The quarterly rate at which the atmosphere recovers, δ_M, is 0.0021 consistently with Reilly and Richards (1993), implying a half-life of carbon in the atmosphere of about 83 years. Knowing that the pre-industrial atmospheric concentration of carbon, $\overline{M}$, is about 581 giga-tons, we can obtain the steady-state value for M that approximately corresponds to the atmospheric concentration of carbon observed in the DICE model in 2080. According to the DICE simulations, at this pollutant concentration level, the fraction of output lost for the damage is around 0.026. From this assumption, we can retrieve the damage parameter η. Finally, to set the coefficient $Z/(Z^{RoW} + Z)$ in the pollution stock equation of Table 1, we use World Bank data for 2018 and observe that the share of worldwide GHG emissions ascribed to the US is around 13%. Finally, all the exogenous components v_t, a_t and u_t follow an AR(1) process:

$$v_t = \rho_v v_{t-1} + \xi_{v,t}, \tag{19}$$

$$a_t = \rho_a a_{t-1} + \xi_{a,t}, \tag{20}$$

$$u_t = \rho_u u_{t-1} + \xi_{u,t}, \tag{21}$$

where ρ_v, $\rho_a, \rho_u \in [0, 1)$ and $\xi_{v,t}$, $\xi_{a,t}$, $\xi_{u,t}$ are normally and independently distributed innovations with mean zero and standard deviations σ_v, σ_a and σ_u, respectively. The autoregressive coefficients of the technology and the intertemporal preference shocks ρ_a and ρ_v, are set to 0.8, while for monetary policy shock, we set ρ_u equal to 0.5. Real shocks are then more persistent than monetary policy shocks. The parameter capturing the intensity of choice θ, the one measuring the memory of agents, ρ, and the standard deviations of the three shocks are calibrated using a simulated minimum distance routine so that in the baseline calibration under a constant carbon tax policy, the model can fairly match the moments of output observed in the US quarterly data for the period 1990Q1-2019Q4.[17] See Table 3.

[16] For details on the DICE model, see Nordhaus (2017, 2018).

[17] It can be shown that under a quantity restriction (i.e., a cap on emissions) output is less volatile, consistently with previous findings (e.g. Fischer and Springborn 2011 and Annicchiarico and Di Dio 2015) and less leptokurtic, while inflation is slightly more volatile than under a tax, because of the uncertainty surrounding emission prices over the business cycle. The standard deviation of quarterly inflation delivered by the model is 24 b.p. under a tax policy and 28 b.p. under a cap, against an observed volatility of 22 b.p.

4 Greening the Economy: The Role of Market Beliefs and Monetary Policy

This section shows how expectations and market beliefs interact with different environmental policies, and seeks to understand the role monetary policy could play in reducing the trade-offs at stake, controlling potential inflationary pressures, and helping reach the climate targets. In Section 4.1 we explore the implications of removing the standard assumption of full rationality for the conduct of environmental policy. Section 4.2 analyzes how the presence of behavioral agents and business cycle fluctuations shape the economy's response to price and quantity-based mitigation scenarios and explores what the implications for price stability are. Finally, Section 4.3 studies the role of monetary policy during the greening process under different underlying environmental regimes, different degrees of monetary policy stringency, and different interest-rate rules.

4.1 Market Beliefs and Environmental Policy: A Simple Example

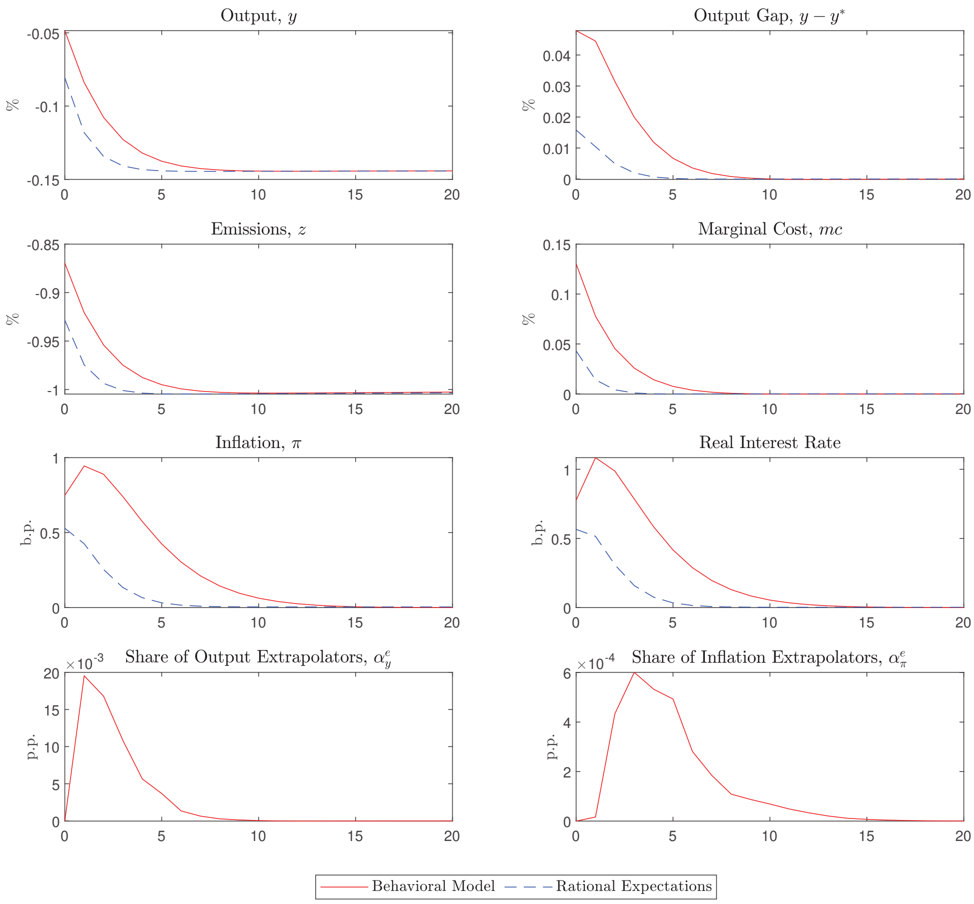
Here we analyze the impact of a mitigation policy under different expectation formations. We solve the model both under the rational expectations hypothesis (the orthodox model) and under the case in which agents are assumed to formulate expectations according to heuristics, as described in the previous sections. To elucidate better the transmission mechanism of environmental policy under different formalizations of the expectations, we start our analysis with an illustrative example. We consider a permanent increase in the carbon price, p_z, to induce a 1% reduction in emissions. To achieve this target, the carbon price p_z must increase by 2.9%.

Figure 2 illustrates the dynamic effects of this modest greening policy in the two variants of the model economy (behavioral vs. rational expectations), where we assume that the fraction of agents using an extrapolative rule for both inflation and output is initially equal to 0.5. In this case, the economy's response to this policy shock abstracts from the presence of business cycle fluctuations, that is, we assume that the economy is in steady state when the carbon pricing shock hits it. Figure 2 allows us to clarify the role that expectations play in reaction to mitigation policies along several dimensions: the time needed to meet the target, the interlinkages between macroeconomic and environmental variables, and the interplay between monetary and climate policy.

We observe that under the same policy stringency in the presence of bounded rationality, the time required to achieve the mitigation target almost doubles compared to the rational expectation case. Note that the 1% reduction is reached in period 4 in the rational expectations model and approximately in period 9 in the behavioral model. This delay implies a lower cumulative reduction in emissions of about 2.4% in the latter scenario.

Different assumptions about expectation formation then strongly alter the dynamic behav-

Figure 2: Increase in the Carbon Price under Rational and Behavioral Expectations



Note: the figure plots the response of the economy to a permanent increase in the carbon price aimed at permanently reducing emissions by 1%. All variables are expressed in percentage deviations from their respective business-as-usual value, with the exceptions of the inflation and the real interest rate, expressed in quarterly basis points (b.p.) deviations, and the shares of extrapolators, expressed in percentage points (p.p.) deviations.

ior of the relevant macro variables. As expected, output decreases in both model configurations in response to the increase in the carbon price. This is due to the rise in marginal costs driven by the higher price of the energy input. However, under the rational expectations hypothesis, agents can fully internalize the effects of the policy and react immediately, thus reducing emissions and production promptly. In this case, the recessionary effects of the policy fully materialize earlier. Rational-expectations agents are aware that climate policy, by permanently changing the supply-side conditions, will affect their permanent income, therefore, they push down consumption. Conversely, the agents' reaction is more conservative in the behavioral model, implying a slower adjustment of real macroeconomic variables. Nonetheless, the aggregate dynamics mask striking differences in the underlying adjustment between extrapolators and fundamentalists. In particular, fundamentalists expect a return of the economy to its natural level, which is negatively affected by the pollution policy. However, these agents do not account for the short-run deviations of output from its natural level and thus do not have a precise perception of the time path of output during the adjustment process.[18] On the other hand, extrapolators are purely backward-looking and initially perceive the climate action as a temporary shock. As a result, these agents slowly adjust their consumption choices, self-sustaining aggregate demand and production during the mitigation period, slowing down the transition toward a greener economy.

Looking at the behavior of inflation and interest rates, we note what kinds of interaction effects are in place between monetary and climate policies. The carbon pricing policy propagates in the economy as a cost-push shock, creating an upsurge in inflation and a drop of output. The output gap is positive because price rigidity dampens the decrease of output and output decreases less than in the case of a fully-flexible price economy. The increase in inflation leads the central bank to raise the nominal interest rate more than proportionally, to bring inflation back to its target. The adjustment process is slowed down by non-rational agents, and inflation remains above the target more persistently. In this case, preserving price stability in response to climate action looks more challenging.[19] Hence, compared to the dynamics of the standard New Keynesian model with rational expectations, the presence of agents following different heuristic expectation rules highly affects the effectiveness of policy interventions and the persistence of the adjustment process, especially in the short run.

In this experiment, we do not consider the role of uncertainty in shaping the economy's response to a climate policy. Indeed, there is significant uncertainty about how a greening policy can affect the economy and the conduct of monetary policy, especially during an ambitious mitigation path. This is especially true in behavioral models where the economy's response to policies may entail waves of optimism and pessimism generated by wrong market beliefs and where the results are sensitive to the initial conditions of the economy (i.e., the share of different agents in the economy and the phase of the business cycle).

4.2 Market Beliefs and Mitigation Scenarios: Price vs. Quantity Regulations

We are now ready to consider a more ambitious mitigation scenario and analyze the uncertainty surrounding the impact of a greening policy on the main macroeconomic variables in an economy with non-rational agents. Specifically, we start by examining a mitigation policy implemented through a gradual increase in the carbon tax able to generate a reduction of emissions by

[18] Recall that here the output gap is expressed as the difference between the output arising under sticky prices and the natural level of output, meant as the output prevailing in the case of fully flexible prices.

[19] In the next section we will see how preserving price stability may be even more difficult under a cap policy prescribing a commensurate quantity restriction on the pollutant.

