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*George Economides, Anastasios Xepapadeas*

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Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
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# Monetary Policy under Climate Change

## Abstract

We study monetary policy under climate change in order to answer the question of whether monetary policy should take into account the expected impacts of climate change. The setup is a new Keynesian dynamic stochastic general equilibrium model of a closed economy in which a climate module that interacts with the economy has been incorporated, and the monetary authorities follow a Taylor rule for the nominal interest rate. The model is solved numerically using common parameter values and fiscal data from the euro area. Our results, which are robust to a large number of sensitivity checks, suggest non-trivial implications for the conduct of monetary policy.

JEL-Codes: E500, E100, Q500.

Keywords: climate change, monetary policy, new Keynesian model, Taylor rule.

*George Economides*
*Department of International and European Economics Studies, Athens University of Economics and Business*
*Greece - 104 34 Athens*
*gecon@aueb.gr*

*Anastasios Xepapadeas*
*Department of International and European Economics Studies, Athens University of Economics and Business*
*Greece - 104 34 Athens*
*xepapad@aueb.gr*

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# 1 Introduction

Climate change has been recognized as the greatest externality of today's global economy. Although there are many uncertainties, the scientific consensus is that climate change is an anthropogenically-induced phenomenon and that a business-as-usual scenario regarding greenhouse gas (GHG) emissions might have serious negative impacts on human wellbeing. The potentially very serious detrimental effects of climate change have triggered the development of a large body of literature which studies not only the effects of climate change, but also the ways in which to moderate these effects (see, e.g., Nordhaus, 2007, 2014; and Stern, 2007, 2008). More specifically, in terms of economic growth it has been argued that climate change and higher temperatures, especially in poor countries, may reduce growth rates and output levels, including agricultural and industrial output (e.g., Dell et al., 2009, 2012).

Following the classic economic approach to correcting externalities, economic policies for climate change that aim at mitigation focus on carbon taxes or cap-and-trade policies (e.g., Stern, 2007, chapter 14; Golosov et al., 2014 ). Climate change policy has therefore been predominantly fiscal policy and very little attention has been paid, thus far, to the implications of climate change for the conduct of monetary policy and the role of Central Banks.

This observation provides a logical explanation of why monetary policy and Central Banks have not thus far been involved in climate change policy: fiscal instruments have been considered to be sufficient, since – as economic theory suggests – externalities should be corrected by taxes or similar types of instruments on the externality-generating activity. Furthermore, since the Central Banks' traditional objectives of inflation and output stabilization are predominantly short term – while climate change impacts could be regarded as long term – it is plausible to assume that the link between monetary policy and climate change is weak, and thus climate change policy considerations are outside the main concerns of monetary policy.

However, under a business-as-usual scenario, or even more "climate friendly" scenarios about the future path of GHG emissions, serious climate change effects are not that far off.[1] Furthermore, the very likely impact of climate change on growth and future output paths might require more involvement of monetary policy which, while aiming at short-term output and employment stabilization, would take into account the impact of climate change on output, as well as the potential impact of climate-change-related fiscal policy measures on inflation.

[1] The target of a maximum 1.5°C increase in global mean temperature could be exceeded as early as the middle of this century, according to all four main scenarios (representative concentration pathways 2.6, 4.5, 6.0 and 8.5 regarding GHG emissions) of the Intergovernmental Panel on Climate Change (IPCC, 2013).

Under these conditions, the design and implementation of monetary policy may need to take on a wider role, in the sense that policy actions aiming at short-term output and employment stabilization should be adjusted in order to account for climate change impacts. Therefore, in addition to their traditional role – inflation and output stabilization – and the use of unconventional policies to help economic recovery since the 2008 world shock, Central Banks may also need to support climate change policies. This implies that Central Banks would need to address long-term as well as short-term issues.

Thus, although strictly speaking monetary policy cannot be regarded as a climate policy instrument, a vital question is whether climate change and the fiscal instruments used to control it could affect the design of monetary policy in a non-trivial way. The purpose and the contribution of the present paper is to explore this issue and to demonstrate how and to what extent monetary policy should be adjusted under conditions of climate change.

Given the macroeconomic impacts of climate change, in order to determine the appropriate monetary policy to deal with these impacts, the nature of climate change should be understood as an economic shock. Perhaps the best way to envision climate change from the point of view of a central banker is as a series of (real) autocorrelated negative supply shocks. Each of these negative supply shocks will likely lead to a contraction in the economy's productive capacity, thus generating higher prices and diminishing growth rates.[2] The more persistent these shocks are, the higher are the chances that they will lead to a permanent reduction of potential output, affecting not only economies' cycles but also their longer-term trends.

In this context, our aim is to identify the main features of monetary policymaking in an economy which is affected by climate change. The setup is a new Keynesian dynamic stochastic general equilibrium (DSGE) model of a closed economy featuring imperfect competition and Rotemberg-type nominal price fixities.[3] The model of the economy is coupled with a climate

[2] We use the term negative shocks since the general consensus is that the impacts of climate change are negative. Although supply shocks due to climate change may be either negative or positive, depending on each region or country, available estimates suggest that their global effect is likely to be negative (see Mendelsohn et al., 2000, and Nordhaus and Boyer, 2000).

[3] Gali (2015) notes that the new Keynesian modeling approach combines the DSGE structure characteristic of real business cycle (RBC) models with assumptions that depart from those found in classical monetary models (see also Wickens, 2008, page 206). In particular, there are three key elements and properties of the basic new Keynesian model. (a) Monopolistic competition: prices and/or wages are set by private economic agents in order to maximize their objectives instead of being determined by an anonymous Walrasian auctioneer seeking to clear all markets. (b) Nominal rigidities: firms are subject to constraints on the frequency with which they can adjust the prices of the goods they sell, or they face costs of adjusting those prices. (c) Short-run non-neutrality of monetary policy: as a consequence of the presence of nominal rigidities, changes in short-term nominal interest rates are not matched by one-for-one changes in expected inflation, thus leading

module, and we assume that energy, produced by the processing of fossil fuels, affects the economy via two different channels. On the one hand, energy enters as a separate factor in the firm's production function, thus increasing output. On the other hand, the processing of fossil fuels generates GHG emissions which increase the GHG concentration in the atmosphere, which in turn increases temperature. Higher temperatures negatively affect economic outcomes. Therefore, these two channels imply conflicting effects for an economy's productivity from the use of fossil fuels. In other words, once we take into account climate change, the use of fossil fuels implies an interesting trade-off which eventually drives our main findings. Our framework could be thought of as an integrated assessment model (IAM) in the sense that we incorporate both an economic and a climate sector in a unified setup.[4]

In our model, monetary policy is assumed to be conducted through the nominal interest rate on government bonds which follows a standard Taylor-type rule (see, e.g., Taylor, 1979, 1993, 1999). Since, as is the usual case with these models, an analytical solution is not possible, the model is solved numerically, employing commonly-used parameter values and fiscal data from the euro area. Our main results, supporting both positive and normative arguments, suggest that the design of monetary policy is affected non-trivially once we allow for climate change effects. In particular, three main results are established.

First, in our setup, and through the two specific channels mentioned above, climate change seems to act as a new propagation mechanism of total factor productivity (TFP) shocks. This mechanism differs from the standard mechanisms already studied in the RBC literature, and works regardless of whether the shocks hitting the economy are purely economic or represent natural disasters. That is, climate change, as a propagation mechanism of TFP shocks, seems not only to lengthen the duration of the effects of disturbances, but also to cause increased fluctuations in economic activity. After a TFP shock, the return of the economy's output to the steady state is slower, and is characterized by oscillations, compared to an economy in which the impact of climate change has not been incorporated. Thus, our results seem to confirm the concern that climate change is associated with longer-term turmoil in economic activity.

Second, in the presence of the detrimental effects of climate change on the economy's productivity, the effect of a negative TFP shock is mitigated. This happens because the negative TFP shock decreases both output and the demand for energy. The latter effect causes a decrease in the use of fossil fuels, which positively affects the productivity of the economy (through the

to variations in real interest rates. See also Gali and Gertler (2007) for a discussion of the main features of the new Keynesian model.

[4]For similar IAMs, see, for example, Golosov et al. (2014), Nordhaus (2014) and Hassler et al. (2016).

slowdown in temperature rise). The strength of this positive effect depends on the magnitude of the damage elasticity of output which captures the detrimental effects of climate change on the economy's productivity. Thus, although output initially falls below the steady-state level due to the negative TFP shock, it rises above it afterwards, before eventually converging again to the steady state. Therefore, incorporating climate change into a standard new Keynesian framework requires revisiting the design of the appropriate monetary policies when the aim is short-term stabilization. This result seems to be robust to a number of sensitivity checks.

Third, the use of carbon taxes in order to deal with the consequences of climate change might possibly produce additional output and price fluctuations. More specifically, the introduction of carbon taxes initially, as expected, causes a drop in output, but eventually the economy will move to a new long-run equilibrium with a higher level of output than the initial steady-state level. In other words, the adoption of climate policies, in the form of carbon taxes, seems to imply a short-term cost in terms of output but is growth enhancing in the long run. This seemingly paradoxical result is not due to the substitution of more distorting taxes (such as labor or capital taxes) by the less distorting carbon taxes, as the literature on the "double dividend hypothesis" would probably suggest (see, e.g., Bovenberg and van der Ploeg, 1995). Instead, ceteris paribus, once carbon taxes are introduced, the demand for energy decreases, which in turn reduces the use of fossil fuels. The decrease in the use of fossil fuels initially reduces output but in the long run it positively affects the productivity of the economy (through the slowdown in temperature rise), ultimately leading to a higher output level. As a result, during the transition from the initial steady state to the new long-run equilibrium, there will be fluctuations in both output and price level, which should be taken into account when designing the appropriate monetary policy actions.

Although there exists a rich literature on the interactions between fiscal and monetary policies (see, e.g., Leeper, 1991; Christiano et al., 2005; Schmitt-Grohe and Uribe, 2005, 2007; Kirsanova et al., 2009; Leeper et al., 2009, 2010; Christiano et al., 2011; and Philippopoulos et al., 2015, 2017a, 2017b), the literature has not addressed the usage of a DSGE study to interrelate climate change and monetary policy in a unified framework and then investigate the implications of the former with regard to the latter.

One notable exception is the work by Annicchiarico and Di Dio (2017), who examine the optimal environmental and monetary policy mix in a new Keynesian model embodying pollutant emissions, abatement technology and environmental damages. Our work differs from that of Annicchiarico and Di Dio (2017) in that: (a) they do not allow for capital accumulation; (b) they do not include real money balances and spending on public consumption in the representative household utility function; and, more importantly, (c) they do not treat energy as a separate factor of production but rather assume that pollution is a by-product of output. This final difference implies that such a model does not exhibit the trade-off feature mentioned above and which is associated with the processing of fossil fuels.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 presents the parameter values and the steady-state solution. Section 4 explains the methodology used and the policy experiments on which we focus. The main results are presented in section 5, section 6 presents monetary policy in the presence of carbon taxes, while robustness checks are provided in section 7. Section 8 concludes the paper.

# 2 The model

The model follows the standard new Keynesian tradition featuring imperfect competition and Rotemberg-type nominal rigidities, and is extended to include a climate sector and state-contingent monetary and fiscal policy rules.

## 2.1 The representative household

The representative household acts competitively. Its objective is to maximize the expected discounted lifetime utility:

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_t, 1-h_t, m_t, g_t), \tag{1a}$$

where $c_t$ is the household's consumption, $h_t$ is the household's hours of work, $m_t$ is the household's real money balances, $g_t$ is per capita spending on public consumption, $0 < \beta < 1$ is the discount factor and $E_0$ is the rational expectations operator. In our numerical simulations, we use a utility function of the form (see e.g., Cooley and Prescott, 1995):

$$u(c_t, 1-h_t, m_t, g_t) = \mu_1 \log c_t + \mu_2 \log(1-h_t) + \mu_3 \log m_t + (1-\mu_1-\mu_2-\mu_3) \log g_t, \tag{1b}$$

where $\mu_1$, $\mu_2$ and $\mu_3$ are standard preference parameters.

The budget constraint of the household, written in nominal terms, is:

$$\begin{aligned}(1+\tau_t^c)p_t c_t + p_t x_t + B_t - B_{t-1} + M_t - M_{t-1} = \\ = (1-\tau_t^y)(p_t r_t k_{t-1} + p_t w_t h_t + D_t) + + R_{t-1}B_{t-1} + p_t g_t^{tr},\end{aligned} \tag{2a}$$

and in real terms is:

$$(1+\tau_t^c)c_t + x_t + b_t - (\frac{1}{\pi_t})B_{t-1} + m_t - (\frac{1}{\pi_t})M_{t-1} = (1-\tau_t^y)(r_t k_{t-1} + w_t h_t + d_t) +$$

$$+\left(\frac{R_{t-1}}{\pi_t}\right)b_{t-1}+g_t^{tr}, \tag{2b}$$

where $p_t$ is the price index; $\pi_t = \frac{p_t}{p_{t-1}}$ is the gross inflation rate; and where small letters denote real variables, e.g., $b_t = \frac{B_t}{p_t}$, $m_t = \frac{M_t}{p_t}$, and $d_t = \frac{D_t}{p_t}$. Here, $B_t$, $M_t$, $D_t$ are the household's end-of-period nominal government bonds, end-of-period nominal money holdings, and nominal dividends paid by firms, respectively. Also, $r_t$ is the real return to inherited capital; $k_{t-1}$, $x_t$ is real investment in physical capital in period $t$; $R_{t-1}$ is the nominal return to government bonds between $t-1$ and $t$; $g_t^{tr}$ is the real lump-sum transfer made to the household from the government; and $0 \leq \tau_t^c, \tau_t^y < 1$ are the tax rates on consumption spending, and on income from capital, labor and firm ownership, respectively.