20% in 5 years in a deterministic rational expectations economy, where, in each period, agents are assumed to be surprised by the policy shock. This assumption is made to rule out any anticipation effects. The mitigation scenario is in line with the emission reduction targets set by the United States for 2030.[20]

We factor in uncertainty by undertaking two series of simulations based on the behavioral version of the model. The design of the experiment is as follows. In the first baseline simulated series, the economy is hit by exogenous shocks on technology, demand, and interest rate. The length of the series is 300 quarters. In the second simulation series, the economy is hit by the same exogenous shocks as in the first simulation series, but it also entails the introduction of a mitigation plan after 200 periods. To compute the response functions of the economy to a mitigation policy introduced in a business-as-usual scenario, we subtract the first simulated series from the second one. Basically, the economy is away from the steady state when the carbon pricing policy is implemented. We then replicate this experiment considering 1,000 random shocks' realizations, $\xi_{v,t}$, $\xi_{a,t}$, $\xi_{u,t}$, and compute the mean response functions and the corresponding standard deviations. In other words, we analyze the effects of carbon pricing conditional on the state of the economy.

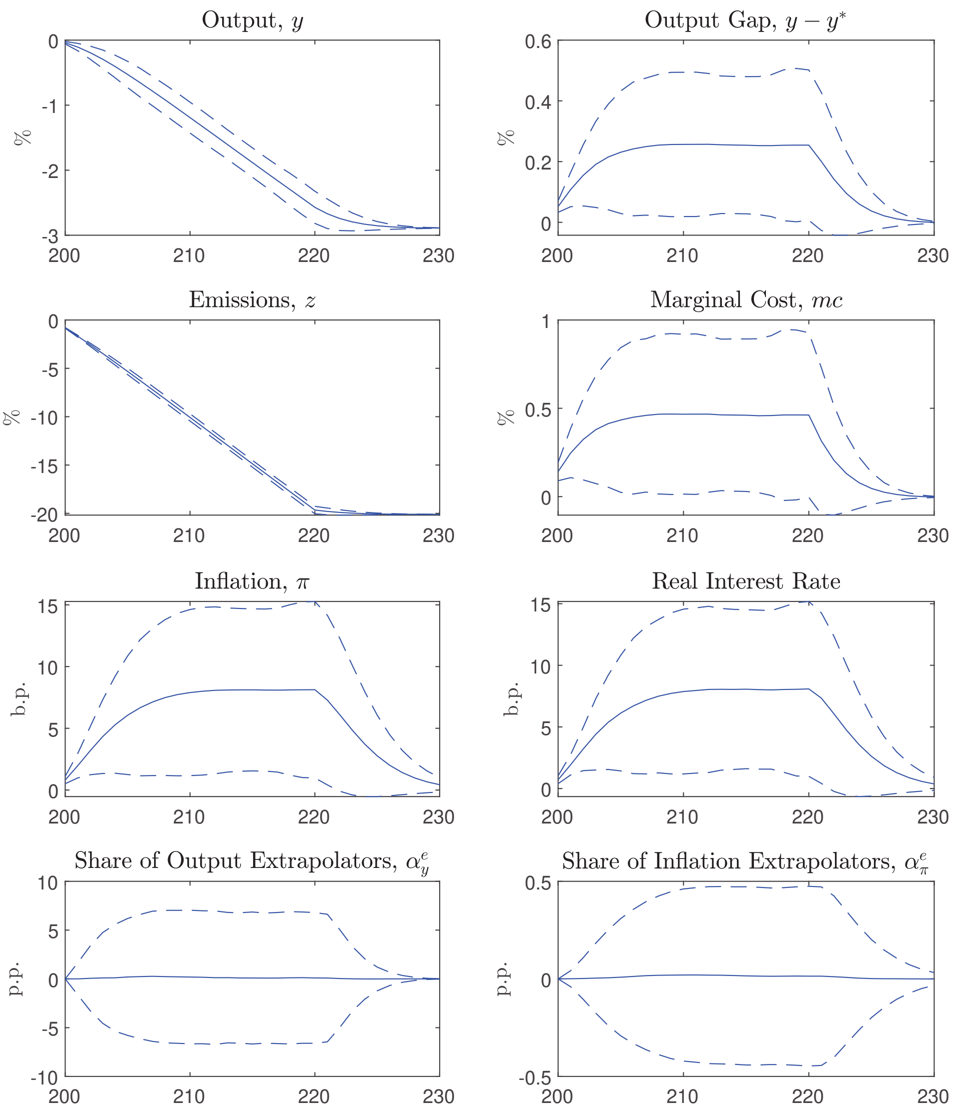
Figure 3 illustrates the mean response (solid lines) and a band of significance of ± 2 standard deviations from the mean (dashed lines). We can observe how expectations and market beliefs can generate large movements in output and inflation through this experiment. Looking closely at the figure, we can see a wide increase in the uncertainty surrounding the short-term effects of the carbon price. The economy's reaction depends on the initial state of the economy that could be in any phase of the business cycle. The range of variation in the dynamic response to the shock is driven endogenously by self-fulfilling movements of optimism and pessimism that amplify fluctuations and affect how the policy shock is transmitted to the economy. By basing their decisions on biased information, non-rational agents make the economy more prone to fluctuations. In addition, the policy shock itself affects market sentiments, which is why it may take longer to adjust to the new long-term equilibrium.[21]

In the context of mitigation policies, this last result is particularly relevant since it brings light on an additional layer of uncertainty surrounding the achievement of climate targets. In a timely and orderly mitigation scenario, as depicted in Figure 3, emissions could follow only slightly different trajectories. We observe that the number of quarters needed to reach the objective of 20% emissions reduction ranges from 20 to 28 quarters. In the case of a disorderly mitigation scenario and/or in the case of a highly perturbed economy, instead, the emission trajectory can be much more unpredictable, making the adjustment process to the target more

[20]The United States has an economy-wide target of reducing its GHG emissions by 50-52% below 2005 levels by 2030. We use the emission data provided by Crippa et al. (2021) to compute the reduction achieved so far and the one still needed to reach the target. Consistently with the short-run analyses presented in the paper and the typical horizon of monetary policy, we present here the first five years of the mitigation plan (20% emission reduction compared to current levels).

[21]In Appendix we show how the economy evolves under rational expectations.

Figure 3: Timely Mitigation under Behavioral Expectations - Carbon Tax



Note: the figure plots the mean response of the economy to a gradual increase in the carbon price aimed at permanently reducing emissions by 20%. Dashed lines show ±2 standard deviations from the mean. All variables are expressed in percentage deviations from their respective business-as-usual value, with the exceptions of the inflation and the real interest rate, expressed in quarterly basis points (b.p.) deviations, and the shares of extrapolators, expressed in percentage points (p.p.) deviations.

Table 4: Macroeconomic Volatility along the Mitigation Path

Timely Mitigation			Delayed Mitigation	
	Tax	Cap	Tax	Cap
σ_z	0.1584	0	0.1972	0
σ_{p_z}	0	0.4774	0	0.6046
σ_{y-y^*}	0.1001	0.0823	0.1242	0.1038
σ_π	2.7081	2.9812	3.2712	3.6587
$E(\pi)$	6.6437	7.7108	8.0425	9.3969
$max(\pi)$	8.1280	9.4923	13.8860	16.172

Note: the table reports the standard deviations for a selection of variables along with mean inflation and its maximum observed value over the mitigation time path; σ_{p_z}, σ_z, σ_{y-y^*} are expressed in percentages, σ_π, $E(\pi)$ and $max(\pi)$ in quarterly basis points.

or less expensive in terms of cumulative emissions.[22] To achieve an equivalent mitigation goal over the same time horizon, but avoid any uncertainty regarding the emission pattern, the government may opt for a quantity-based instrument rather than a price instrument. However, a quantity approach may entail excessive volatility of the emission prices. To understand the uncertainty inherent to the selected instrument, in the first two columns of Table 4, we compare the performance of a carbon tax and an emission cap during the mitigation path considered in Figure 3. We look at the variability of a selection of variables and at the inflation dynamics. By introducing more uncertainty regarding the time path of emission prices, a cap policy delivers more inflation volatility and higher inflation than a tax policy.[23] In this respect, maintaining price stability looks more challenging under a quantity restriction than under a carbon tax. In the third and fourth columns of the same table, we consider a delayed scenario in which the greening policy is introduced one year later. For comparability, we design this scenario so that after 20 quarters the amount of cumulative emission variation is as in the timely case. We can see that whether the regulator chooses a tax or a quantity-based instrument entails a more intense trade-off between emission and inflation stabilization.

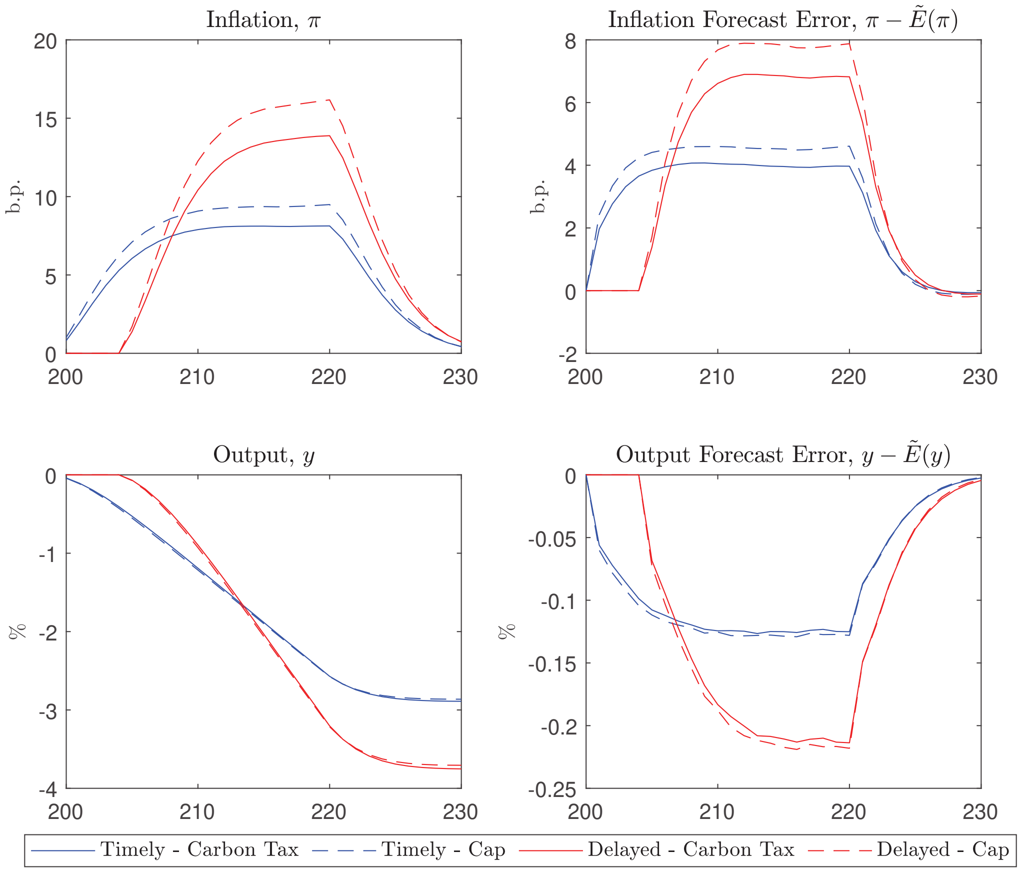
To better appreciate the dynamics of the economy in the four scenarios of Table 4 in Figure 4 we show the inflation and the output dynamics, along with their market forecast errors. The forecast errors for both variables are substantially more significant in the delayed scenario, while a cap is clearly more inflationary than a tax along the adjustment process. Agents tend to undermine inflation and overstate output more intensively under a cap than under a tax, and under a delayed scenario than under a timely mitigation process.[24]

[22] The time path of emissions in a highly perturbed economy is shown in Appendix.

[23] In a highly perturbed scenario choosing between price and quantity regulations would entail a major policy trade-off between emission certainty and price stability. In Appendix we show the time path of permits price and inflation in a highly perturbed scenario.

[24] In Appendix we show that under rational expectations the forecast errors are driven only by the pollution policy that is phased in as a surprise policy shock.

Figure 4: Mitigation Scenarios - Macroeconomic Dynamics and Market Forecast Errors



Note: the figure plots the mean response of the economy to different mitigation scenarios entailing the same cumulative emissions after 20 quarters in the deterministic counterparts. Inflation and its forecast errors are expressed in quarterly basis points (b.p.) deviations, while output and its forecast errors are in percentage deviations.

Table 5: Macroeconomic Volatility along the Mitigation Path: The Role of Monetary Policy

	Tax					Cap				
ι_y										
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
0	0.2097	0.1327	3.6079	7.8440	9.7411	0.6259	0.1080	3.9248	8.9555	11.1760
0.125	0.1584	0.1001	2.7081	6.6437	8.1280	0.4775	0.0823	2.9812	7.7108	9.4923
0.5	0.0778	0.0490	1.3043	4.5251	5.3703	0.2390	0.0410	1.4712	5.4329	6.4966
1.5	0.0210	0.0131	0.3342	2.4704	2.8330	0.0661	0.0112	0.3869	3.0859	3.5594
2	0.0134	0.0083	0.2062	2.0277	2.3086	0.0422	0.0071	0.2391	2.5563	2.9232
3	0.0072	0.0044	0.1018	1.5032	1.6974	0.0224	0.0037	0.1162	1.9159	2.1686
ι_π										
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
1.1	0.1998	0.1265	3.4545	7.6721	9.6154	0.6395	0.1104	4.0471	9.1434	11.5907
1.2	0.1882	0.1191	3.2440	7.3882	9.1995	0.5926	0.1023	3.7381	8.7399	10.9906
1.5	0.1584	0.1001	2.7081	6.6437	8.1280	0.4775	0.0823	2.9812	7.7108	9.4923
3	0.0776	0.0487	1.2679	4.3878	5.1074	0.2013	0.0344	1.1845	4.8382	5.5797
4	0.0532	0.0333	0.8435	3.5764	4.0750	0.1302	0.0221	0.7341	3.8862	4.3777
5	0.0386	0.0240	0.5934	3.0223	3.3988	0.0909	0.0153	0.4907	3.2560	3.6094
ι_r										
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
0	0.1584	0.1001	2.7081	6.6437	8.1280	0.4775	0.0823	2.9812	7.7108	9.4923
0.5	0.2150	0.1358	3.6263	7.4956	9.1287	0.6590	0.1134	4.0268	8.7150	10.4960
0.7	0.3128	0.1980	5.3100	8.9110	11.1092	0.9848	0.1698	6.0158	10.4125	12.7421
0.9	0.9265	0.5900	16.5975	18.2039	24.3147	3.1754	0.5507	20.3834	22.3629	30.1979

Note: the table reports the standard deviations for a selection of variables along with mean inflation and its maximum observed value over the mitigation time path; σ_{p_z}, σ_z, σ_{y-y^*} are expressed in percentages, σ_π, $E(\pi)$ and $max(\pi)$ in quarterly basis points.

4.3 The Role of Monetary Policy

In this section, we explore the role of monetary policy in shaping the economy's response to climate policy. In particular, we address the following questions. Can monetary policy reduce the uncertainty regarding the economy's response during the transition? Can monetary policy affect the timing by which a specific mitigation objective is reached?

To address these questions, we consider different values for the interest rate rule parameters, ι_y, ι_π and ι_r, and see how monetary policy interacts with the instrument chosen to achieve the mitigation goal. The results are summarized in Table 5. A higher reactivity of the interest rate to the output gap or inflation strongly reduces the average volatility of the economy. This is true independently of the underlying environmental regime adopted. The intuition for this result is that a significant stabilization effort of central banks mitigates the intensity of the waves of optimism and pessimism triggered by (wrong) market beliefs, thus reducing the uncertainty surrounding the mitigation policy. By reacting more to the output gap or inflation, monetary policy is more restrictive and induces the economy to converge quickly to its new long-run equilibrium. In this case, the fundamentalist rules, envisaging the return of the economy to its natural level, are validated by monetary policy. Under the central bank's more vigorous stabilization effort, there is no longer any trade-off between inflation control and climate policy: more price stabilization can be achieved without leading to more uncertainty about meeting the climate target.

On the other hand, for an increasing ι_r, the Taylor rule becomes less reactive to current variations of the output gap and inflation. Thus we observe that macroeconomic volatility goes up. An excessive degree of inertia delivers higher variability as monetary policy cannot stabilize the economy in reaction to the current economic conditions. More importantly, it can be shown that for ι_r set to 0.9, the time needed to reach the mitigation objective ranges from 18 to 38 quarters, so with a potential mitigation delay of more than 4 years.

Overall, from these results, we observe that when the central bank assigns more weight either to inflation or to the output gap, it can align different objectives, namely stabilizing inflation around the inflation target, while facilitating the decarbonization process by avoiding unnecessary volatility and by shortening the time needed to reach a given mitigation target, whether the chosen mitigation instrument is a tax or a cap. Put another way, conventional monetary policy can work alongside climate policy, reducing the uncertainty surrounding mitigation strategies and at the same time stabilizing both the output gap and inflation. Central banks can then support climate policies without overstretching their competencies.

4.3.1 Alternative Interest Rate Rules

To further shed light on the role of monetary policy in the mitigation process, we show how our results may change under alternative implementable interest rate rules. In particular, we consider the following forms:
(i) backward-looking interest-rate rule:

$$r_t = \iota_\pi \pi_{t-1} + \iota_y (y_{t-1} - y^*_{t-1}) + u_t, \tag{22}$$

(ii) forward-looking interest-rate rule:

$$r_t = \iota_\pi E_t \pi_{t+1} + \iota_y E_t (y_{t+1} - y^*_{t+1}) + u_t, \tag{23}$$

(iii) market expectations-based interest-rate rule:

$$r_t = \iota_\pi \tilde{E}_t \pi_{t+1} + \iota_y \tilde{E}_t (y_{t+1} - y^*_{t+1}) + u_t, \tag{24}$$

(iv) interest rate rule reacting to output growth:

$$r_t = \iota_\pi \pi_t + \iota_y (y_t - y_{t-1}) + u_t. \tag{25}$$

Table 6: Macroeconomic Volatility along the Mitigation Path under Alternative Monetary Rules

Tax					
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
$r_t = \iota_\pi \pi_t + \iota_y (y_t - y_t^*)$	0.1584	0.1001	2.7081	6.6437	8.1280
$r_t = \iota_\pi \pi_{t-1} + \iota_y (y_{t-1} - y_{t-1}^*)$	0.1885	0.1188	3.1408	7.1380	8.5656
$r_t = \iota_\pi E_t \pi_{t+1} + \iota_y E_t (y_{t+1} - y_{t+1}^*)$	0.1577	0.0998	2.7323	6.8825	8.6229
$r_t = \iota_\pi \tilde{E}_t \pi_{t+1} + \iota_y \tilde{E}_t (y_{t+1} - y_{t+1}^*)$	0.2978	0.1886	5.1800	9.9000	12.6396
$r_t = \iota_\pi \pi_t + \iota_y (y_t - y_{t-1})$	0.2156	0.1365	3.7277	8.2961	10.3813
Cap					
	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
$r_t = \iota_\pi \pi_t + \iota_y (y_t - y_t^*)$	0.4775	0.0823	2.9812	7.7108	9.4923
$r_t = \iota_\pi \pi_{t-1} + \iota_y (y_{t-1} - y_{t-1}^*)$	0.5853	0.1005	3.5268	8.3282	9.9898
$r_t = \iota_\pi E_t \pi_{t+1} + \iota_y E_t (y_{t+1} - y_{t+1}^*)$	0.4720	0.0814	3.0077	8.0467	10.1408
$r_t = \iota_\pi \tilde{E}_t \pi_{t+1} + \iota_y \tilde{E}_t (y_{t+1} - y_{t+1}^*)$	1.0218	0.1766	6.5035	12.1937	15.8057
$r_t = \iota_\pi \pi_t + \iota_y (y_t - y_{t-1})$	0.6422	0.1108	4.0555	9.4710	11.8816

Note: the table reports the standard deviations for a selection of variables along with mean inflation and its maximum observed value over the mitigation time path; σ_{p_z}, σ_z, σ_{y-y^*} are expressed in percentages, σ_π, $E(\pi)$ and $max(\pi)$ in quarterly basis points.

Rules (i) and (ii) belong to the class of monetary-policy rules that are typically analyzed in the monetary policy literature and require no less information on the part of the central bank than the contemporaneous feedback rule based on the current values of inflation and the output gap.[25] Rule (iii) is a simple implementable expectations-based rule based on the assumption that policymakers can observe the average forecasts made by heterogeneous agents. The rationale of this rule is that monetary policy should react aggressively to market expectations.[26] Finally, in the feedback rule (iv) the change in interest rate is set as a function of output growth rather than of output gap. This last specification implies that the central bank does not need to know the flexible-price level of aggregate activity.

For comparability across monetary rules, we set the policy parameter values as in Table 2. The results are summarized in Table 6. Clearly, inflation is more stabilized under the baseline interest rate rule and the forward interest rule. Under both a backward monetary policy rule and a rule envisaging a reaction to output growth the variability of all variables and average inflation tend to increase. In the former case, this can be explained by the fact

[25]See e.g. Schmitt-Grohé and Uribe (2007).