The motion of physical capital is given by:

$$k_t = (1-\delta)k_{t-1} + x_t, \tag{3}$$

where $0 < \delta < 1$ is the depreciation rate of capital.

The household acts competitively, taking prices and policy as given. The first-order conditions of maximization problem (1a) include the budget constraint in (2b) and:

$$\frac{1}{(1+\tau_t^c)c_t} = \frac{1}{(1+\tau_{t+1}^c)c_{t+1}}\beta\left[1-\delta+(1-\tau_{t+1}^y)r_{t+1}\right] \tag{4a}$$

$$\frac{1}{(1+\tau_t^c)c_t} = \frac{1}{(1+\tau_{t+1}^c)c_{t+1}}\beta(\frac{1+R_t}{\pi_{t+1}}) \tag{4b}$$

$$\frac{\mu_3}{m_t} = \frac{\mu_1}{(1+\tau_t^c)c_t} - \beta\frac{\mu_1}{(1+\tau_{t+1}^c)c_{t+1}}\frac{1}{\pi_{t+1}} \tag{4c}$$

$$\frac{\mu_2}{1-h_t} = \frac{\mu_1 w_t(1-\tau_t^y)}{(1+\tau_t^c)c_t}. \tag{4d}$$

Equations (4a) and (4b) are the standard Euler equations for capital and bonds respectively, (4c) is the optimality condition for money balances, and (4d) is the optimality condition for work hours. Therefore, (4a-d) and (2b) summarize the optimal behavior of the household.

## 2.2 Firms

We assume that there is only one firm producing the final good by using intermediate goods which are produced by $N$ intermediate firms. In this setup, we also allow for an energy sector, in which energy is produced, and which in turn is used – together with the other factor inputs – by the intermediate firms to produce the intermediate varieties.

### 2.2.1 Final goods production

The final good producer combines intermediate goods, $y_{t,j}$, to produce $y_t$. Using the Dixit-Stiglitz aggregator (Dixit and Stglitz, 1977), we define aggregate output as:

$$y_t = \left[ \sum_{j=1}^{N} \lambda_j (y_{t,j})^{\theta} \right]^{\frac{1}{\theta}}, \tag{5}$$

where $j = 1, 2, .., N$ are intermediate goods, and where in order to avoid scale effects we assume that $\sum_{j=1}^{N} \lambda_j = 1$. The parameter $\theta > 0$ is the elasticity of substitution across intermediate goods produced and measures the degree of imperfect competition in the intermediate goods market. Obviously, when $\theta = 1$, intermediate goods are perfect substitutes and thus their market is perfectly competitive.

The final good producer chooses $y_{t,j}$ to maximize its profits, which are given by:

$$p_t y_t - \sum_{j=1}^{N} p_{t,j} \lambda_j y_{t,j}. \tag{6}$$

Taking prices as given, the first-order condition with respect to $y_{t,j}$ yields:

$$y_{t,j} = y_t \left( \frac{p_t}{p_{t,j}} \right)^{\frac{1}{1-\theta}}, \tag{7a}$$

or equivalently:

$$p_{t,j} = p_t \left( \frac{y_t}{y_{t,j}} \right)^{1-\theta}. \tag{7b}$$

Equations (7a)-(7b) give the demand (inverse demand) faced by each intermediate firm for its product.

### 2.2.2 Intermediate goods production

There are $N$ intermediate firms, each of which aims at maximizing the following profit function (written in nominal terms):

$$D_{t,j} = p_{t,j} y_{t,j} - p_t r_t k_{t-1,j} - p_t w_t h_{t,j} - P_t^e E_{t,j} - p_t \tau_t^e E_{t,j} - \frac{x}{2} \left( \frac{p_{t,j}}{p_{t-1,j}} - \pi_j \right)^2 p_t y_t, \tag{8}$$

subject to equation (7b), and the following production function:

$$y_{t,j} = \widehat{A}_t k_{t-1,j}^{\alpha_1} h_{t,j}^{\alpha_2} E_{t,j}^{1-\alpha_1-\alpha_2}, \tag{9}$$

taking the general price level and aggregate output, $p_t$ and $y_t$ respectively, as given. $E_{t,j}$ is firm $j$'s demand for energy, which in turn is used in the production process; $P_t^e$ is the price of each unit of energy; and $\tau_t^e$ is a carbon tax per unit of energy used, imposed by the government.

Notice that we follow Rotemberg (1982) and introduce sluggish price adjustment by assuming that the firm faces a resource cost that is quadratic in the inflation rate of the good it produces. This is captured by the last term in equation (8), where $x$ measures the degree of price stickiness and $\pi_j$ is the equilibrium gross inflation rate on the price of commodity $j$. This is similar to functional forms used by Schmitt-Grohe and Uribe (2004) and Bi et al. (2013). The specific adjustment costs penalize large price changes in excess of steady-state inflation and make the firm's problem dynamic. Obviously, if $x = 0$, prices are fully flexible.

Finally, we assume that $\widehat{A}_t \equiv e^{-\psi(T_t - T_0)} A_t$ is an adjusted TFP factor which incorporates the detrimental effects of climate change into the production function, and where $T_t$ is the average global temperature at time $t$, and $T_0$ is the average global temperature in the pre-industrial period. Thus $T_t - T_0$ can be interpreted as the temperature anomaly at time $t$ relative to the pre-industrial period, and $e^{-\psi(T_t - T_0)}$ is a damage function defined in terms of the temperature anomaly. Parameter $\psi$ measures the magnitude of damage due to climate change and is known as the damage elasticity of output. The evolution of temperature is affected by the use of energy produced by fossil fuels, which in turn increases the concentration of GHGs in the atmosphere (see also subsection 2.2.4).

Therefore each intermediate firm, when using energy, faces two opposite effects. On the one hand, the more energy it demands and uses, the greater the increase in its ouput. On the other hand, the more energy it demands and uses, the higher the increase in temperature caused by climate change, which comes as a result of the increasing use of fossil fuels, which in turn increases carbon dioxide ($CO_2$) concentration in the atmosphere.

The above-described link between fossil fuels, energy and eventually climate, exerts a detrimental effect on the production through the adjusted TFP parameter, $\widehat{A}_t$. Each intermediate firm does not internalize, when making its decisions, the aforementioned detrimental effect, hence it takes the environmental externality as given. The first-order conditions of dynamic maximization problem (8) with respect to factor inputs, $k_{t-1,j}$, $h_{t,j}$ and $E_{t,j}$ respectively, are:

$$-p_t y_t^{1-\theta} y_{t,j}^{\theta} \alpha_1 (1-\theta) k_{t-1,j}^{-1} + \alpha_1 p_{t,j} y_{t,j} k_{t-1,j}^{-1} - p_t r_t +$$

$$+x(\pi_{t,j} - \widetilde{\pi}) p_t^2 p_{t-1,j}^{-1} y_t^{1-\theta} y_{t,j}^{\theta-1} (1-\theta) \alpha_1 k_{t-1,j}^{-1} y_t -$$

$$-\beta x(\pi_{t+1,j} - \widetilde{\pi}) p_{t+1} p_{t+1,j} p_{t,j}^{-2} p_t y_t^{1-\theta} y_{t,j}^{\theta-1} (1-\theta)\alpha_1 k_{t-1,j}^{-1} y_{t+1} = 0 \tag{10a}$$

$$-p_t y_t^{1-\theta} y_{t,j}^{\theta} \alpha_2 (1-\theta) h_{t,j}^{-1} + \alpha_2 p_{t,j} y_{t,j} h_{t,j}^{-1} - p_t w_t +$$

$$+x(\pi_{t,j} - \widetilde{\pi}) p_t^2 p_{t-1,j}^{-1} y_t^{1-\theta} y_{t,j}^{\theta-1} (1-\theta)\alpha_2 h_{t,j}^{-1} y_t -$$

$$-\beta x(\pi_{t+1,j} - \widetilde{\pi}) p_{t+1} p_{t+1,j} p_{t,j}^{-2} p_t y_t^{1-\theta} y_{t,j}^{\theta-1} (1-\theta)\alpha_2 h_{t,j}^{-1} y_{t+1} = 0 \tag{10b}$$

$$-p_t y_t^{1-\theta} y_{t,j}^{\theta} (1-\alpha_1-\alpha_2)(1-\theta) E_{t,j}^{-1} + (1-\alpha_1-\alpha_2) p_{t,j} y_{t,j} E_{t,j}^{-1} - P_t^e - p_t \tau_t^e +$$

$$+x(\pi_{t,j} - \widetilde{\pi}) p_t^2 p_{t-1,j}^{-1} y_t^{1-\theta} y_{t,j}^{\theta-1} (1-\theta)(1-\alpha_1-\alpha_2) E_{t,j}^{-1} y_t -$$

$$-\beta x(\pi_{t+1,j} - \widetilde{\pi}) p_{t+1} p_{t+1,j} p_{t,j}^{-2} p_t y_t^{1-\theta} y_{t,j}^{\theta-1} (1-\theta)(1-\alpha_1-\alpha_2) E_{t,j}^{-1} y_{t+1} = 0. \tag{10c}$$

### 2.2.3 Energy sector

In the energy sector, we assume a single firm which uses fossil fuels to produce energy. Therefore, the problem faced by this firm is to maximize its intertemporal profits, which in nominal terms, is given by:

$$D_t^e = \sum_{s=0}^{t} \beta^t (P_s^e - C^e) E_s, \tag{11a}$$

or in real terms is:

$$d_t^e = \sum_{s=0}^{t} \beta^t (p_s^e - c^e) E_s, \tag{11b}$$

subject to:

$$\sum_{s=0}^{t} E_s \leq S_0, \tag{11c}$$

where $S_0$ is the global stock of fossil fuels; $c^e$ is the real cost of producing one unit of energy, which, for simplicity, we assume remains constant; and $p_s^e$ is the relative price of each unit of energy. Maximization problem (11a), assuming that the resource constraint is not binding because fossil reserves are not exhausted during the planning horizon, implies that in each period $t$, the relative price of each unit of energy must be equal to the real marginal cost of producing this unit of energy. That is:

$$p_t^e = c^e, \tag{11d}$$

which in turn implies zero real profits.

### 2.2.4 Greenhouse gas emissions, global temperature changes and the damage function

In the DICE 2013R (Nordhaus and Sztorc, 2013) – a widely used IAM which couples the economy and climate – climate is represented by a three-reservoir model in which the reservoirs represents carbon in the atmosphere, the upper oceans and the deep oceans. In this setup, the increases in radiative forcing, $F_t$, which induces changes in the global mean temperature, are determined by the well-known relationship $F_t = \eta \log_2 \left( \frac{S_t^{AT}}{S_{t=1750}^{AT}} \right) + F_t^{EX}$, where $S_t^{AT}$, $S_{t=1750}^{AT}$ represent carbon concentration at time $t$ and the pre-industrial period $t = 1750$ respectively, $\eta$ is climate sensitivity, and $F_t^{EX}$ is external forcing (DICE 2013R). Using a composition of two mappings – the first from carbon concentration changes, relative to the pre-industrial period, to temperature anomaly, and the second from the temperature anomaly to damages – Golosov et al. (2014) defined the damage function as an exponential function of changes in carbon concentration, or $e^{-\gamma\left(S_t^{AT} - S_{t=1750}^{AT}\right)}$, where $\gamma$ is the damage elasticity of output with respect to the change in carbon concentration relative to the pre-industrial period.

In this paper, using recent developments in the climate literature (e.g., Matthews et al., 2009; Matthews et al., 2012; Pierrehumbert, 2014), we employ a representation of the climate model which is coupled with the economy (see also Hassler et al., 2016, section 3.2.6; Brock and Xepapadeas, 2017, for this representation) that leads to a simplification of the damage function.

The simplification is based on linking emissions of $CO_2$ directly with changes in global mean temperature through the carbon-climate response (CCR), instead of linking $CO_2$ emissions to $CO_2$ concentration through carbon sensitivity and $CO_2$ concentration to changes in global mean temperature through climate sensitivity. The CCR is approximately constant and aggregates the climate and carbon sensitivities (including climate-carbon feedbacks) into a single metric representing the net temperature change per unit of carbon emitted (MacDougall, 2016; Brock and Hansen, 2017, figure 2).