[26]This rule is used in several papers dealing with non-rational agents. See Evans and McGough (2005), Preston (2006) and Branch and McGough (2010) among others. The market expectation $\tilde{E}_t y_{t+1}^*$ is introduced in the model as done for inflation and output in Section 2.4, and depends on the expectation formulated by fundamentalists, $\tilde{E}_t^f y_{t+1}^* = 0$, and on that formulated by extrapolators, $\tilde{E}_t^e y_{t+1}^* = y_{t-1}^*$.

that, by changing the nominal interest in reaction to past events, the central bank is less able to limit the current exuberance of the markets. This result is consistent with those observed in Table 5 for positive values of the persistence parameter ι_r. In the latter case, the monetary rule becomes less stringent by reacting to output variations that during the greening path are negative. However, the worst-performing rule is the one based on market expectations. When the interest rate changes in response to private-sector expectations, the volatility of all variables is almost two times the one observed under the contemporaneous baseline rule. This is because monetary policy, instead of limiting divergent behavioral dynamics around the mitigation path, somehow validates the 'wrong' expectations that partially ignore the ongoing structural change. This is why an expectations-based rule is potentially destabilizing. Finally, it can be shown that the uncertainty regarding the time horizon by which the mitigation target is reached slightly changes only in the case of an expectations-based rule, with a time frame that goes from 21 to 30 quarters. Under all the other rules, this time frame stays almost unchanged.

5 Sensitivity Analysis and Extensions

In this section, we carry out a series of checks to assess the robustness of the previous results against changes in the values of the behavioral parameters that might be surrounded by uncertainty and might be particularly relevant in shaping the economy's response to a gradual decarbonization process. We also propose a couple of extensions of our analysis, allowing for asynchronous updating of the forecasting rules, trending-based rules, and skepticism about the ability of the central bank to keep inflation at its target during the mitigation path.

5.1 Memory and Willingness to Learn

In this section, we look at the role played by the parameters θ, which measures the willingness to learn and ρ, which measures agents' memory. The results are shown in Table 7.

For small values of the willingness to learn, agents are less sensitive to the performance of their forecasting rule and tend to decide more randomly. As a result, the initial state of the economy is less relevant for the dynamic adjustments of output, emissions, and inflation, and the uncertainty surrounding the greening path is lower.

For large values of θ instead, agents learn from their past mistakes and revise how they formulate expectations based on past performances. We observe a more significant variability of the main macroeconomic variables during the greening plan and a more substantial inflationary pressure, especially under a cap policy. Suppose that the mitigation process starts when the economy is in an expansionary phase. In that case more agents expect that income will stay high in the future on the basis of the extrapolative rule. A higher expected income drives current demand upward, validating the initial expectations. In this case, emissions will converge to the

Table 7: Macroeconomic Volatility along the Mitigation Path: The Role of Willingness to Learn and Memory

	Tax					Cap				
θ										
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
500	0.0260	0.0164	0.4440	4.6315	5.5010	0.0783	0.0135	0.4887	5.6256	6.6495
1000	0.0519	0.0328	0.8879	5.0261	6.0161	0.1565	0.0270	0.9774	6.0345	7.2069
2500	0.1299	0.0821	2.2198	6.2097	7.5614	0.3914	0.0674	2.4436	7.2610	8.8791
3050	0.1584	0.1001	2.7081	6.6437	8.1280	0.4775	0.0823	2.9812	7.7108	9.4923
3200	0.1662	0.1051	2.8413	6.7621	8.2826	0.5009	0.0863	3.1278	7.8334	9.6595
ρ										
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
0	0.1737	0.1093	2.9030	6.7951	8.2708	0.5215	0.0894	3.1774	7.8626	9.6561
0.2	0.1678	0.1059	2.8332	6.7384	8.2204	0.5045	0.0867	3.1077	7.8069	9.5989
0.4	0.1584	0.1001	2.7081	6.6437	8.1280	0.4775	0.0823	2.9812	7.7108	9.4923
0.6	0.1417	0.0897	2.4631	6.4746	7.9459	0.4286	0.0740	2.7251	7.5327	9.2794
0.9	0.0744	0.0473	1.3450	5.8345	7.1174	0.2229	0.0387	1.4730	6.8288	8.2953

Note: the table reports the standard deviations for a selection of variables along with mean inflation and its maximum observed value over the mitigation time path; σ_{p_z}, σ_z, σ_{y-y^*} are expressed in percentages, σ_π, $E(\pi)$ and $max(\pi)$ in quarterly basis points.

new equilibrium following a higher trajectory. On the other hand, if the greening action is taken when the economy is in a recession, the same mechanism will work in the opposite direction. The initial lower level of income implies that more agents expect a lower level of income for the following period, reducing aggregate demand and so the current output. Again expectations are self-validating, and the economy will converge toward the new long-run equilibrium along a lower trajectory.

When ρ is low, agents learn less from the mistakes made in the past and attach a larger weight to the last period's performance in evaluating a forecasting rule. As a result, the economy is more sensitive to the current state of the economy, and the business cycle has a greater influence on the mitigation process. On the other hand, for values of ρ closer to 1, agents have more memory and attach a high weight to past mistakes. For this reason, they react relatively less to the last period's forecast error, and there is less uncertainty surrounding the greening process. However, it can be shown that emissions converge slowly to their target. This is because agents do not react promptly to the new economic conditions following the increase in carbon pricing. Since most recent mistakes and events have a relatively marginal role in driving the choice between heuristics, agents do not immediately adjust their forecasting rule, and the economy will reach the new steady state with some delay.

Table 8: Macroeconomic Volatility along the Mitigation Path: Asynchronous Updating of Expectations

	Tax					Cap				
δ_i										
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
0	0.1584	0.1001	2.7081	6.6437	8.1280	0.4775	0.0823	2.9812	7.7108	9.4923
0.2	0.1536	0.0972	2.6413	6.5869	8.0726	0.4635	0.0800	2.9136	7.6531	9.4283
0.4	0.1454	0.0921	2.5236	6.4960	7.9776	0.4401	0.0760	2.7924	7.5583	9.3177
0.6	0.1307	0.0829	2.2970	6.3393	7.8002	0.3966	0.0686	2.5505	7.3903	9.1091
0.8	0.1001	0.0636	1.7939	6.0373	7.4164	0.3033	0.0526	1.9868	7.0568	8.6525
1	0.0000	0.0000	0.0000	4.2370	4.9861	0.0000	0.0000	0.0000	5.2168	6.0923

Note: the table reports the standard deviations for a selection of variables along with mean inflation and its maximum observed value over the mitigation time path; σ_{p_z}, σ_z, σ_{y-y^*} are expressed in percentages, σ_π, $E(\pi)$ and $max(\pi)$ in quarterly basis points.

5.2 Asynchronous Updating

We now introduce the possibility of asynchronous updating by changing how the fraction of agents opting for a specific rule evolves over time.[27]. In particular, we now replace equation (18) with the following:

$$\alpha^i_{x,t} = \delta_i \alpha^i_{x,t-1} + (1-\delta_i)\frac{e^{\theta U^i_{x,t}}}{\sum_i e^{\theta U^i_{x,t}}}, \quad 0 \le \delta_i \le 1 \tag{26}$$

where the asynchronous updating parameter δ_i captures inertia in the choice of the heuristics. In the extreme case of $\delta_i = 0$ there is synchronous updating and the economy evolves as in our baseline model, where agents stand ready to opt for the best performing rule, given their state of mind. A the other extreme, for $\delta_i = 1$, agents never update their forecasting rule no matter their performance, that is like saying that agents are stubborn. Table 8 shows the economy's volatility for different values of δ_i. We observe that when agents are more reluctant to switch from one rule to another on the basis of their forecast errors, the economy is less volatile, and keeping inflation stable becomes less challenging.

5.3 Other Expectation Rules

Our analysis has been conducted using elementary forecasting rules for both variables and under the assumption that only a fraction of agents perceive the central bank's commitment to maintaining price stability as entirely credible. However, during a greening transition process that is expected to be inflationary, it makes sense to assume that also fundamentalists may

[27] This is along the lines of Diks and Van Der Weide (2005), Hommes et al. (2005a) and Hommes et al. (2019) and is consistent with the evidence provided by Hommes et al. (2005b).

cast doubt about the credibility of the inflation-targeting regime, reducing the effectiveness of forward guidance. This may be particularly relevant under a delayed scenario. In addition, one can assume that agents may revise their way of formulating expectations about output and inflation on the basis of a trend-following rule. Again, during a structural change, agents may also account for the information provided by the last observed variation in their forecast variable in developing their expectations.

To address the issue of credibility of the inflation targeting policy, we start by considering two extreme cases. One is to assume that there is 100% skepticism. In this case, all agents are extrapolators when they formulate expectations about inflation. The market inflation expectation is then $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1}$. The other extreme case, i.e., full credibility of the inflation target, assumes that all agents are fundamentalists when forecasting inflation. The market inflation expectation is then $\tilde{E}_t(\pi_{t+1}) = 0$. We also allow for a more complex heuristic considering a trend-adjusted rule for inflation so that the private sector inflation expectation is now $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1} + g_\pi(\pi_{t-1} - \pi_{t-2})$ where $g_\pi > 0$ measures the responsiveness of the expected inflation to the last observed inflation variation. As in Hommes (2011), we assign two possible values to g_π, namely 0.4 and 1.3, so distinguishing between strong- and weak-trending following rules. Table 9 shows the results. As expected, when all agents maintain skepticism about the credibility of the inflation-targeting policy or adopt trend-following rules to forecast inflation, keeping price stability becomes tougher. For a strong-trend following rule, the task becomes even more arduous. In revising their prices, agents expecting persistent deviations of inflation from its target would set too high or too low prices, thus validating their 'wrong' expectations and destabilizing the real side of the economy. Consequently, emissions are more perturbed along their path than in the baseline case.

Finally, we account for the implications of having a trend-following rule for output by assuming that extrapolators, instead of simply using a random walk rule to predict the next period value of output, formulate their expectations according to a trend-adjusted rule of the form: $\tilde{E}_{e,t}(y_{t+1}) = y_{t-1} + g_y(y_{t-1} - y_{t-2})$, with $g_y > 0$. Fundamentalists act as in the baseline case since by expecting future output to be equal to its natural counterpart, they already factor in the effects of the ongoing structural change. The last two lines of Table 9 report our findings for the case of weak- and strong-trend following rules for output. When extrapolators react vigorously to the output trend, the inflation rate is strongly stabilized under both regulatory regimes. Under a tax, we note that emissions are much less volatile than in all other cases. Under this rule, extrapolators adjust their expectations for the negative trend, and the economy moves more smoothly towards its new long-run equilibrium. In the case of a weak-trend following rule, instead, results do not seem to change substantially.