This relationship, which is consistent with the observational record of global temperature change and anthropogenic $CO_2$ emissions, has been named the transient climate response (TCRE) to $CO_2$ emissions (e.g., MacDougall et al., 2016). The TCRE embodies both the physical effect of $CO_2$ on climate and the biochemical effect of $CO_2$ on the global carbon cycle (Matthews et al., 2009). The TCRE, denoted by $\Lambda$, is defined as $\Lambda = \frac{\Delta T(t)}{CE(t)}$, where $CE(t)$ denotes cumulative carbon emissions up to time $t$, and $\Delta T(t)$ is the change in temperature during the same period. The constancy of $\Lambda$ suggests a roughly linear relationship between a change in global average temperature and cumulative emissions. Knutti and Rogelj (2015, p. 364) point out "...that every ton of $CO_2$ adds about the same amount of warming, no matter when and where it is emitted. TCRE, the warming per unit of carbon emissions, is a property of the Earth System, largely independent of the scenario."[5]

MacDougall and Friedlingstein (2015) and MacDougall (2016) provide analytical arguments for the constancy of TCRE over a relevant range of cumulative emissions of carbon. MacDougall (2016, p. 42) states that:

> ... TCRE arises from a combination of (1) positive carbon-climate feedbacks increasing the airborne fraction of carbon; (2) weakening radiative forcing per unit $CO_2$ at higher atmospheric concentrations of $CO_2$ and (3) contributions from non-$CO_2$ radiative forcing. Notably without the contribution from non-$CO_2$ radiative forcing the simulated TCRE remains approximately constant until 1700 Pg C of $CO_2$ have been emitted to the atmosphere.

Using the definition of TCRE, the temperature anomaly can be written as

$$T_t - T_0 = \Lambda \sum_{s=0}^{t} E_s, \tag{12}$$

where the best estimate of the value of $\Lambda$ is between 0.8-2.5°C per trillion tons of carbon (TtC) (MacDougal, 2016); $E_s$ are global carbon emissions, which in each period $t$ are equal to $\sum_{j=1}^{N} E_{t,j}$; and $E_0$ are global pre-industrial emissions.

[5] This linear relationship has also been recognized by the IPCC (2013, p. 1113), where it is stated that:

> In conclusion, taking into account the available information from multiple lines of evidence (observations, models and process understanding), the near linear relationship between cumulative CO2 emissions and peak global mean temperature is well established in the literature and robust for cumulative total $CO_2$ emissions up to about 2000 PgC. It is consistent with the relationship inferred from past cumulative CO2 emissions and observed warming, is supported by process understanding of the carbon cycle and global energy balance, and emerges as a robust result from the entire hierarchy of models.

Then the exponential damage function with respect to the temperature anomaly, $e^{-\psi(T_t - T_0)}$, can be written, using the representation based on TCRE, as $e^{-\psi\left(\Lambda \sum_{s=0}^{t} E_s\right)}$, and the TFP adjusted for climate change can be written as:[6]

$$\widehat{A}_t \equiv e^{-\psi\left(\Lambda \sum_{s=0}^{t} E_s\right)} A_t.$$

### 2.2.5 Government budget constraint

The budget constraint of the consolidated government sector, expressed in nominal terms and aggregate quantities, is:

$$B_t - B_{t-1} + M_t - M_{t-1} + p_t \tau_t^c c_t + \tau_t^y (p_t r_t k_{t-1} + p_t w_t h_t + D_t) +$$

$$+ p_t \tau_t^e \sum_{j=1}^{N} \lambda_j E_{t,j} = R_{t-1} b_{t-1} + p_t g_t + p_t g_t^{tr}, \tag{13a}$$

and in real terms is:

$$b_t - \left(\frac{1}{\pi_t}\right) b_{t-1} + m_t - \left(\frac{1}{\pi_t}\right) m_{t-1} + \tau_t^c c_t + \tau_t^y (r_t k_{t-1} + w_t h_t + d_t) +$$

$$+ \tau_t^e \sum_{j=1}^{N} \lambda_j E_{t,j} = R_{t-1} \left(\frac{1}{\pi_t}\right) b_{t-1} + g_t + g_t^{tr}. \tag{13b}$$

In each period, one of the fiscal policy instruments, $\tau_t^c$, $\tau_t^y$, $\tau_t^e$, $g_t$, $g_t^{tr}$ and $b_t$, has to follow residually to satisfy the government budget constraint.

### 2.2.6 Decentralized equilibrium

We now combine all the above to solve for a symmetric decentralized equilibrium (DE) for any feasible monetary and fiscal policy. The DE is defined as a sequence of allocations, prices and policies such that: (i) the household maximizes utility; (ii) all firms maximize profits; (iii) all constraints, including the government budget constraint, are satisfied; and (iv) all markets clear. Notice that in a symmetric DE, it holds that $y_t \equiv y_{t,j}$, $k_t \equiv k_{t,j}$, $h_t \equiv h_{t,j}$, $E_t \equiv E_{t,j}$ and $p_t \equiv p_{t,j}$.

To proceed with the solution, we need to define the policy regime. Regarding monetary policy, we assume, as is usually the case, that the nominal interest rate $R_t$ is used as a policy instrument, while money balances are

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[6] In the numerical simulations presented in sections 5, 6 and 7, we have assumed that the carbon emissions of the last 300 years determine the temperature anomaly through the TCRE representation.

endogenously determined. Regarding fiscal policy, we assume that tax rates and public spending, $\tau_t^c$, $\tau_t^y$, $\tau_t^e$, $g_t$, and $g_t^{tr}$, are set exogenously, while the end-of-period public debt, $b_t$, follows residually from the government budget constraint.

Therefore, the DE of the above economy is given by:

$$\frac{1}{(1+\tau_t^c)c_t} = \frac{1}{(1+\tau_{t+1}^c)c_{t+1}}\beta\left[1-\delta+(1-\tau_{t+1}^y)r_{t+1}\right] \tag{14a}$$

$$\frac{1}{(1+\tau_t^c)c_t} = \frac{1}{(1+\tau_{t+1}^c)c_{t+1}}\beta(\frac{1+R_t}{\pi_{t+1}}) \tag{14b}$$

$$\frac{\mu_3}{m_t} = \frac{\mu_1}{(1+\tau_t^c)c_t} - \beta\frac{\mu_1}{(1+\tau_{t+1}^c)c_{t+1}}\frac{1}{\pi_{t+1}} \tag{14c}$$

$$\frac{\mu_2}{1-h_t} = \frac{\mu_1 w_t(1-\tau_t^y)}{(1+\tau_t^c)c_t} \tag{14d}$$

$$(1+\tau_t^c)c_t + k_t - (1-\delta)k_{t-1} + b_t - (\frac{1}{\pi_t})b_{t-1} + m_t - (\frac{1}{\pi_t})m_{t-1} =$$

$$= (1-\tau_t^y)(r_t k_{t-1} + w_t h_t + d_t) + \left(\frac{R_{t-1}}{\pi_t}\right) b_{t-1} + g_t^{tr} \tag{14e}$$

$$y_t = e^{-\psi\Lambda\sum_{s=0}^{t} E_s} A_t k_{t-1}^{\alpha_1} h_t^{\alpha_2} E_t^{1-\alpha_1-\alpha_2} \tag{14f}$$

$$r_t k_{t-1} = \alpha_1\theta y_t + x(\pi_t - \widetilde{\pi})\pi_t(1-\theta)\alpha_1 y_t - \beta x(\pi_{t+1} - \widetilde{\pi})\pi_{t+1}^2(1-\theta)\alpha_1 y_{t+1} \tag{14g}$$

$$w_t h_t = \alpha_2\theta y_t + x(\pi_t - \widetilde{\pi})\pi_t(1-\theta)\alpha_2 y_t - \beta x(\pi_{t+1} - \widetilde{\pi})\pi_{t+1}^2(1-\theta)\alpha_2 y_{t+1} \tag{14h}$$

$$p_t^e E_t + \tau_t^e E_t = (1-\alpha_1-\alpha_2)\theta y_t + x(\pi_t - \widetilde{\pi})\pi_t(1-\theta)(1-\alpha_1-\alpha_2)y_t -$$

$$-\beta x(\pi_{t+1} - \widetilde{\pi})\pi_{t+1}^2(1-\theta)(1-\alpha_1-\alpha_2)y_{t+1} \tag{14i}$$

$$d_t = y_t - r_t k_{t-1} - w_t h_t - p_t^E E_t - \tau_t^E E_t - \frac{x}{2}(\pi_t - \widetilde{\pi})^2 y_t \tag{14j}$$

$$b_t - \left(\frac{1}{\pi_t}\right) b_{t-1} + m_t - \left(\frac{1}{\pi_t}\right) m_{t-1} + \tau_t^c c_t + \tau_t^y(r_t k_{t-1} + w_t h_t + d_t) +$$

$$+\tau_t^e E_t = R_{t-1}\left(\frac{1}{\pi_t}\right) b_{t-1} + g_t + g_t^{tr} \tag{14k}$$

$$p_t^e = c^e, \tag{14l}$$

where $p_t^e \equiv \frac{P_t^e}{p_t}$ is the relative per unit price of energy.

The above dynamic DE system consists of 12 equations in 12 variables, $\{y_t, c_t, h_t, k_t, E_t, b_t, m_t, r_t, w_t, p_t^e, d_t, \pi_t\}_{t=0}^{\infty}$, given the independently-set policy instruments, $\left\{R_t, \tau_t^c, \tau_t^y, \tau_t^e, g_t, g_t^{tr}\right\}_{t=0}^{\infty}$, technology $\{A_t\}_{t=0}^{\infty}$ and initial conditions for the state variables.

### 2.2.7 Aggregate resource constraint

By properly combining some of the above equations, we can obtain the aggregate resource constraint of the economy given below:

$$c_t + k_t - (1-\delta)k_{t-1} + g_t + p_t^e E_t = y_t - \frac{x}{2}\left(\pi_t - \widetilde{\pi}\right)^2 y_t, \tag{14m}$$

which makes clear the resource losses that rapid price adjustment produces.

### 2.2.8 Monetary and fiscal policy rules

Following the related literature (see e.g., Schmitt-Grohe and Uribe, 2004, Bi et al., 2013, Philippopoulos et al., 2015), we focus on simple rules for the exogenously-set monetary and fiscal policy instruments, which means that the monetary and fiscal authorities react to a small number of macroeconomic indicators.

In particular, we allow the nominal interest rate $R_t$ to follow a standard Taylor rule, meaning that it can react to inflation and output as deviations from a policy target. The target values are defined below. More specifically, following, e.g., Bi et al. (2013), we use a monetary policy rule of the functional form:

$$R_t = \widetilde{R} + \phi^{\pi}(\pi_t - \widetilde{\pi}) + \phi^{y}(y_t - \widetilde{y}), \tag{14n}$$

where $\widetilde{R}$, $\widetilde{\pi}$ and $\widetilde{y}$ denote target values, and $\phi^{\pi}$ and $\phi^{y}$ are feedback monetary policy coefficients. In the steady state it holds that $\pi_t = \widetilde{\pi}$ and $y_t = \widetilde{y}$, and therefore $R_t = \widetilde{R}$. Unless otherwise stated, the target values for the inflation rate and the output, $\widetilde{\pi}$ and $\widetilde{y}$, will be 1 and the level of the output in the steady state respectively.

Regarding public spending, we assume that both types of spending, $g_t$ and $g_t^{tr}$, are shares of GDP. We assume that:

$$g_t = s_t^g y_t \tag{14o}$$

$$g_t^{tr} = s_t^{tr} y_t, \tag{14p}$$

where $s_t^g$ and $s_t^{tr}$ are policy instruments.

Moreover, and in order to ensure dynamic stability along the transition path, we allow total tranfers as a share of GDP, $s_t^{tr}$, to react to deviations of public debt over output from a target. We assume that:

$$s_t^{tr} = s^{tr} - \phi^{tr}(\frac{b_{t-1}}{y_{t-1}} - \frac{\widetilde{b}}{\widetilde{y}}), \tag{14q}$$

where $\frac{\widetilde{b}}{\widetilde{y}}$ denotes target value, and $\phi^{str}$ is a feedback fiscal policy coefficient. In the steady state it holds that $\frac{b_{t-1}}{y_{t-1}} = \frac{\widetilde{b}}{\widetilde{y}}$, and therefore $s_t^{tr} = s^{tr}$. The target for the public debt-to-output ratio will be the corresponding steady-state value.

#### 2.2.9 The final equilibrium system

Given the feedback policy coefficients, the final equilibrium system consists of the 12 DE equations, (14a)–(14l), plus the monetary and fiscal policy rules shown in (14n)–(14q). To solve this non-linear difference equation system, we use non-linear methods (see subsection 4.1). We proceed as follows. We first solve numerically for the long-run equilibrium of this model employing common parameter values and data from the euro area. Section 3 presents the baseline parameterization used and derives the steady-state solution of this economy. Later sections will study the various policy experiments.

## 3 Parameterization and steady state

### 3.1 Parameterization

Table 1 reports the baseline parameter values for policy, technology and preferences used to obtain the values of the endogenous variables. We use conventional values. We note at the outset that our main results are robust to changes in these parameter values. Thus, although our numerical simulations below are not meant to provide a rigorous quantitative study, they illustrate the qualitative dynamic features of the model in a robust way.

**Table 1: Parameterization**

The time unit is a year. Regarding preference parameters, we use values employed by most of the related literature. The discount factor, $\beta$, and the depreciation rate of physical capital, $\delta$, are set equal to 0.99 and 0.015

respectively, to be consistent with a value for the real interest rate of about 3.5% per year.[7]

The weights given to private consumption, leisure and real money balances, $\mu_1$, $\mu_2$, and $\mu_3$, are set equal to 0.35, 0.6 and 0.02 respectively. The weight given to public goods and services then follows residually and is equal to 0.03 (see, e.g., Cooley and Prescott, 1995).

Regarding technology parameters in the production function of goods (see equation (14f)), the Cobb-Douglas exponents of physical capital and labor, $\alpha_1$ and $\alpha_2$, are set equal to 0.33 and 0.60 respectively, so that the exponent of energy input follows residually and is equal to 0.07. These values are within standard ranges (see, e.g., Cooley and Prescott, 1995). The scale parameter in the same function, $A$, is set at 1. Following Bi et al. (2013), we set the parameter $x$, which measures the degree of price stickiness, equal to 100. Following Eggertsson et al. (2014), we use a value equal to 0.85 for the elasticity of substitution across intermediate goods produced, $\theta$, which is also a measure of imperfect competition.

The steady-state values of the exogenously-set fiscal policy instruments are set close to their data averages for the euro area, using Eurostat data. For instance, the consumption tax rate, $\tau_t^c$, and the income tax rate, $\tau_t^y$, are set equal to 0.19 and 0.30 respectively, which are the averages of the respective effective tax rates in the data. These values are kept constant during the planning horizon. Moreover, we set the government consumption, $g_t$, and total transfers, $g_t^{tr}$, both as a share of GDP, $s_t^g$ and $s_t^{tr}$, equal to 0.2 and 0.192 respectively. During the planning horizon, $s_t^g$ remains constant, whereas – in order to ensure dynamic stability – we allow $s_t^{tr}$ to react to deviations of debt over output from its steady-state value (see also equation (14q)). Regarding the carbon tax, $\tau_t^e$, we start by setting its value equal to 0. However, we relax this assumption later in section 6.

The aforementioned fiscal policy mix produces a long-run public debt-to-output ratio, $\frac{b_t}{y_t}$, equal to around 0.9 (which is very close to the value observed in the data for the euro area).

Regarding the feedback policy coefficients, $\phi^{\pi}$, $\phi^{y}$ and $\phi^{tr}$, we follow the related literature on monetary and fiscal policy rules (see, e.g., Bi et al., 2013, and Philippopoulos et al., 2015) and set the values of 1.5, 0.01 and 0.3 respectively. We set the inflation target, $\widetilde{\pi}$, equal to 1, whereas the output, nominal interest rate and public debt-to-output ratio targets, $\widetilde{y}$, $\widetilde{R}$ and $\frac{\widetilde{b}}{\widetilde{y}}$, are set equal to their steady state values. The real cost of producing energy, $c^e$, is set equal to 1.1. Notice however that our results do not depend

[7] The value of the discount factor implies an annual time discount rate of 1%. There has been a long discussion about the choice of the time discount rate (see, e.g., Dasgupta, 2008). Our choice of 1% is within the range regarded as appropriate in the relevant literature. The discount factor of Golosov et al. (2014) implies an annual time discount rate of 1.5%. Note that our results are robust to changes in time discount rate choices around 1%.

qualitatively on the value of $c^e$.

Finally, regarding the climate module, for the TCRE to $CO_2$ emissions which is captured by parameter $\Lambda$, we follow the related literature (Leduc et al., 2016, supplementary information) where the mean response is reported to be 1.7±0.4°C per TtC and set it equal to 1.7. Note that the best estimate of this parameter is considered to be between 0.8-2.5°C per TtC. For the parameter $\psi$, we follow the calibration approach of Golosov et al. (2014) which is based on Nordhaus (2008). For a temperature anomaly of 2.5°C, the calculated loss is 0.48% of GDP, while a catastrophically large anomaly of 6°C with probability 6.8% will result in a loss of 30% of GDP. This implies that, using the temperature-anomaly representation of the damage function, $e^{-\psi(T_t - T_0)}$, the ex ante damage cost can be calculated as $p\psi^H + (1-p)\,\psi^L$ where $\psi^H$, $\psi^L$ are the the solutions of $e^{-\psi \cdot 6} = 0.7$ and $e^{-\psi \cdot 2.5} = 0.9952$ and $p$ is the probability of the catastrophic temperature anomaly. Using the Nordhaus values, $\psi = 0.0058$. In IPCC (2007) it is stated that global mean losses could be 1-5% of GDP for 4°C of warming. Using the same calibration approach, this implies values of $\psi$ between 0.0025 and 0.13. Given the well-known uncertainties associated with the damage function, we experimented with a large number of values for $\psi$ and $\Lambda$. In our simulations, the value of $\psi = 0$ corresponds to the case in which the design of economic policy does not take into account climate change effects.

### 3.2 Steady state

Table 2 reports the steady-state solution of the simple new Keynesian model presented in section 2, when we use the parameter values and the policy instruments discussed in subsection 3.1 and presented in Table 1. Notice that in order to derive the steady-state solution of the above model economy, we assume that, in the long run, there are no price rigidities; therefore $x = 0$ and climate change does not affect the productivity of the economy. Thus $\psi = 0$ and $\tau_t^e = 0$ for all $t$. The resulting long-run solution is well defined and intuitive.[8]

**Table 2: Steady State Solution**

## 4 Methodology and policy experiments

In this section, we explain the experiments and focus on how the effects of these experiments are computed. Recall that, along the transition path, nominal rigidities imply that money is not neutral so interest rate policy matters to the real economy. Recall also that, along the transition path,

[8] Notice that the steady-state solution in Table 2 implies that the resulting GDP shares of capital, debt and private investment – 0.6232, 0.90 and 0.117, respectively – are relatively close to the Eurozone data averages.

different counter-cyclical policy rules, and hence different values of feedback policy coefficients, can have different implications.

### 4.1 Methodology

Using the above numerical values, we solve the system described by equations (14a)-(14o) by using a Newton-type non-linear method as implemented in DYNARE. DYNARE uses a relaxation algorithm in order to numerically solve the non-linear equations. We solve the model under perfect foresight in the sense that the distribution of shocks with which we feed the model is known to the agents of the economy. In other words, the dynamics of our model will be driven only by temporary (or permanent) changes in the value of $A_t$ or by any other exogenous deterministic shock.

### 4.2 Policy experiments

In our setup, as usually happens in the standard new Keynesian model, the role of policy is only to stabilize the economy against temporary shocks. For instance, a positive temporary TFP shock produces an increase in output, which in turn increases inflation. Thus the policy question is how the nominal interest rate – which, in our case, follows a simple Taylor rule – should react to deviations from targets, when the latter are given for instance by the long-run solution. Technically speaking, in this case we depart from, and end up at, the same steady state. In the standard new Keynesian setup, this would require an increase in the nominal interest rate so as to offset the tendency of prices to increase above the target after the positive TFP shock.

In the present paper, we reconsider the above policy question in a new Keynesian framework in which the innovative feature is that the effects of climate change have been incorporated. In particular, we investigate whether the reaction of the nominal interest rate is affected, and towards what direction, by the assumption that climate change affects the economy's productivity. As mentioned earlier, in our setup, energy (produced by fossil fuels) affects productivity in two oposite ways. On the one hand, energy increases output since it enters the production function as a separate factor, and on the other hand the more the energy used, the higher the adverse effect on climate (through the increase in temperature) and therefore the higher the detrimental effect on TFP productivity through the damage function which maps temperature developments to physical and financial consequences. Hence, the final result is somewhat ambiguous.

Finally, notice that in all numerical simulations presented in the paper, we assume that after the realization of the (positive or negative) shock, $A_t$ (i.e., TFP productivity ) evolves according to the following deterministic AR(1) rule:

$$A_t = (A)^{1-\varphi^A}(A_{t-1})^{\varphi^A}, \tag{15}$$

where the persistence parameter $\varphi^A$ is set at 0.9,[9] while the value of $A$ (i.e., the steady-state TFP productivity) is set at 1.

# 5 Main results

This section presents the main results of our numerical simulations. Through these results, we try to answer whether the reaction of monetary policy to deviations from targets is affected once policymakers acknowledge the detrimental effects of climate change on the economy's productivity. Initially, we assume that monetary policy reacts only to the inflation gap component, therefore the monetary policy coefficient, $\phi^y$ – which measures the strength of reaction to deviations from the output target – is set equal to 0; however, in section 7 we relax this assumption.

Climate change is reflected in the parameter $\psi$, which is the damage elasticity of output that captures the detrimental effect of climate change on the economy's productivity. When climate change is not taken into account by monetary authorities, it holds that $\psi = 0$. Therefore, to explore the link between monetary policy and climate change, we compare the paths of the adjusted TFP component, output, inflation rate, nominal interest rate, and the agent's welfare when $\psi = 0$, to the same paths when $\psi > 0$. At the same time, in both the aforementioned cases, the economy is hit by a negative TFP shock (namely, a 1% decrease in $A_t$ which returns gradually to its initial value according to equation (15)).[10] In order to test the robustness of our results, we examine the impact of the TFP shock for $\psi = (0.1, 0.2, 0.3, 0.4, 0.5, 0.6)$.

Notice that what is crucial here is not the path of TFP, $A_t$, itself, but rather the path of the adjusted TFP component, $\widehat{A}_t \equiv e^{-\psi\left(\Lambda \sum_{s=0}^{t} E_s\right)} A_t$.[11] In other words, climate change seems to act as a new propagation mechanism of the otherwise standard TFP shocks hitting the economy, which works differently from the mechanisms already studied in the relevant RBC literature.

The paths of the adjusted TFP component, the output, the inflation rate, the nominal interest rate, as well as the representative agent's welfare, all as deviations from the steady state, are presented in Figures 1a-e respectively.

Figure 1a here

[9] Our results do not depend qualitatively on the value of $\varphi^A$.

[10] We omit the case of a positive TFP shock since the results are symmetrically opposite to the ones we derive in the case of a negative TFP shock. However, they are available upon request.

[11] Notice that when $\psi = 0$, $\widehat{A}_t = A_t$.

Figure 1b here
Figure 1c here
Figure 1d here
Figure 1e here

First of all, as can be seen in Figure 1a, climate change, as a propagation mechanism of TFP shocks, seems to lengthen the duration of the effects of disturbances. Namely, after a negative shock on $A_t$, the return of the economy's adjusted TFP component $\widehat{A}_t$ to the steady state is slower, and is characterized by oscillations, when compared to an economy in which the impact of climate change has not been incorporated. How slow the return will be depends on how many past periods matter for climate change.

Moreover, as shown in Figure 1c, the disinflation, $\pi_t$, caused by a decrease in TFP productivity is lower, the higher $\psi$ is. In other words, the higher the detrimental impact of climate change on the economy, the lower the disinflation, and hence, as shown in Figure 1d, the smaller the required reaction of the nominal interest rate, $R_t$, which aims at stabilizing the inflation rate around the target, $\widetilde{\pi}$.

The intuition behind these results is clear. In the presence of the detrimental effects of climate change on the economy's productivity, the effect of a negative TFP shock – as can be seen in Figure 1a through the path of the adjusted TFP component – is gradually mitigated, although initially the output decreases more relative to the case in which climate change is not taken into account. This happens because the negative TFP shock decreases the demand for energy which requires a decrease in the use of fossil fuels. The decrease in the use of fossil fuels in turn slows down the temperature rise, a development which positively affects the productivity of the economy. In other words, we have two opposite, conflicting effects: a direct negative effect through the negative shock in $A_t$, and an indirect positive effect through the mitigation of the detrimental impact of climate change. The former tends to decrease the adjusted TFP component, whereas the latter tends to increase it. Initially it is the former effect that dominates, but over time this is reversed, and as a result the adjusted TFP component rises above its steady-state value before eventually converging to it. The strength of the indirect positive effect on the adjusted TFP component depends on the magnitude of $\psi$. However, the qualitative nature of our results does not depend on the value of $\psi$, although the effect of the TFP shock is mitigated faster, the higher $\psi$ is. The latter affects only the size of the distance between the paths for $\psi = 0$ and $\psi > 0$ at each point in time. The higher the parameter $\psi$ is, the larger the distance is between the paths for $\psi = 0$ and $\psi > 0$ at each point in time.

The combination of all the above effects in the end cause a lower disinflation – relative to the case in which $\psi = 0$ – and therefore require a relatively smaller increase in the nominal interest rate $R_t$. Moreover, as shown in Figure 1e, once monetary policy takes into account the detrimental effects of climate change, the deviation of individual welfare from the steady state becomes significantly smaller relative to the case in which climate change effects are ignored. However, the return of individual welfare to its steady-state value is slower.

The rest of the endogenous variables in our economy behave normally and according to the predictions of economic theory.

## 6 Monetary policy in the presence of carbon taxes

A carbon tax is regarded as the most direct and transparent approach for establishing a price of GHG emissions (McKibbin et al., 2017). However, the design of a carbon tax scheme requires that policymakers take decisions about a number of important issues. For example, the magnitude of the carbon tax may depend on the social cost of carbon or an emissions goal. Another important issue is how the resulting revenues will be used.

Moreover, the introduction of a carbon tax is not considered to be a costless intervention, since it could produce significant fluctuations in the output level and the inflation rate as a result of the increase in the cost of using energy. Hence, in terms of monetary policy, a natural question that arises concerns the appropriate monetary policy reaction in light of introduction of, or a change to, a carbon tax. This section focuses exactly on this issue, namely determining what the appropriate monetary policy should be once carbon taxes are implemented.

To do so, we choose to work with an economy which is described by the parameter values presented in Table 1, and in which the parameter which describes the detrimental effects of climate on the economy's productivity, $\psi$, is equal to 0.5. Notice however that our qualitative results do not depend on the magnitude of $\psi$.