Table 9: Macroeconomic Volatility along the Mitigation Path: Other Expectation Rules

	Tax				
	σ_z	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
Baseline	0.1584	0.1001	2.7081	6.6437	8.1280
Inflation targeting skepticism $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1}$	0.1441	0.0910	6.1445	20.9906	38.2703
Inflation targeting credibility $\tilde{E}_t(\pi_{t+1}) = 0$	0.1735	0.1098	1.7203	3.7914	4.3634
Strong-trend following rule for inflation $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1} + 1.3(\pi_{t-1} - \pi_{t-2})$	0.2203	0.1397	28.1793	66.1670	107.1897
Weak-trend following rule for inflation $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1} + 0.4(\pi_{t-1} - \pi_{t-2})$	0.1360	0.0859	7.3463	25.6732	45.3238
Strong-trend following rule for output $\tilde{E}^e_t(y_{t+1}) = y_{t-1} + 1.3(y_{t-1} - y_{t-2})$	0.0788	0.0492	1.1943	2.0836	2.6467
Weak-trend following rule for output $\tilde{E}^e_t(y_{t+1}) = y_{t-1} + 0.4(y_{t-1} - y_{t-2})$	0.1358	0.0857	2.2868	5.3782	6.3607
	Cap				
	σ_{p_z}	σ_{y-y^*}	σ_π	$E(\pi)$	$max(\pi)$
Baseline	0.4775	0.0823	2.9812	7.7108	9.4923
Inflation targeting skepticism $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1}$	0.4308	0.0742	6.2204	23.4153	41.5472
Inflation targeting credibility $\tilde{E}_t(\pi_{t+1}) = 0$	0.5364	0.0926	1.8470	4.4050	5.1235
Strong-trend following rule for inflation $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1} + 1.3(\pi_{t-1} - \pi_{t-2})$	0.6790	0.1174	26.1196	66.6758	108.5485
Weak-trend following rule for inflation $\tilde{E}_t(\pi_{t+1}) = \pi_{t-1} + 0.4(\pi_{t-1} - \pi_{t-2})$	0.4043	0.0695	7.3475	28.3265	48.2071
Strong-trend following rule for output $\tilde{E}^e_t(y_{t+1}) = y_{t-1} + 1.3(y_{t-1} - y_{t-2})$	0.2320	0.0394	1.2558	2.4593	3.0899
Weak-trend following rule for output $\tilde{E}^e_t(y_{t+1}) = y_{t-1} + 0.4(y_{t-1} - y_{t-2})$	0.4081	0.0702	2.5039	6.2443	7.4330

Note: the table reports the standard deviations for a selection of variables along with mean inflation and its maximum observed value over the mitigation time path; σ_{p_z}, σ_z, σ_{y-y^*} are expressed in percentages, σ_π, $E(\pi)$ and $max(\pi)$ in quarterly basis points.

6 Conclusions

There is an ongoing debate among economists and policy analysts about the implications of climate change for monetary policy, and many central banks have already included climate change considerations in their assessments of potential economic and financial risks. This paper shows the relevance of market expectations and business cycle fluctuations on the interaction between monetary and climate policy by focusing on two specific aspects of this debate. The first aspect regards the potential implications of different mitigation instruments for the ability of central banks to conduct monetary policy successfully and keep inflation under control. The second aspect concerns the role that central banks themselves can play in supporting the transition process and reducing the macroeconomic uncertainty inherent to the policy tool selected to fight climate change.

The presence of behavioral agents with cognitive limitations amplifies business cycle fluctuations and allows for the emergence of waves of optimism and pessimism along the mitigation path, injecting further uncertainty regarding the impact and effectiveness of climate policies. In this context, a green transition is found to pose a more significant threat to the ability of central banks to maintain price stability than in the case of an economy with rational agents. Moreover, the trade-offs between cap-and-trade and carbon tax policies are accentuated, with the two instruments delivering different dynamic adjustments. On the one hand, for price regulation, the time needed to achieve an emission-reduction target can be longer than in standard rational expectation models, especially in a highly perturbed economy. On the other hand, a cap-and-trade scheme entails more certainty about future emission levels. Still, it implies significant uncertainty on allowances prices, production costs, and inflation dynamics, posing a major threat to price stability.

Looking at the role of central banks, we find that, under price regulation, a monetary policy more reactive to the output gap or inflation can help stabilize emissions, thus reducing the degree of uncertainty regarding the achievement of climate targets. Under both environmental regimes, more vigorous response to current fluctuations in macroeconomic variables can help moderate inflation volatility and reduce the pressure on prices due to the more stringent climate policy. Central banks seem then to be able to tame market sentiments and support, in some respect, the green transition.

Delays in the implementation of stringent climate policies, the lack of confidence in the ability of central banks to maintain price stability during the green transition, and the adoption of monetary rules reacting to market expectations, rather than to current macroeconomic variables, are all factors that can magnify the uncertainty along the mitigation path and worsen the impact on price stability.

The main policy message arising from this paper is that, regardless of the adoption of new instruments targeted to support the low-carbon transition, central banks can contribute to fighting climate change by primarily acting in the perimeter of their mandate. By implementing successful stabilization policies, central banks can highly reduce the uncertainty surrounding the introduction of carbon pricing policies, ensuring better conditions for successful climate actions.

References

Alessi, L., Battiston, S., and Kvedaras, V. (2021). Over with carbon? Investors' reaction to the Paris Agreement and the US withdrawal. JRC Working Papers in Economics and Finance 2021-12, Joint Research Centre, European Commission.

Anderson, S. P., De Palma, A., and Thisse, J.-F. (1992). *Discrete choice theory of product differentiation*. MIT press.

Annicchiarico, B., Carattini, S., Fischer, C., and Heutel, G. (2021). Business cycles and environmental policy: Literature review and policy implications. Working Paper 29032, National Bureau of Economic Research.

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.

Annicchiarico, B. and Diluiso, F. (2019). International transmission of the business cycle and environmental policy. *Resource and Energy Economics*, 58:101112.

Annicchiarico, B., Surricchio, S., and Waldmann, R. J. (2019). A behavioral model of the credit cycle. *Journal of Economic Behavior and Organization*, 166:53–83.

Branch, W. A. (2009). A New Keynesian model with heterogeneous expectations. *Journal of Economic Dynamics and Control*, 33(5):1036–1051.

Branch, W. A. and McGough, B. (2010). Dynamic predictor selection in a New Keynesian model with heterogeneous expectations. *Journal of Economic Dynamics and Control*, 34(8):1492–1508.

Brock, W. A. and Hommes, C. H. (1997). A rational route to randomness. *Econometrica*, 65(5):1059–1095.

Bullard, J. and Mitra, K. (2002). Learning about monetary policy rules. *Journal of Monetary Economics*, 49(6):1105–1129.

Cai, Y. and Lontzek, T. S. (2019). The social cost of carbon with economic and climate risks. *Journal of Political Economy*, 127(6):2684–2734.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics*, 12(3):383–398.

Carney, M. (2015). *Breaking the tragedy of the horizon–climate change and financial stability.* Speech given at Lloyd's of London, 29 September.

Chan, Y. T. (2020). Are macroeconomic policies better in curbing air pollution than environmental policies? A DSGE approach with carbon-dependent fiscal and monetary policies. *Energy Policy*, 141:111454.

Christiano, L. J., Boldrin, M., and Fisher, J. D. M. (2001). Habit Persistence, Asset Returns, and the Business Cycle. *American Economic Review*, 91(1):149–166.

Christiano, L. J., Eichenbaum, M., and Evans, C. L. (2005). Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy. *Journal of Political Economy*, 113(1):1–45.

Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J., Grassi, G., Rossi, S., et al. (2021). GHG emissions of all world countries–2021 Report. Report, Office of the European Union, Luxembourg.

De Grauwe, P. (2011). Animal spirits and monetary policy. *Economic Theory*, 47(2-3):423–457.

De Grauwe, P. (2012a). Booms and busts in economic activity: A behavioral explanation. *Journal of Economic Behavior and Organization*, 83(3):484–501.

De Grauwe, P. (2012b). *Lectures on behavioral macroeconomics.* Princeton University Press.

De Grauwe, P. and Gerba, E. (2018). The role of cognitive limitations and heterogeneous expectations for aggregate production and credit cycle. *Journal of Economic Dynamics and Control*, 91:206–236.

De Grauwe, P. and Ji, Y. (2020). Structural reforms, animal spirits, and monetary policies. *European Economic Review*, 124:103395.

De Grauwe, P. and Macchiarelli, C. (2015). Animal spirits and credit cycles. *Journal of Economic Dynamics and Control*, 59:95–117.

Dietrich, A., Müller, G. J., and Schoenle, R. (2021). The expectations channel of climate change: implications for monetary policy. CEPR Discussion Paper No. DP15866.

Diks, C. and Van Der Weide, R. (2005). Herding, a-synchronous updating and heterogeneity in memory in a CBS. *Journal of Economic Dynamics and Control*, 29(4):741–763.

Diluiso, F., Annicchiarico, B., Kalkuhl, M., and Minx, J. C. (2021). Climate actions and macro-financial stability: The role of central banks. *Journal of Environmental Economics and Management*, 110:102548.

ECB (2021). ECB presents action plan to include climate change considerations in its monetary policy strategy. Press Release 8 July 2021, ECB.

Economides, G. and Xepapadeas, A. (2018). Monetary policy under climate change. CESifo Working Paper Series 7021, CESifo.

Economides, G. and Xepapadeas, A. (2019). The effects of climate change on a small open economy. CESifo Working Paper Series 7582, CESifo.

EIA (2020). Monthly energy review, December 2020. Technical report, U.S. Energy Information Administration.

Evans, G. W. and Honkapohja, S. (2012). *Learning and expectations in macroeconomics*. Princeton University Press.

Evans, G. W. and McGough, B. (2005). Monetary policy, indeterminacy and learning. *Journal of Economic Dynamics and Control*, 29(11):1809–1840.

Evans, G. W. and Ramey, G. (1992). Expectation calculation and macroeconomic dynamics. *American Economic Review*, 82(1):207–224.

Ferrari, M. M. and Pagliari, M. S. (2021). No country is an island. international cooperation and climate change.

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.

Gabaix, X. (2020). A behavioral New Keynesian model. *American Economic Review*, 110(8):2271–2327.

Gigerenzer, G. and Gaissmaier, W. (2011). Heuristic decision making. *Annual Review of Psychology*, 62:451–482.

Gigerenzer, G. and Selten, R. (2002). *Bounded rationality: The adaptive toolbox*. MIT press.

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

Grether, D. M. and Plott, C. R. (1979). Economic theory of choice and the preference reversal phenomenon. *American Economic Review*, 69(4):623–638.

Hommes, C. (2011). The heterogeneous expectations hypothesis: Some evidence from the lab. *Journal of Economic Dynamics and Control*, 35(1):1–24.

Hommes, C., Huang, H., and Wang, D. (2005a). A robust rational route to randomness in a simple asset pricing model. *Journal of Economic Dynamics and Control*, 29(6):1043–1072.

Hommes, C. and Lustenhouwer, J. (2019). Inflation targeting and liquidity traps under endogenous credibility. *Journal of Monetary Economics*, 107:48–62.

Hommes, C., Massaro, D., and Weber, M. (2019). Monetary policy under behavioral expectations: Theory and experiment. *European Economic Review*, 118:193–212.

Hommes, C., Sonnemans, J., Tuinstra, J., and Van de Velden, H. (2005b). Coordination of expectations in asset pricing experiments. *The Review of Financial Studies*, 18(3):955–980.

IPCC (2018). *Global warming of* $1.5°C$. Technical report, Geneva, Switzerland: IPCC.

Karp, L. S. and Traeger, C. P. (2018). Prices versus quantities reassessed. CESifo Working Paper no. 7331.

Kurz, M., Piccillo, G., and Wu, H. (2013). Modeling diverse expectations in an aggregated New Keynesian model. *Journal of Economic Dynamics and Control*, 37(8):1403–1433.