Note also that the way in which we treat the carbon tax revenues is equivalent to assuming that all revenues are returned to households in the form of a lump-sum transfer. Therefore, they are not used for policies aimed at mitigating climate change effects, or the economy's adaptation to climate change, which could possibly moderate the adverse effects. Moreover, as stated in the introduction, these revenues are not used to substitute for other more distorting taxes. Also, as mentioned earlier, the goal of monetary policy is to stabilize inflation around the target. Therefore, in the experiment presented below, the feedback policy parameter, $\phi^y$, is equal to 0.

Figures 2a-c show the paths of output, inflation rate, and nominal interest rate for different values of the carbon tax rate. We allow the value of the carbon tax per unit of energy used, $\tau^e$ – which is fixed over the planning horizon – to vary in the interval $[0, 1]$. Technically speaking, our economy is at a steady state in which the carbon tax is 0. A positive carbon tax is imposed at this steady state and the economy ends up at a new steady state which corresponds to the new value of the carbon tax.

Figure 2a here
Figure 2b here
Figure 2c here

As shown in Figure 2a, an increase in the carbon tax is eventually growth enhancing in the sense that the economy moves to a steady state with higher output. However, in the short run, the imposition of a carbon tax decreases output. The higher the carbon tax rate, the higher the initial drop in output, and the higher the steady-state output.

The intuition is clear: once carbon taxes are introduced, the demand for energy decreases, which in turn reduces the use of fossil fuels. The decrease in the use of fossil fuels initially reduces output but in the long run positively affects the productivity of the economy (through the slowdown in temperature rise), thus leading to a higher output level.

Similarly, as shown in Figure 2b, during the transition from the initial steady state to the new long-run equilibrium, there will also be fluctuations in the price level, which initially falls below, and later rises above, the steady-state level. In the long run it converges to its steady-state value, which is independent of the value of the carbon tax and, as before, is equal to 1.

Obviously, these fluctuations represent a challenge for monetary authorities and should be taken into account when designing the appropriate monetary policy actions. This is demonstrated in Figure 2c, where the nominal interest rate initially decreases to offset the effects of disinflation, and later increases to deal with the increased inflation. In the end, the nominal interest rate converges to its steady-state value, which is independent of the value of the carbon tax, and is the same as in the economy without carbon taxes.

Note that, just as with output, the higher the carbon tax rate, the larger the fluctuations both in inflation and nominal interest rate. Finally, we find that the steady-state solutions for the various levels of the carbon tax rate are all well defined and intuitive (results available upon request); and that during the transition path, the rest of the endogenous variables in our economy behave normally and according to the predictions of economic theory.

# 7 Robustness

As a final step, we conduct a sensitivity analysis. We check robustness to changes in parameter values and to two generalizations of the model that allow for policy reaction to output gap and for trend inflation. Our main results remain unaffected.

### 7.1 Alternative parameterizations of the model

Our results are robust to changes in the magnitude of all key parameter values. For instance, we experimented with changes in the values of the Rotemberg parameter in the firm's problem, $x$, the degree of imperfect competition in the intermediate goods market, $\theta$, and the preference parameters for real money balances and public goods, $\mu_3$ and $1-\mu_1-\mu_2-\mu_3$ respectively, whose values are relatively unknown. Our main results do not change.

We also experimented with changes in the value of: climate sensitivity $\Lambda$, which measures the response of temperature to emissions released in the atmosphere; the parameter $\psi$, which captures the detrimental effects of climate change on the economy's productivity; the real cost of producing energy $c^e$; and the level of the carbon tax $\tau^e$. Again the results do not change. Results are available upon request.

### 7.2 The Central Bank, monetary policy and the output gap

We assume that monetary policy also reacts to the output gap component. More specifically, we assume that the monetary policy coeffcient, $\phi^y$, which measures the strength of reaction to deviations from output target, $\widetilde{y}$, is equal to 0.01.[12] As already mentioned, the output target, $\widetilde{y}$, is considered to be the level of output at the steady state. Again we present only the case in which the economy is hit by a temporary negative TFP shock (namely a 1% decrease in $A_t$, which returns gradually to its initial value according to (15)). We investigate how the paths of output, the inflation rate, the nominal interest rate, and individual welfare, all as deviations from their steady-state values, are affected. The paths of these variables are presented in Figures 3a-d which reflect qualitatively similar results to the ones in which monetary policy reacted only to deviations from the inflation target (see Figures 1b-e). Obviously, the intuition is also similar. We also note that the rest of the endogenous variables in our economy behave normally and according to the predictions of economic theory.

Figure 3a here
Figure 3b here
Figure 3c here
Figure 3d here

[12] Our results do not depend qualitatively on the value of $\phi^y$.

### 7.3 Allowing for trend inflation

We now allow for trend or steady-state inflation. We consider the gross steady-state rate of inflation, $\pi$, to be 1.02. This value is perceived to be the target value of the European Central Bank. Again we choose to present only the case of a temporary negative TFP shock (namely a 1% decrease in $A_t$ which gradually returns to its initial value according to (15)). Figures 4a-d show the paths of output, inflation rate, nominal interest rate, and individual welfare. It is clear that the main qualitative results remain the same.

Figure 4a here
Figure 4b here
Figure 4c here
Figure 4d here

# 8 Concluding remarks

In this paper we extended the standard new Keynesian model by allowing for climate change effects. Within this setup, our objective was to answer the question posed in the introduction of whether the conduct of monetary policy, when it follows a simple Taylor rule, is affected by the presence of climate change in a non-trivial way. Our results suggest that climate change and the use of instruments to mitigate its detrimental effects does affect the design of monetary policy.

Three main results, with both positive and normative implications, emerged from our analysis. The first is that climate change seems to act as a new propagation mechanism of the standard TFP shocks, which appears not only to lengthen the duration of the effects of disturbances, but also to cause increased fluctuations in economic activity. The second is that under negative (or positive) TFP shock, the adjustment in the nominal interest should be less, relative to the corresponding adjustment when climate change is not taken into account. The third is that monetary policy should be adjusted in a non-trivial way when climate change is taken into account and energy (or carbon) taxes are present, relative to the case in which climate change is ignored. When carbon taxes are implemented, an additional – rather surprising – result is that the carbon tax could be growth enhancing, with the result being independent of double-dividend arguments.

It should be noted that these results are robust to parameter changes, and that they hold in the two cases where: (i) the Central Bank cares about inflation only; and (ii) the Central Bank cares about both inflation and the output gap.

The present model could be extended along different dimensions. Since a criticism to IAMs is the damage function (see Pindyck, 2013), different functional forms and parametrizations for the damage function could be explored, along with the explicit introduction of tipping points. In addition, the model could be enriched by incorporating additional environmental policy instruments aiming, for instance, at mitigation of the climate change effects through adaptation to climate change, to investigate if and how these additional policy instruments are interrelated with the conduct of monetary policy.

Moreover, the modeling of the energy sector of the economy could be extended by introducing two types of firms producing "brown" and "green" energy. Also the current setup could be augmented by introducing a properly modeled financial sector to investigate the financial risks associated with climate change and how monetary policy could deal with them.

Finally, since monetary policy appears to be affected by climate change, it would be interesting to focus on optimal policies by examining what should be the optimal coefficients of reaction to deviations from target in the simple Taylor rule, when for instance the objective is the maximization of household's intertemporal welfare. In the same context, an additional approach would be to investigate which macroeconomic indicators monetary policy should react to in the presence of climate change.

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**Table 1: Parameterization**

| Parameters and policy variables | Description | Value |
|---|---|---|
| $\beta$ | discount factor | 0.99 |
| $\mu_1$ | weight given to consumption | 0.35 |
| $\mu_2$ | weight given to leisure | 0.6 |
| $\mu_3$ | weight given to real money balances | 0.02 |
| $1-\mu_1-\mu_2-\mu_3$ | weight given to public consumption | 0.03 |
| $\alpha_1$ | exponent of physical capital | 0.33 |
| $\alpha_2$ | exponent of labour | 0.6 |
| $1-\alpha_1-\alpha_2$ | exponent on energy | 0.07 |
| $A$ | TFP productivity | 1 |
| $\delta$ | depreciation rate of physical capital | 0.015 |
| $x$ | degree of price stickiness | 100 |
| $\theta$ | measure of imperfect competition | 0.85 |
| $\tau_t^c$ | consumption tax rate | 0.19 |
| $\tau_t^y$ | income tax rate | 0.30 |
| $\tau_t^e$ | carbon tax rate | 0 |
| $\frac{g_t}{y_t}$ | government cons/GDP | 0.2 |
| $\frac{g_t^{tr}}{y_t}$ | government transf/GDP | 0.192 |
| $\frac{b_t}{y_t}$ | public debt/GDP | 0.9 |
| $\phi^{\pi}$ | reaction to inflation gap | 1.5 |
| $\phi^{y}$ | reaction to output gap | 0.01 |
| $\phi^{tr}$ | reaction to fiscal imbalances | 0.3 |
| $\Lambda$ | climate sensitivity | 1.7 |
| $\psi$ | damage effect | 0 to 0.6 |
| $c^e$ | real cost per unit of energy | 1.1 |

**Table 2: Steady-State Solution**

| Variable | Value |
|---|---|
| $y$ | 0.4836 |
| $k$ | 3.7829 |
| $h$ | 0.2193 |
| $e$ | 0.0262 |
| $c$ | 0.3014 |
| $m$ | 2.0492 |
| $b$ | 0.4352 |
| $g$ | 0.0967 |
| $g^{tr}$ | 0.0926 |
| $w$ | 1.1249 |
| $r$ | 0.0359 |
| $R$ | 0.0101 |
| $c/y$ | 0.6232 |
| $b/y$ | 0.90 |
| $inv/y$ | 0.118 |
| $Welfare$ | $-0.6240$ |