Lagarde, C. (2021). *Climate Change and Central Banking*. Speech at the ILF conference on Green Banking and Green Central Banking, Frankfurt am Main, 25 January 2021.

Levine, P., Pearlman, J., Perendia, G., and Yang, B. (2012). Endogenous persistence in an estimated DSGE model under imperfect information. *The Economic Journal*, 122(565):1287–1312.

Manski, C. F. and McFadden, D. (1981). Alternative estimators and sample designs for discrete choice analysis. *Structural analysis of discrete data with econometric applications*, 2:2–50.

Massaro, D. (2013). Heterogeneous expectations in monetary DSGE models. *Journal of Economic Dynamics and Control*, 37(3):680–692.

Montoro, C. (2012). Oil shocks and optimal monetary policy. *Macroeconomic Dynamics*, 16(2):240–277.

NGFS (2019). A call for action: Climate change as a source of financial risk. Technical Report April, Network for Greening the Financial System.

NGFS (2020a). Climate change and monetary policy initial takeaways. Technical Report June, Network for Greening the Financial System.

NGFS (2020b). The macroeconomic and financial stability impacts of climate change, research priorities. Technical Report June, Network for Greening the Financial System.

Nordhaus, W. D. (2007). *The challenge of global warming: Economic models and environmental policy*, volume 4. New Haven: Yale University.

Nordhaus, W. D. (2008). *A question of balance*. Yale University Press.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523.

Nordhaus, W. D. (2018). Projections and uncertainties about climate change in an era of minimal climate policies. *American Economic Journal: Economic Policy*, 10(3):333–60.

Pesaran, M. and Weale, M. (2006). Survey expectations. In Elliott, G., Granger, C., and Timmermann, A., editors, *Handbook of Economic Forecasting*, volume 1, chapter 14, pages 715–776. Elsevier, 1 edition.

Preston, B. (2006). Adaptive learning, forecast-based instrument rules and monetary policy. *Journal of Monetary Economics*, 53(3):507–535.

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.

Rudebusch, G. D. et al. (2019). Climate change and the Federal Reserve. *FRBSF Economic Letter*, 9.

Schmitt-Grohé, S. and Uribe, M. (2007). Optimal simple and implementable monetary and fiscal rules. *Journal of Monetary Economics*, 54(6):1702–1725.

Schoenmaker, D. (2021). Greening monetary policy. *Climate Policy*, 21(4):581–592.

Stavins, R. N. (2020). The future of us carbon-pricing policy. *Environmental and Energy Policy and the Economy*, 1(1):8–64.

Thaler, R. (1980). Toward a positive theory of consumer choice. *Journal of Economic Behavior and Organization*, 1(1):39–60.

Tversky, A. and Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, 185(4157):1124–1131.

Villeroy de Galhau, F. (2021). *The role of central banks in the greening of the economy*. Speech at 5th edition of the Rencontres on "Climate Change and Sustainable Finance", 11 February 2021.

Weitzman, M. L. (1974). Prices vs. quantities. *The Review of Economic Studies*, 41(4):477–491.

Woodford, M. (2010). Robustly optimal monetary policy with near-rational expectations. *American Economic Review*, 100(1):274–303.

Appendix

Households

In the period t the typical household i chooses $C_{i,t}$, $B_{i,t}$ and $N_{i,t}$, to maximize (1), subject to (2). At the optimum, the following conditions must hold:

$$1+\varrho\frac{B_{i,t}}{P_t}\left(C_{i,t}-hC_{t-1}\right)^{\gamma}=\beta R_t\tilde{E}_{i,t}\left\{\left[\exp(\mu_{t+1}-\mu_t)\right]\left(\frac{C_{i,t}-hC_{t-1}}{C_{i,t+1}-hC_t}\right)^{\gamma}\frac{1}{\Pi_{t+1}}\right\}, \tag{A-1}$$

$$\chi N_{i,t}^{\varphi}=\frac{W_t}{P_t}\left(C_{i,t}-hC_{t-1}\right)^{-\gamma}, \tag{A-2}$$

where equation (A-1) describes the time path of consumption of a household of type i, while equation (A-2) is the labor supply.

Production and Calvo's Pricing Problem with Past Indexation

The typical intermediate-good producer i solves a cost-minimization intratemporal problem given the available technology and taking input prices as given. At the optimum, the demand for labor immediately is

$$\frac{W_t}{P_t}=MC_t\Delta_t^{\frac{\varkappa-1}{\varkappa}}Y_{i,t}^{\frac{1}{\varkappa}}\left(1-\zeta\right)\left(A_tN_{i,t}\right)^{-\frac{1}{\varkappa}}A_t, \tag{A-3}$$

while the demand for the energy source is

$$\frac{P_{Z,t}}{P_t}=MC_t\Delta_t^{\frac{\varkappa-1}{\varkappa}}Y_{i,t}^{\frac{1}{\varkappa}}\zeta Z_{i,t}^{-\frac{1}{\varkappa}}. \tag{A-4}$$

We now solve the price-setting problem. To make the notation more compact, let $\Psi_t = \Pi_t^{-1}\Pi_{t-1}^{\kappa}$. Given the price indexation rule, during the time interval in which the typical firm cannot re-set its price, its relative price $p_{i,t+s} = P_{i,t+s}/P_{t+s}$ evolves as:

$$p_{i,t+s} = \left(\prod_{k=1}^{s} \Psi_{t+k}\right) p_{i,t}^{*}, \tag{A-5}$$

where $p_{i,t}^{*} = P_{i,t}^{*}/P_t$. We have made use of the fact that $\Pi = 1$. Clearly, for $s = 0$, we have $p_{i,t} = p_{i,t}^{*}$.

Let $Y_{i,t+s|t}$ denote the demand in period $t+s$ faced by a firm i having reset its price in the period t, that is $Y_{i,t+s|t} = p_{i,t+s}^{-\sigma} Y_{t+s}$. Using the result in (A-5) $Y_{i,t+s|t}$ can be expressed as:

$$Y_{i,t+s|t} = \left[\left(\prod_{k=1}^{s} \Psi_{t+k}\right) p_{i,t}^{*}\right]^{-\sigma} Y_{t+s}. \tag{A-6}$$

Now consider the case of the firm able to re-optimize in period t. As mentioned above, the representative firm i will choose the price $p_{i,t}^{*}$ to maximize the current market value of the profits generated while that price remains constant. The optimization problem can be written as:

$$\max_{p_{i,t}^{*}} \tilde{E}_{i,t} \sum_{t=0}^{\infty} \varpi^{s} \left[Q_{i,t,t+s}\left(p_{i,t+s}Y_{i,t+s|t} - MC_{t+s}Y_{i,t+s|t}\right)\right], \tag{A-7}$$

subject to (A-6), where $Q_{i,t,t+s} = \beta^{s}\lambda_{i,t+s}/\lambda_{i,t}$ is the real stochastic discount factor with λ denoting the marginal utility of consumption. The first-order condition for the optimal price is then:

$$p_{i,t}^{*} = \frac{\sigma}{\sigma-1} \frac{\tilde{E}_{i,t}\sum_{t=0}^{\infty} \varpi^{s}\beta^{s}\lambda_{i,t+s}Y_{t+s}\left(\prod\limits_{k=1}^{s}\Psi_{t+k}\right)^{-\sigma} MC_{t+s}}{\tilde{E}_{i,t}\sum_{t=0}^{\infty} \varpi^{s}\beta^{s}\lambda_{i,t+s}Y_{t+s}\left(\prod\limits_{k=1}^{s}\Psi_{t+k}\right)^{1-\sigma}}. \tag{A-8}$$

Aggregation

In this model agents are heterogeneous because they formulate expectations differently, i.e., they have different market beliefs. To solve the aggregation problem we first need to log-linearize the model around the deterministic steady state.

Equations (A-1) and (A-2) can be easily log-linearized around a zero-inflation steady state to obtain:

$$\begin{aligned} c_{i,t} \;&=\; \tilde{E}_{i,t}c_{i,t+1} - h\left(c_t - c_{t-1}\right) - \frac{1-h}{\gamma}\left(r_t - \tilde{E}_{i,t}\pi_{t+1}\right) + \\ &\quad -\frac{1-h}{\gamma}\left(\tilde{E}_{i,t}\mu_{t+1} - \mu_t\right) + \bar{\varrho}b_{i,t}, \end{aligned} \tag{A-9}$$

$$\varphi n_{i,t} = w_t - \frac{\gamma}{1-h}c_{i,t} + \frac{\gamma h}{1-h}c_{t-1}, \tag{A-10}$$

where c_i and n_i denote consumption and labor expressed as natural log deviations from their steady-state values, $\bar{\varrho} = (1-h)^{1+\gamma}Y^{1+\gamma}\varrho/\gamma$, $b_{i,t} = B_{i,t}/YP_t$, w_t refers to the natural log deviation of the real wage from its steady-state level, $\pi_t = \Pi_t - 1$ and $r_t = R_t - R$.

Equation (A-9) can be re-written as

$$\begin{aligned} c_{i,t} &= \tilde{E}_{i,t}c_{t+1} + \left(\tilde{E}_{i,t}c_{i,t+1} - \tilde{E}_{i,t}c_{t+1}\right) - h\left(c_t - c_{t-1}\right) + \\ & -\frac{1-h}{\gamma}\left(r_t - \tilde{E}_{i,t}\pi_{t+1}\right) - \frac{1-h}{\gamma}\left(\tilde{E}_{i,t}\mu_{t+1} - \mu_{t-1}\right) + \varrho b_{i,t}, \end{aligned} \tag{A-11}$$

where now $\tilde{E}_{i,t}c_{t+1}$ is the subjective expectations of aggregate consumption. Let $c_t = \int_0^1 c_{i,t}di$ denote aggregate consumption, then from the above equation, we have:

$$\begin{aligned} c_t &= \tilde{E}_t c_{t+1} - \frac{1-h}{\gamma}\left(r_t - \tilde{E}_t\pi_{t+1}\right) - hc_t + hc_{t-1} + \\ & + \int_0^1 \left(\tilde{E}_{i,t}c_{i,t+1} - \tilde{E}_{i,t}c_{t+1}\right) di + v_t, \end{aligned} \tag{A-12}$$

where $\tilde{E}_t c_{t+1}$ and $\tilde{E}_t\pi_{t+1}$ are the market forecasts for consumption and inflation. Note that we have used the fact that in equilibrium it must be that $\int_0^1 b_{i,t}di = 0$. For simplicity, we assume that $v_t = -\frac{1-h}{\gamma}\left(\int_0^1 \tilde{E}_{i,t}\mu_{t+1} - \mu_t\right)$, where v_t follows a first-order autoregressive process.[28] To facilitate aggregation, following Hommes et al. (2019), we further assume the average expectation of individual consumption is equal to the average expectation of aggregate consumption, that is $\int_0^1 \tilde{E}_{i,t}c_{i,t+1}di = \int_0^1 \tilde{E}_{i,t}c_{t+1}di$.

Aggregate labor supply immediately follows from (A-2):

$$\varphi n_t = w_t - \gamma(1-h)^{-1}c_t + \gamma h(1-h)^{-1}c_{t-1}, \tag{A-13}$$

where w_t is the wage rate expressed as natural log deviation from its steady-state value.

Equations (4), (A-3) and (A-4) can be easily log-linearized to obtain:

$$y_t = \delta_t + \ \epsilon_Z z_t + \epsilon_N\left(a_t + n_t\right), \tag{A-14}$$

$$w_t = mc_t + \frac{\varkappa - 1}{\varkappa}\delta_t + \frac{1}{\varkappa}\left(y_t - n_t\right) + \left(1 - \frac{1}{\varkappa}\right)a_t, \tag{A-15}$$

$$p_{Z,t} = mc_t + \frac{\varkappa - 1}{\varkappa}\delta_t + \frac{1}{\varkappa}\left(y_t - z_t\right), \tag{A-16}$$

where $\epsilon_N \equiv (\Delta AN/Y)^{\frac{\varkappa-1}{\varkappa}}(1-\zeta)$, $\epsilon_Z \equiv (\Delta Z/Y)^{\frac{\varkappa-1}{\varkappa}}\zeta$, $p_{Z,t}$ is the relative price of emissions expressed in log deviation from its steady state level. All the other variables refer to their capital-letter counterparts, always expressed as natural log deviations from their respective steady-state values.

Log-linearizing (A-8) around the zero-inflation steady state delivers:

$$\widehat{p}_{i,t}^* = (1 - \varpi\beta)\, mc_t - \varpi\beta\tilde{E}_{i,t}\psi_{t+1} + \varpi\beta\tilde{E}_{i,t}\widehat{p}_{i,t+1}^*, \tag{A-17}$$

where $\widehat{p}_{i,t}^* = (p_{i,t}^* - p^*)/p^*$and $\psi_{t+1} = -\pi_{t+1} + \kappa\pi_t$. Let $\widehat{p}_t^* = \int_0^1 \widehat{p}_{i,t}^*di$. The pricing equation can then be re-written as:

$$\widehat{p}_{i,t}^* = (1 - \varpi\beta)\, mc_t - \beta\varpi\kappa\pi_t + \varpi\beta\tilde{E}_{i,t}\left(\widehat{p}_{t+1}^* + \pi_{t+1}\right) + \varpi\beta\left(\tilde{E}_{i,t}\widehat{p}_{i,t+1}^* - \tilde{E}_{i,t}\widehat{p}_{t+1}^*\right), \tag{A-18}$$

where we have used the fact that $\psi_{t+1} = -\pi_{t+1} + \kappa\pi_t$.

[28] Alternatively, one can also make explicit the expectation rules on the variable v.

Given the definition of aggregate price index $P_t = \int_0^1 \left(P_{i,t}^{1-\sigma}\right)^{1/(1-\sigma)} di$, in the presence of price stickiness and indexation, we have:

$$P_t^{1-\theta} = \int_0^{1-\varpi} \left(P_{i,t}^{*}\right)^{1-\sigma} di + \int_0^{\varpi} \left(P_{i,t-1}\Pi_{t-1}^{\kappa}\right)^{1-\sigma} di \tag{A-19}$$

that in log-linear terms can be expressed as:

$$(1-\varpi)\widehat{p}_t^{*} = \varpi\left(\pi_t - \kappa\pi_{t-1}\right). \tag{A-20}$$

Substituting into equation (A-18) gives:

$$\widehat{p}_{i,t}^{*} = (1-\varpi\beta)\, mc_t - \varpi\beta\kappa\pi_t - \varpi\beta\frac{\varpi}{1-\varpi}\kappa\pi_t + \frac{\varpi}{1-\varpi}\beta\tilde{E}_{i,t}\pi_{t+1} + \varpi\beta\left(\tilde{E}_{i,t}\widehat{p}_{i,t+1}^{*} - \tilde{E}_{i,t}\widehat{p}_{t+1}^{*}\right). \tag{A-21}$$

The above equation can be aggregated over all firms re-setting their price to obtain:

$$\pi_t = \frac{1-\varpi\beta}{1+\beta\kappa}\frac{1-\varpi}{\varpi}mc_t + \frac{\beta}{1+\beta\kappa}\tilde{E}_t\pi_{t+1} + \frac{\kappa}{1+\beta\kappa}\pi_{t-1} + (1-\varpi)\beta\int_0^1\left(\tilde{E}_{i,t}\widehat{p}_{i,t+1}^{*} - \tilde{E}_{i,t}\widehat{p}_{t+1}^{*}\right) di. \tag{A-22}$$

Now observe that all firms have access to the same technology, have the same marginal costs, and are subject to the same random shocks. As one above, we then assume that the aggregate expectation on the optimal future price set by each firm manager $\int_0^1 \tilde{E}_{i,t}\widehat{p}_{i,t+1}^{*} di$ is equal to the aggregate expectations on the average optimal price of the economy $\int_0^1 \tilde{E}_{i,t}\widehat{p}_{t+1}^{*} di$. It follows that (A-22) can be written as:

$$\pi_t = \frac{1-\varpi\beta}{1+\beta\kappa}\frac{1-\varpi}{\varpi}mc_t + \frac{\beta}{1+\beta\kappa}\tilde{E}_t\pi_{t+1} + \frac{\kappa}{1+\beta\kappa}\pi_{t-1}. \tag{A-23}$$

The above equation is the New Keynesian Phillips curve with price indexation and non-rational agents.

Finally, the log-linearized versions of equations (7)-(10) immediately follow:

$$m_t = \delta_M\frac{Z}{Z+Z^{RoW}}z_t + (1-\delta_M)m_{t-1} + \delta_M\frac{Z^{RoW}}{Z+Z^{RoW}}z_t^{RoW}, \tag{A-24}$$

$$\delta_t = -\eta\left(M-\overline{M}\right)m_t, \tag{A-25}$$

$$r_t = \iota_r r_{t-1} + (1-\iota_r)[\iota_\pi\pi_t + \iota_y(y_t - y_t^{*})] + u_t, \tag{A-26}$$

$$c_t = y_t, \tag{A-27}$$

where m_t is the log-deviation of $M_t - \overline{M}$ from its steady state value.

Using the equilibrium condition (A-27) in the aggregate Euler equation (A-12), we obtain:

$$y_t\,(1+h) = \tilde{E}_t y_{t+1} + h y_{t-1} - \frac{1-h}{\gamma}\left(r_t - \tilde{E}_t\pi_{t+1}\right) + v_t. \tag{A-28}$$

We can then combine (A-13), (A-14), (A-15) with (A-16) to get rid of n_t and w_t, and obtain:

$$mc_t = \left(\frac{\varphi+\frac{1}{\varkappa}}{\epsilon_N} - \frac{1}{\varkappa} + \frac{\gamma}{1-h}\right)y_t - \left(\frac{\varphi+\frac{1}{\varkappa}}{\epsilon_N} + \frac{\varkappa-1}{\varkappa}\right)\delta_t - \epsilon_Z\frac{\varphi+\frac{1}{\varkappa}}{\epsilon_N}z_t - (1+\varphi)\,a_t - \gamma\frac{h}{1-h}y_{t-1}, \tag{A-29}$$

$$p_{Z,t} = mc_t + \frac{\varkappa - 1}{\varkappa}\delta_t + \frac{1}{\varkappa}(y_t - z_t). \tag{A-30}$$

The above two equations, along with (A-23), (A-25)-(A-24) and (A-28) describe the aggregate model summarized in Table 1 where we have assumed that $z_t^{NI} = 0$ and written the coefficients of equation (A-29) in a compact form.

Under flexible prices, the typical firm i will set the price $P_{i,t}$ to maximize profits given the demand schedule $Y_{i,t} = (P_{i,t}/P_t)^{-\sigma} Y_t$. At the optimum $MC = (\sigma - 1)/\sigma$, so that in the log-linearized model $mc_t = 0$. Combining (A-29) with (A-30) and assuming $mc_t = 0$, the natural level of output immediately follows:

$$y_t^* = \frac{\epsilon_N \frac{\varphi+1}{\varphi+\frac{1}{\varkappa}} a_t + \left[1 + \epsilon_N \frac{\frac{\varkappa-1}{\varkappa}}{\varphi+\frac{1}{\varkappa}} + \ \epsilon_Z(\varkappa - 1)\right]\delta_t^* - \epsilon_Z \varkappa p_{Z,t}^* + \epsilon_N \frac{\gamma h(1-h)^{-1}}{\varphi+\frac{1}{\varkappa}} y_{t-1}^*}{1 - \epsilon_Z \varkappa - \epsilon_N \frac{\frac{1}{\varkappa} - \gamma(1-h)^{-1}}{\varphi+\frac{1}{\varkappa}}}, \tag{A-31}$$

where $\delta_t^* = -\eta\left(M - \overline{M}\right) m_t^*$, $m_t^* = \delta_M \frac{Z}{Z+Z^{RoW}} z_t^* + (1-\delta_M) m_{t-1}^*$ while z_t^* must satisfy the equation below:

$$p_{Z,t}^* = \frac{\varkappa - 1}{\varkappa}\delta_t^* + \frac{1}{\varkappa}(y_t^* - z_t^*). \tag{A-32}$$

From (A-31) we can see that the natural level of output is decreasing in the policy variable $p_{Z,t}^*$. Clearly, if the government sets the price of emissions, then $p_{Z,t}^* = p_{Z,t}$, while in the case of a cap control we will have $z_t^* = z_t$.

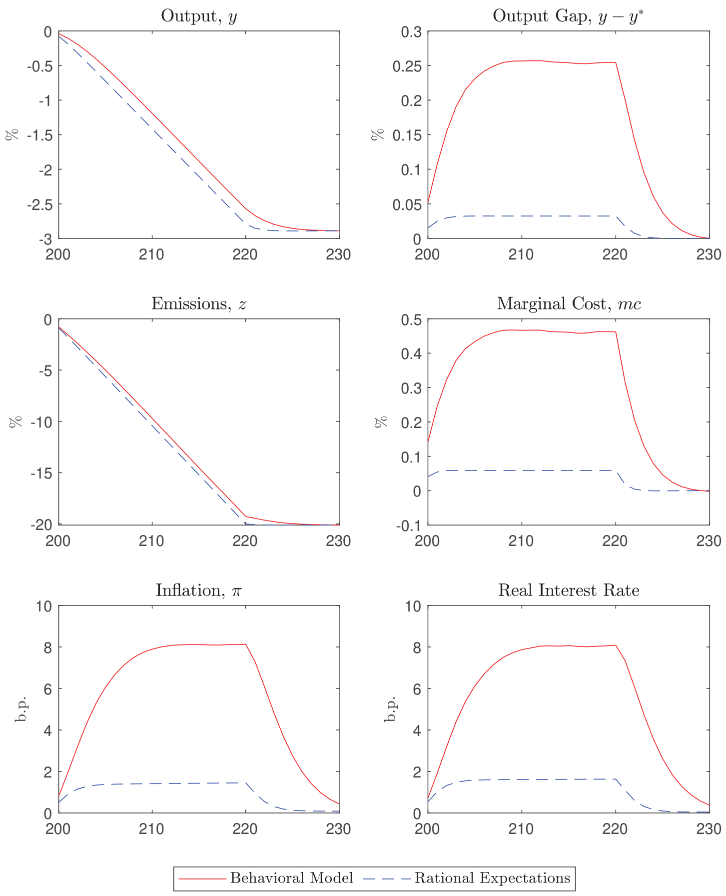
Additional Results

In this appendix, we report some additional results. Figure A-1 shows the economy's response to a timely mitigation policy under rational and behavioral expectations. It is interesting to see that, in the case of a gradual emission reduction, the time path of emissions does not differ substantially between the two cases, contrary to what happens to inflation and all the other variables.