**Figure 1a**

**% Deviation of Adjusted TFP from the Steady State**

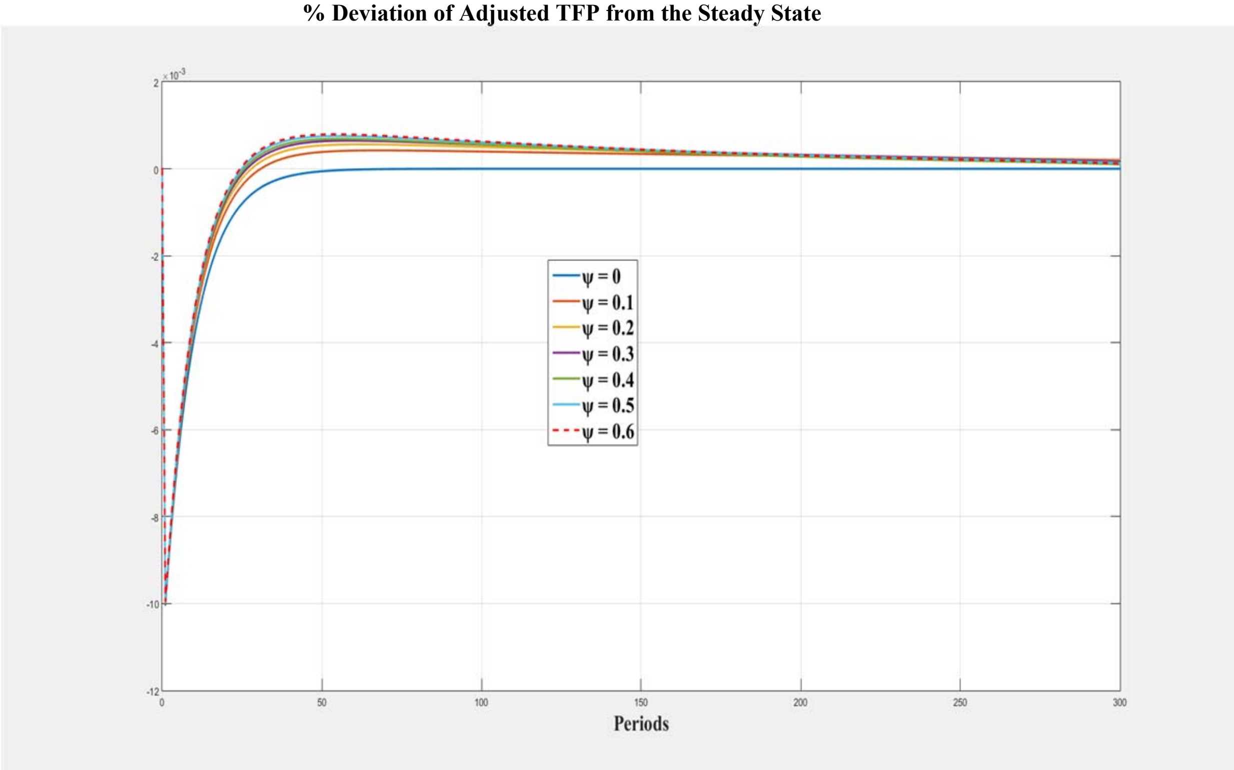


**Figure 1b**

**% Deviation of Output from the Steady State**

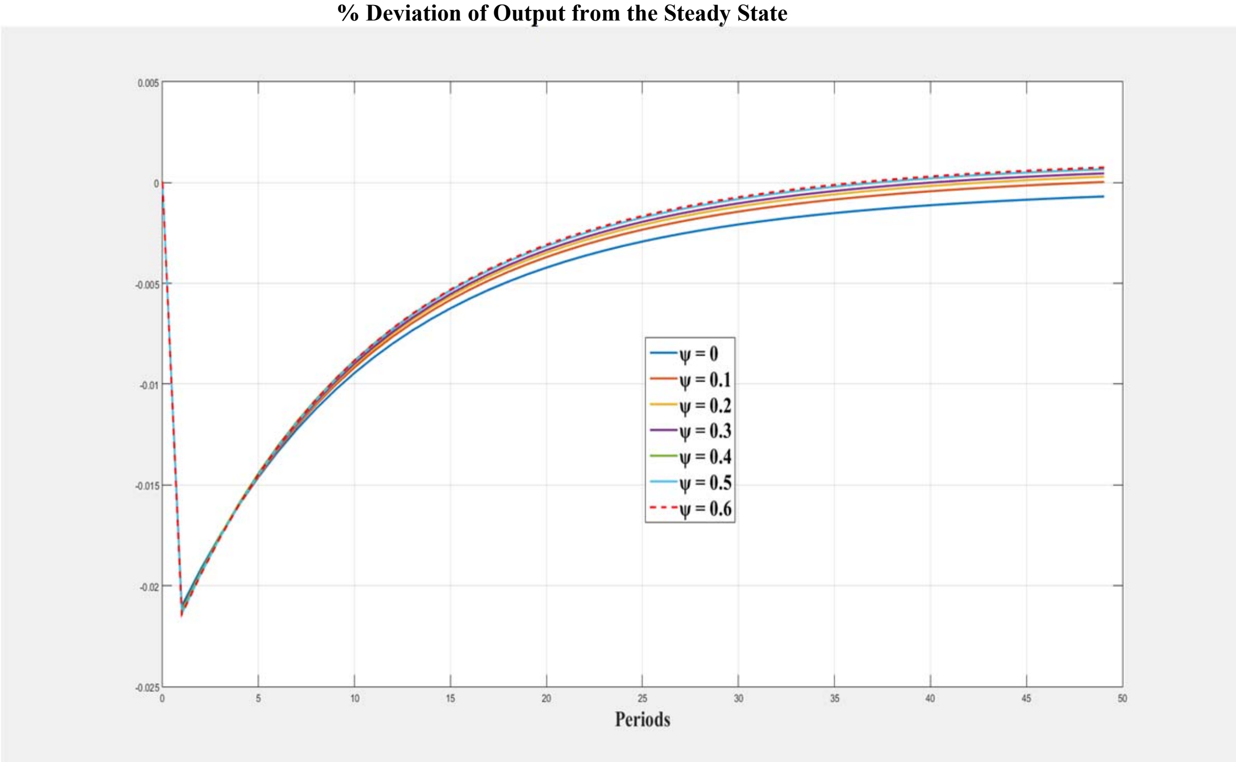

**Figure 1c**

**% Deviation of Inflation Rate from the Steady State**

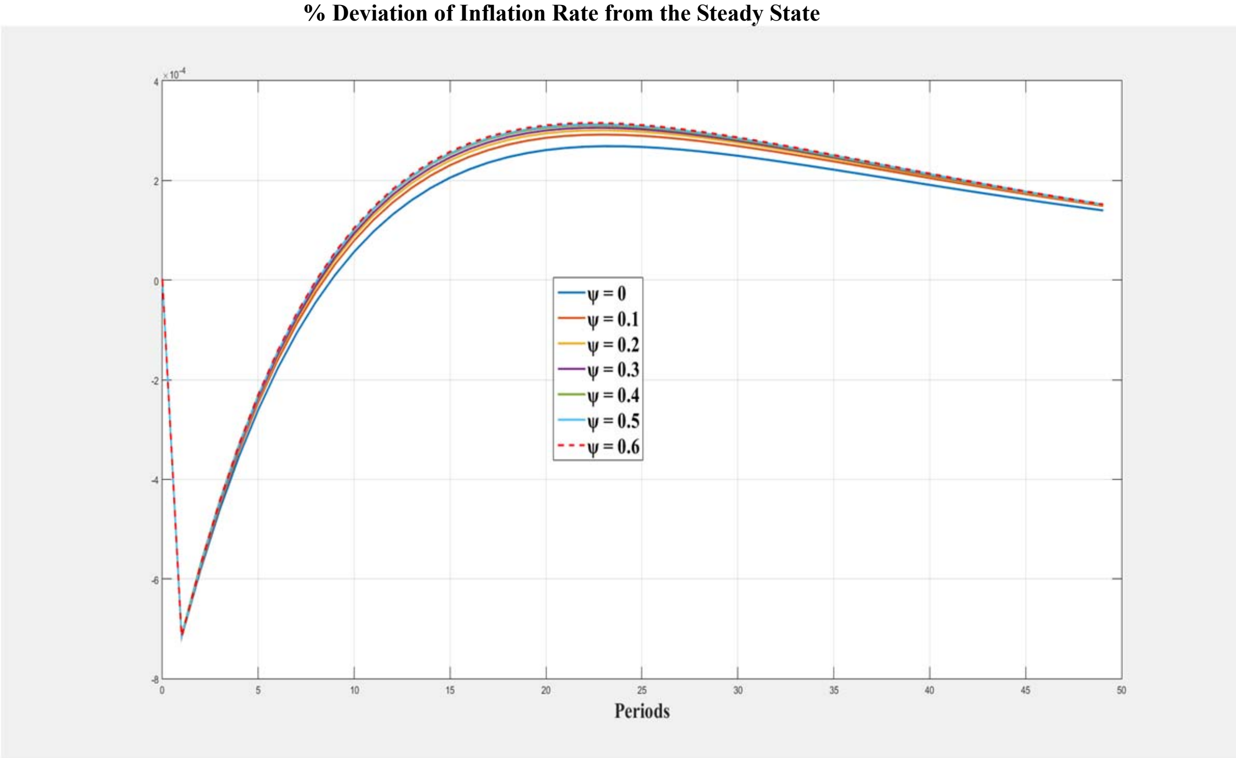


**Figure 1d**

**% Deviation of Nominal Interest Rate from the Steady State**

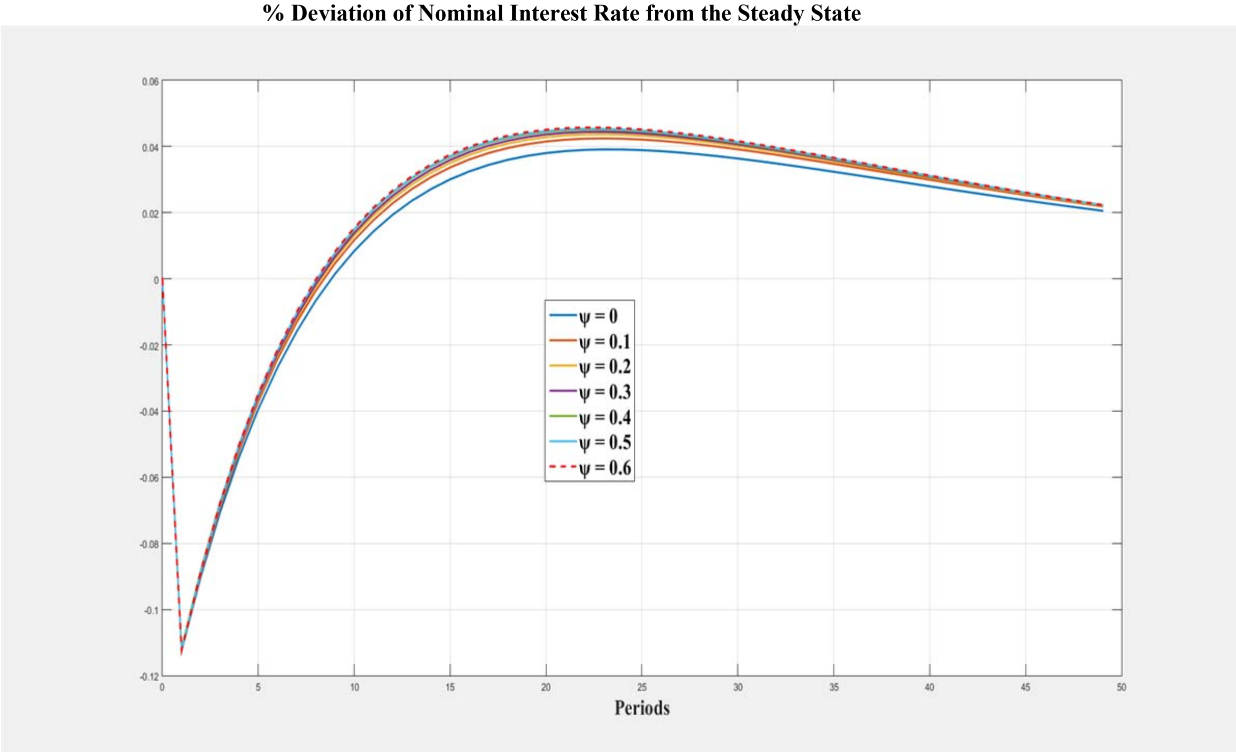

**Figure 1e**
**% Deviation of Welfare from the Steady State**

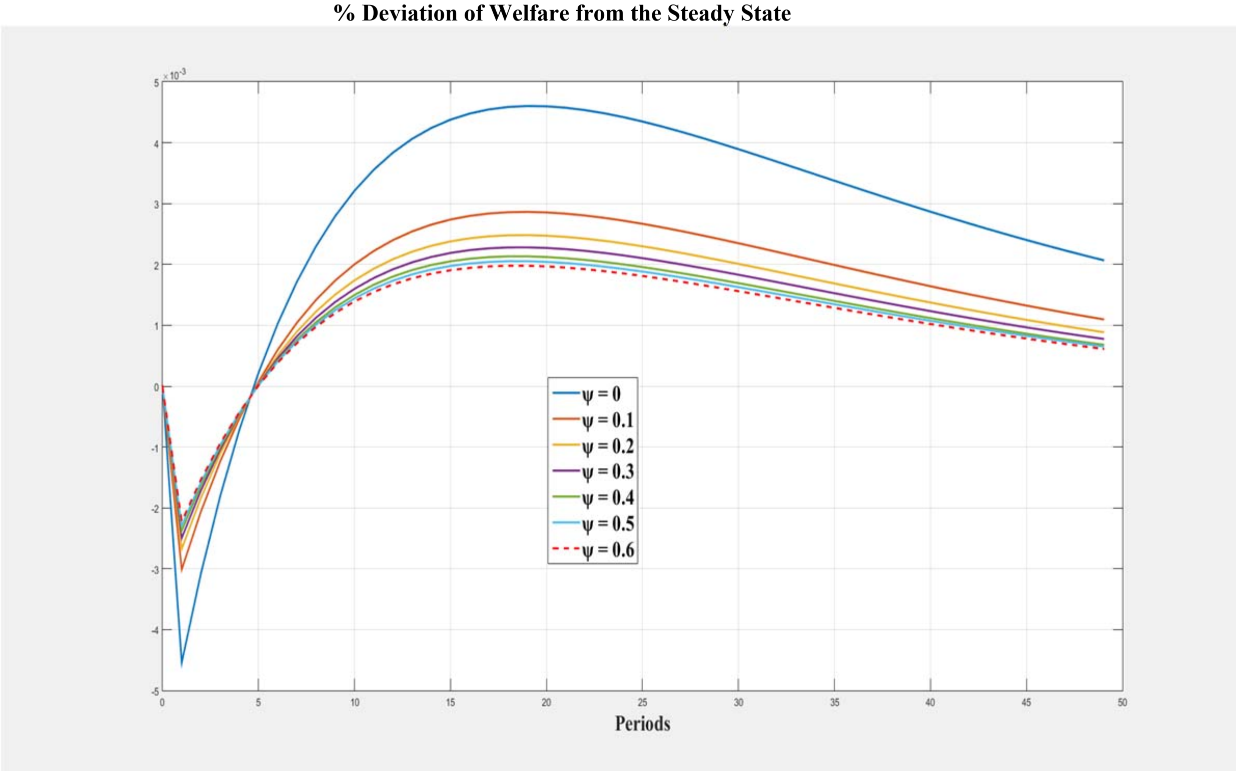

**Figure 2a: Carbon Taxes**
**% Deviation of Output from the Steady State without Carbon Taxes**

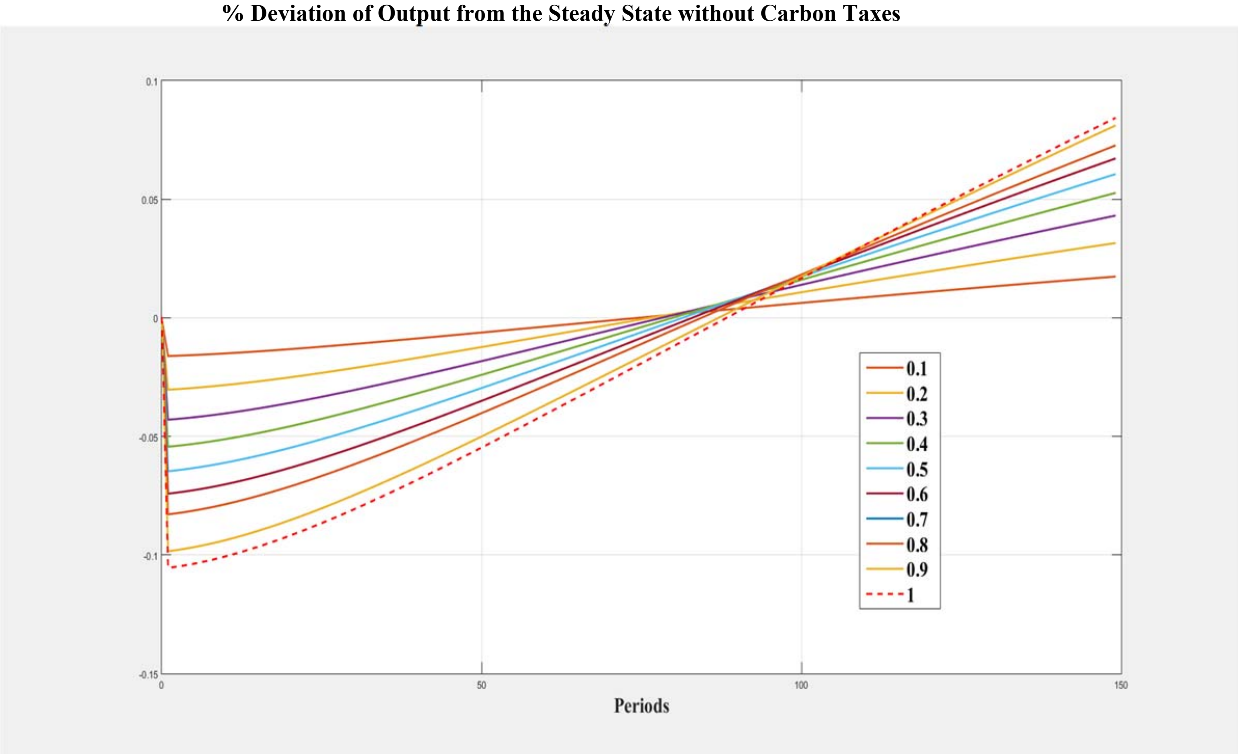


**Figure 2b: Carbon Taxes**
**% Deviation of Inflation Rate from the Steady State**

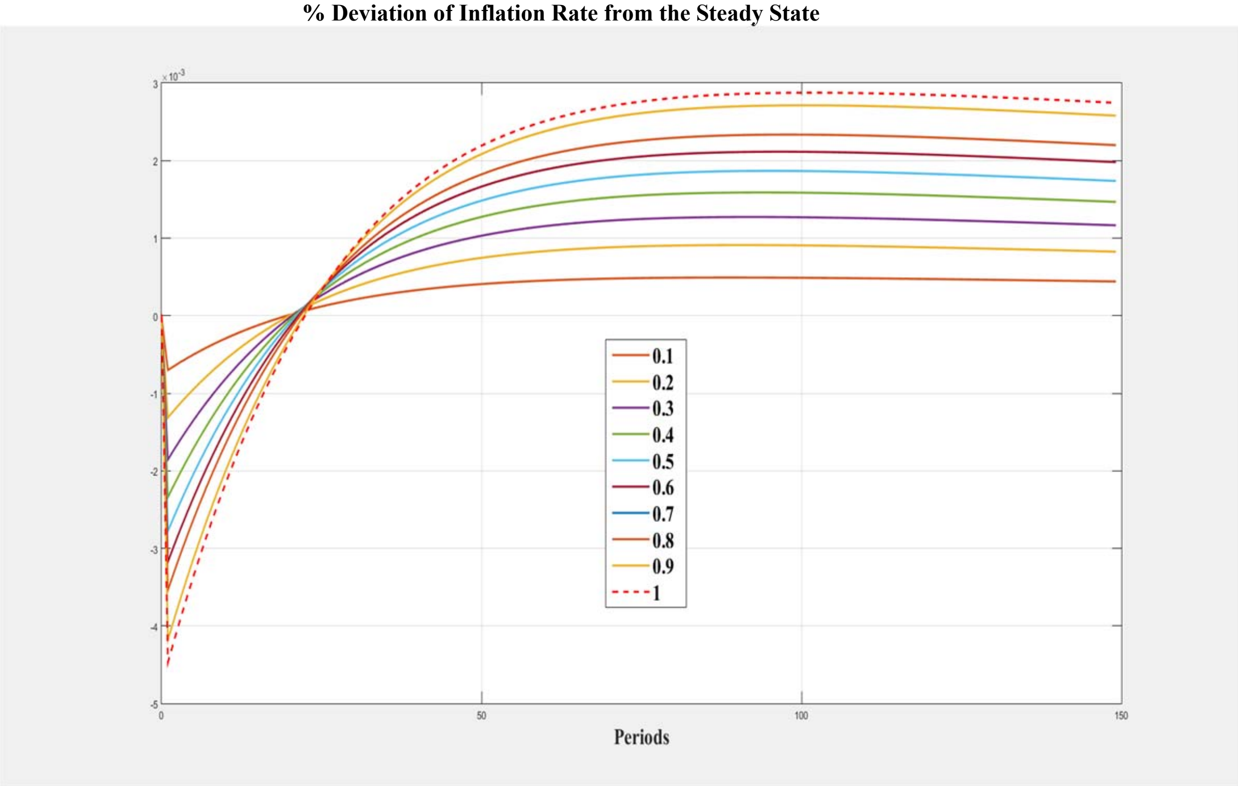

**Figure 2c: Carbon Taxes**

**% Deviation of Nominal Interest Rate from the Steady State**

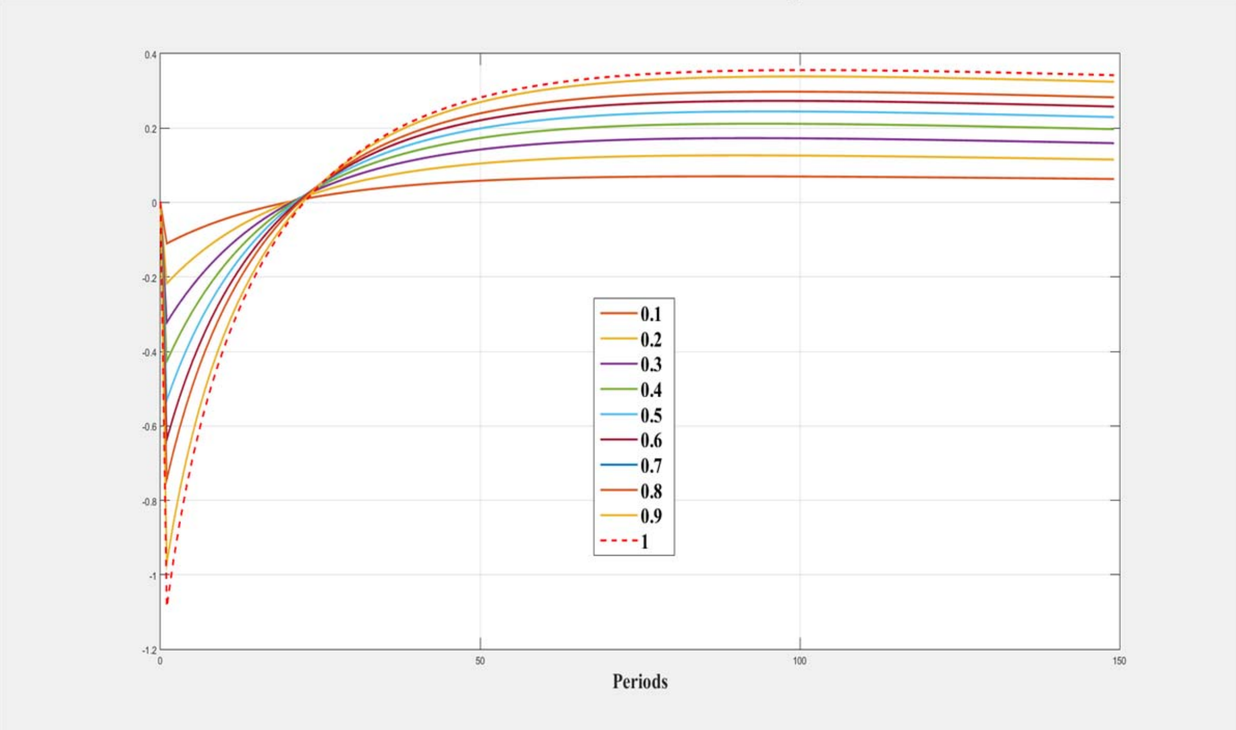

**Figure 3a: The Central Bank cares also about the output gap**
**% Deviation of Output from the Steady State**

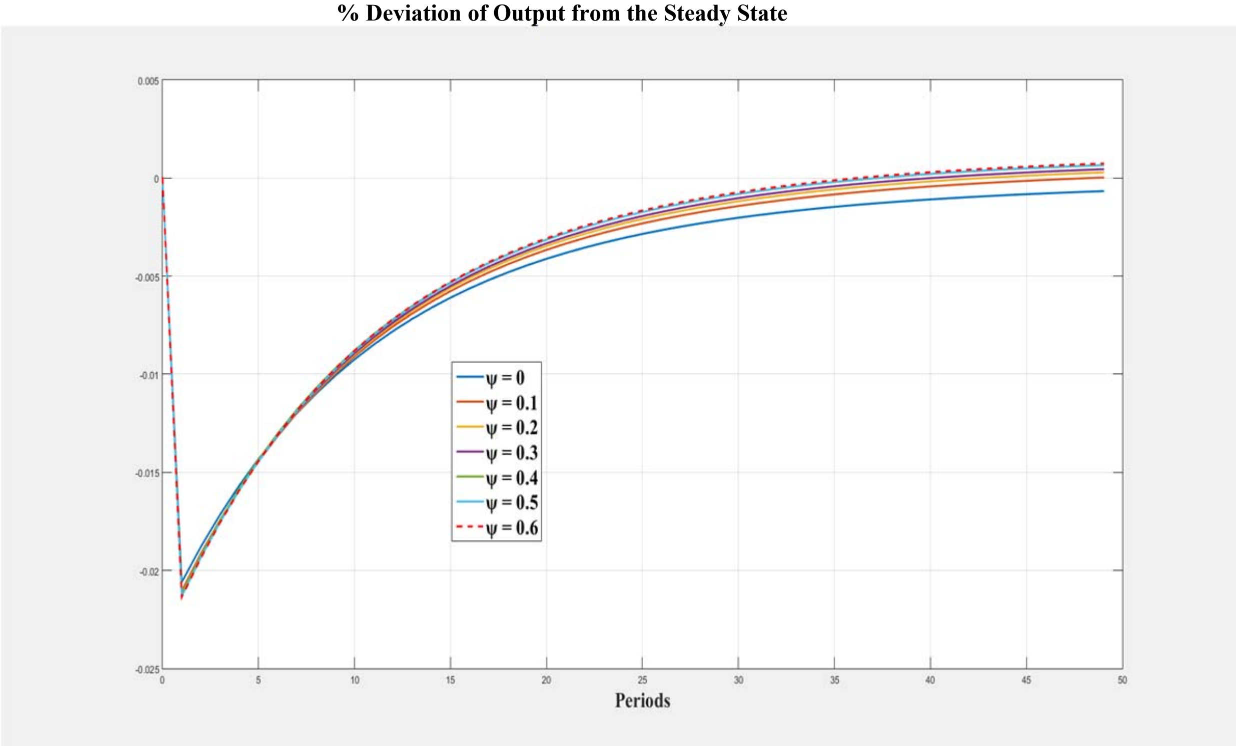


**Figure 3b: The Central Bank cares also about the output gap**
**% Deviation of Inflation Rate from the Steady State**

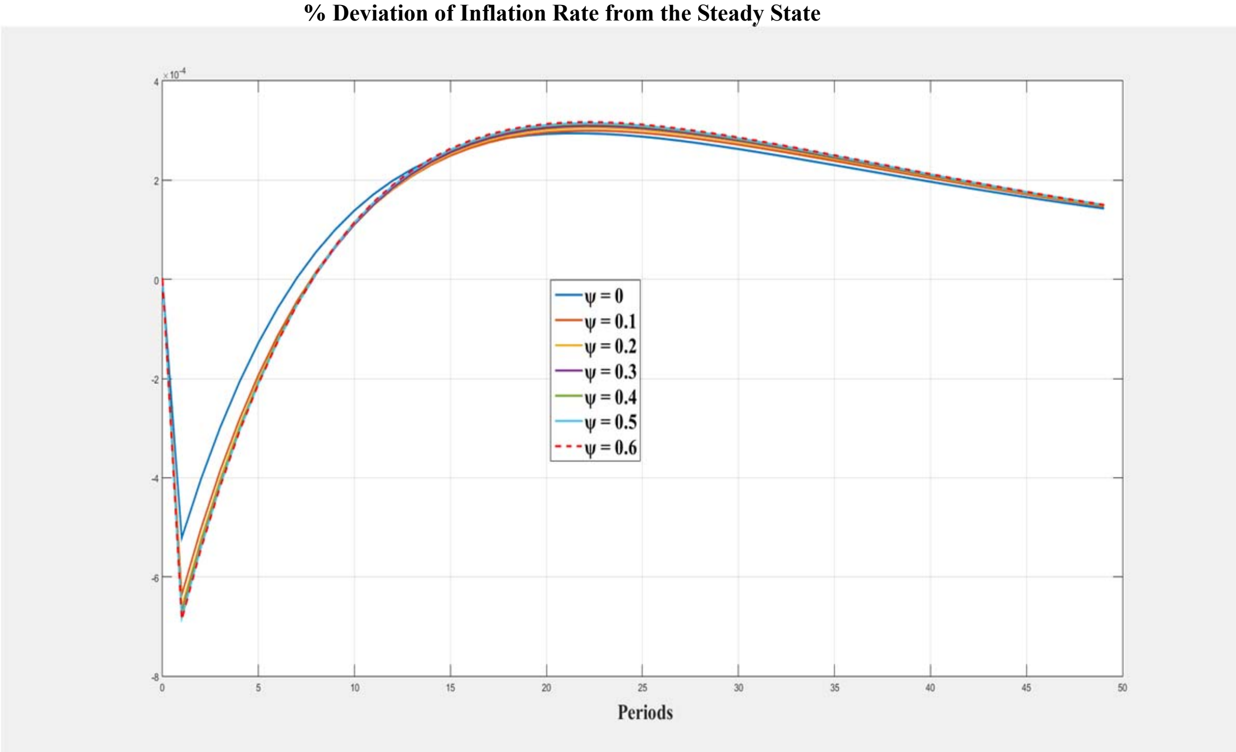