Figure A-2 is the rational expectations counterpart of Figure 3 of the main text. Here the forecast errors are driven only by the pollution policy phased in as a surprise policy shock.

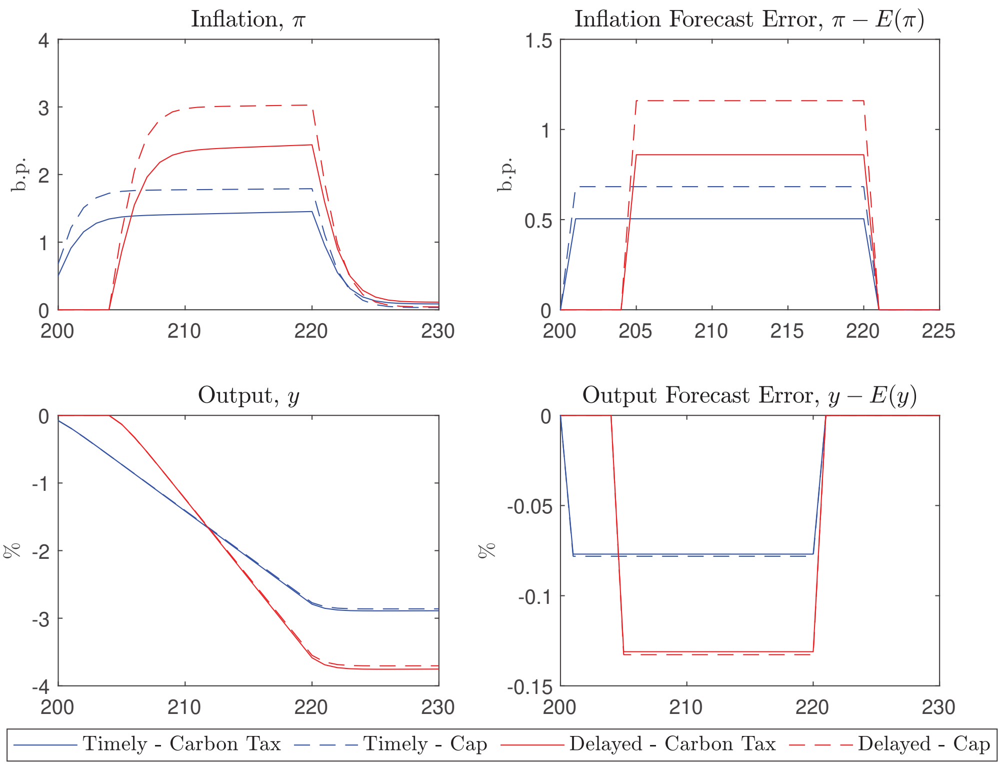
Figure A-3 plots the response of emissions to a gradual increase in the carbon tax, as in the main scenario of Figure 3, but in a highly perturbed economy, where the standard deviations of shocks driving business cycle fluctuations are three times larger than in the baseline case. In a similar scenario, Figure A-4 shows the response of the emission permits price and the inflation rate to a gradual quantity restrictions of emissions (cap-and-trade scheme). Comparing these two figures makes it clear that the choice between price and quantity regulations poses a significant policy trade-off between emission certainty and price stability in a perturbed economy. Inflation targeting becomes more problematic.

Figure A-1: Orderly Mitigation under Rational and Behavioral Expectations - Carbon Tax



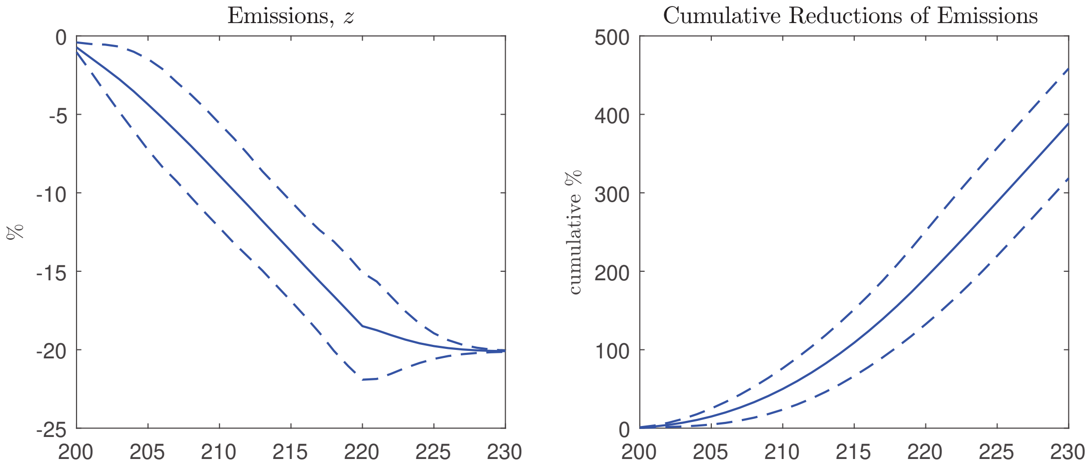
Note: the figure plots the economy's response to a gradual increase in the carbon price aimed at permanently reducing emissions by 20%. All variables are expressed in percentage deviations from their respective business-as-usual value, with the exceptions of inflation and of the real interest rate that are expressed in quarterly basis points (b.p.) deviations, while the shares of extrapolators are expressed in percentage points (p.p.) deviations.

Figure A-2: Mitigation Scenarios - Macroeconomic Dynamics and Market Forecast Errors under Rational Expectations



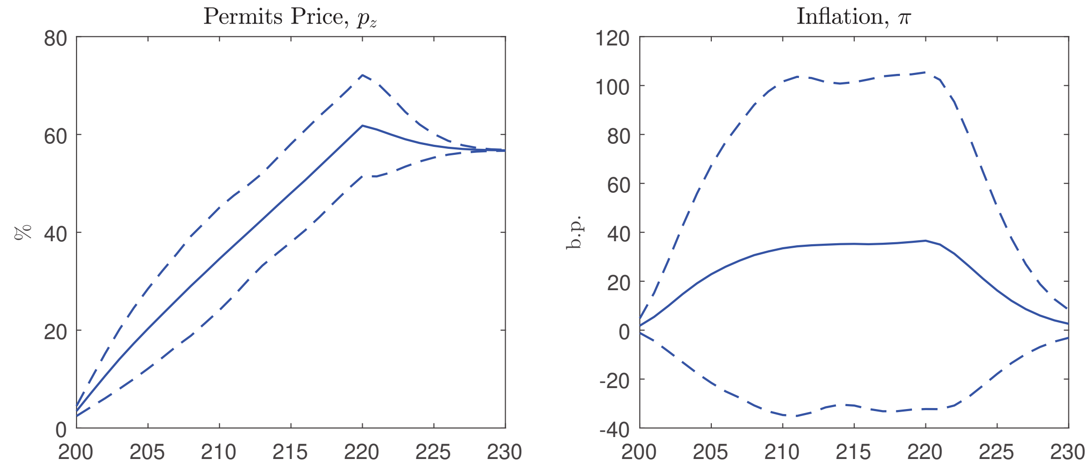
Note: the figure plots the response of the economy to different mitigation scenarios entailing the same cumulative emissions after 20 quarters in the deterministic counterparts. Inflation and its forecast errors are expressed in quarterly basis points (b.p.) deviations, while output and its forecast errors are in percentage deviations.

Figure A-3: Emission Dynamics in a Highly Perturbed Economy



Note: the figure plots the time path of emissions in a highly perturbed economy. The climate policy consists of a gradual increase in the carbon price aimed at permanently reducing emissions by 20% in a deterministic setting. Cumulative reductions are simply the cumulative variations of emissions.

Figure A-4: Permits Price and Inflation in a Highly Perturbed Economy



Note: the figure plots the time path of permits price and inflation in a highly perturbed economy. The climate policy consists of a gradual emission restriction.

RECENT PUBLICATIONS BY *CEIS Tor Vergata*

Dimension Reduction for High Dimensional Vector Autoregressive Models
Gianluca Cubadda and Alain Hecq
CEIS Research Paper, 534, March 2022

Child labour theories and policies
Furio Camillo Rosati
CEIS Research Paper, 533, March 2022

Indirect Savings from Public Procurement Centralization
Clarissa Lotti and Giancarlo Spagnolo
CEIS Research Paper, 532, February 2022

Who cares when Value (Mis)reporting May Be Found Out?
An Acquiring-a-Company Experiment with Value Messages and Information Leaks
Daniela Di Cagno, Werner Güth, Tim Lohse, Francesca Marazzi and Lorenzo Spadoni
CEIS Research Paper, 531, January 2022

Relational Skills and Corporate Productivity
Leonardo Becchetti, Sara Mancini and Nazaria Solferino
CEIS Research Paper, 530, January 2022

Born to Run: Adaptive and Strategic Behavior in Experimental Bank-Run Games
Federico Belotti, Eloisa Campioni, Vittorio Larocca, Francesca Marazzi, Luca Panaccione and Andrea Piano Mortari
CEIS Research Paper, 529, December 2021

The Effect of Mandatory Non-financial Reporting on CSR (and Environmentally Sustainable) Investment: a Discontinuity Design Approach
Leonardo Becchetti, Sara Mancini and Nazaria Solferino
CEIS Research Paper, 528, November 2021

On Some Problems of Using the Human Development Index in Economic History
Nicola Amendola, Giacomo Gabbuti and Giovanni Vecchi
CEIS Research Paper, 527, November 2021

Banking Diversity, Financial Complexity and Resilience to Financial Shocks: Evidence From Italian Provinces
Beniamino Pisicoli
CEIS Research Paper, 526, November 2021

Reduced Rank Regression Models in Economics and Finance
Gianluca Cubadda and Alain Hecq
CEIS Research Paper, 525, November 2021

DISTRIBUTION

Our publications are available online at www.ceistorvergata.it

DISCLAIMER

COPYRIGHT

MEDIA INQUIRIES AND INFORMATION

For media inquiries, please contact Barbara Piazzi at +39 06 72595652/01 or by e-mail at piazzi@ceis.uniroma2.it. Our web site, www.ceistorvergata.it, contains more information about Center's events, publications, and staff.

DEVELOPMENT AND SUPPORT

For information about contributing to CEIS Tor Vergata, please contact at +39 06 72595601 or by e-mail at segr.ceis@economia.uniroma2.it