**Figure 3c: The Central Bank cares also about the output gap**

**% Deviation of Nominal Interest Rate from the Steady State**

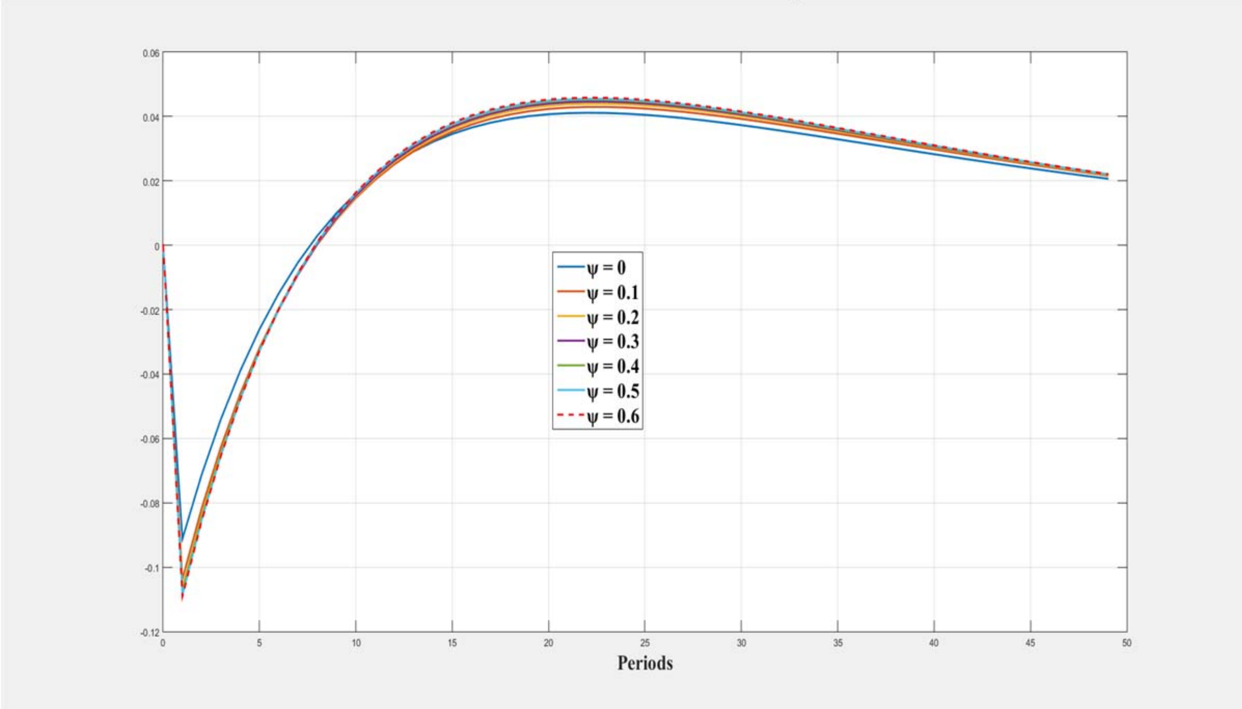


**Figure 3d: The Central Bank cares also about the output gap**

**% Deviation of Welfare from the Steady State**

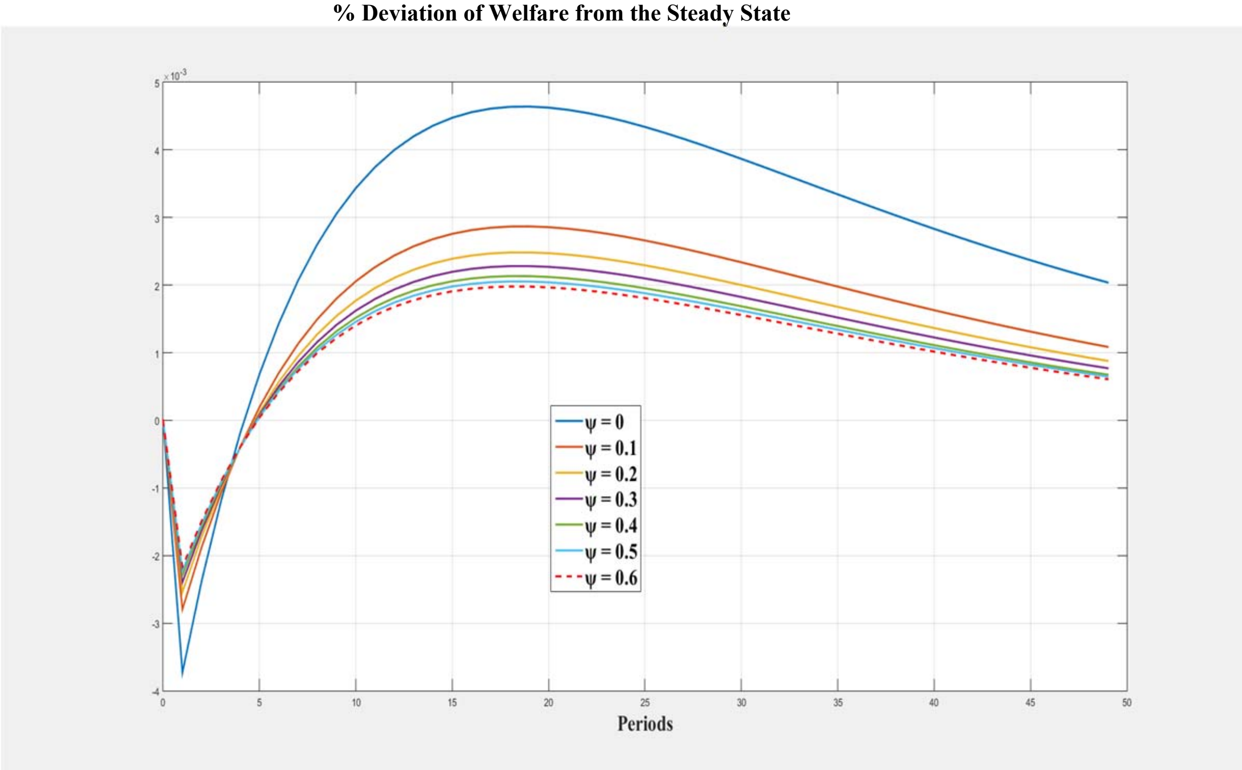

**Figure 4a: Steady State Inflation 2%**
**% Deviation of Output from the Steady State**

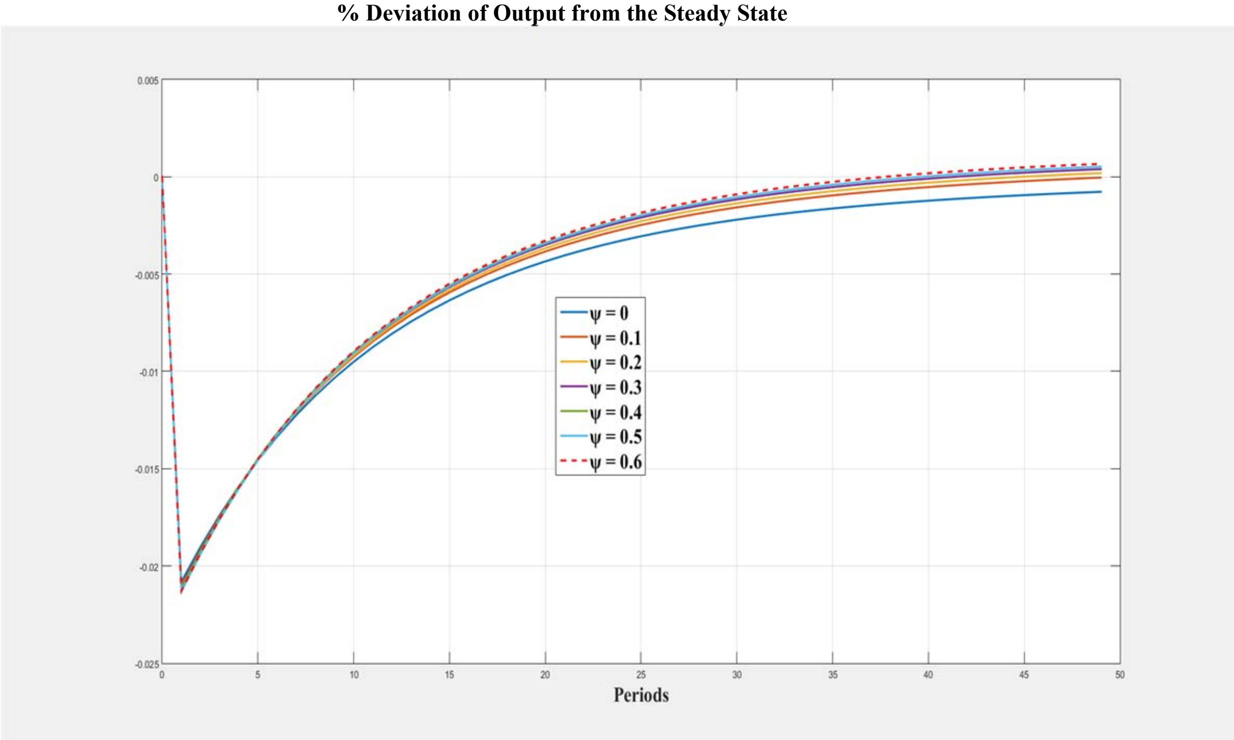


**Figure 4b: Steady State Inflation 2%**
**% Deviation of Inflation Rate from the Steady State**

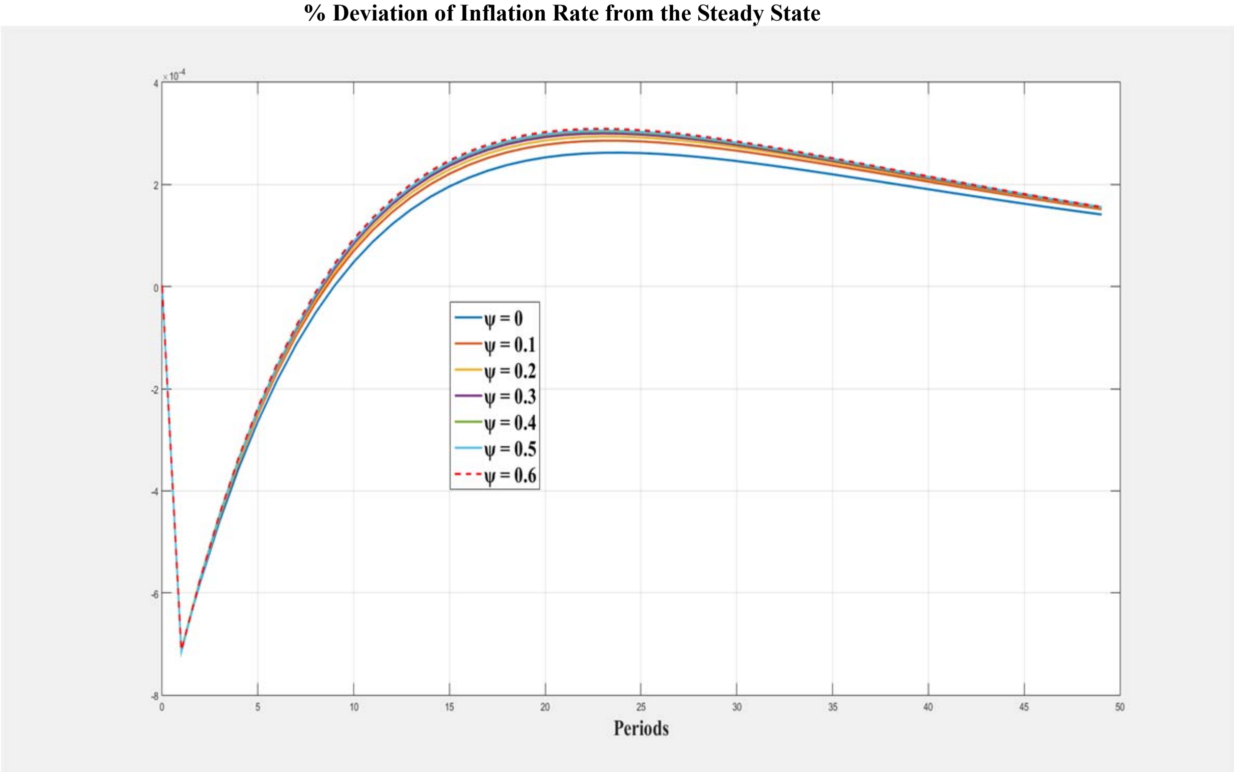

**Figure 4c: Steady State Inflation 2%**
**% Deviation of Nominal Interest Rate from the Steady State**

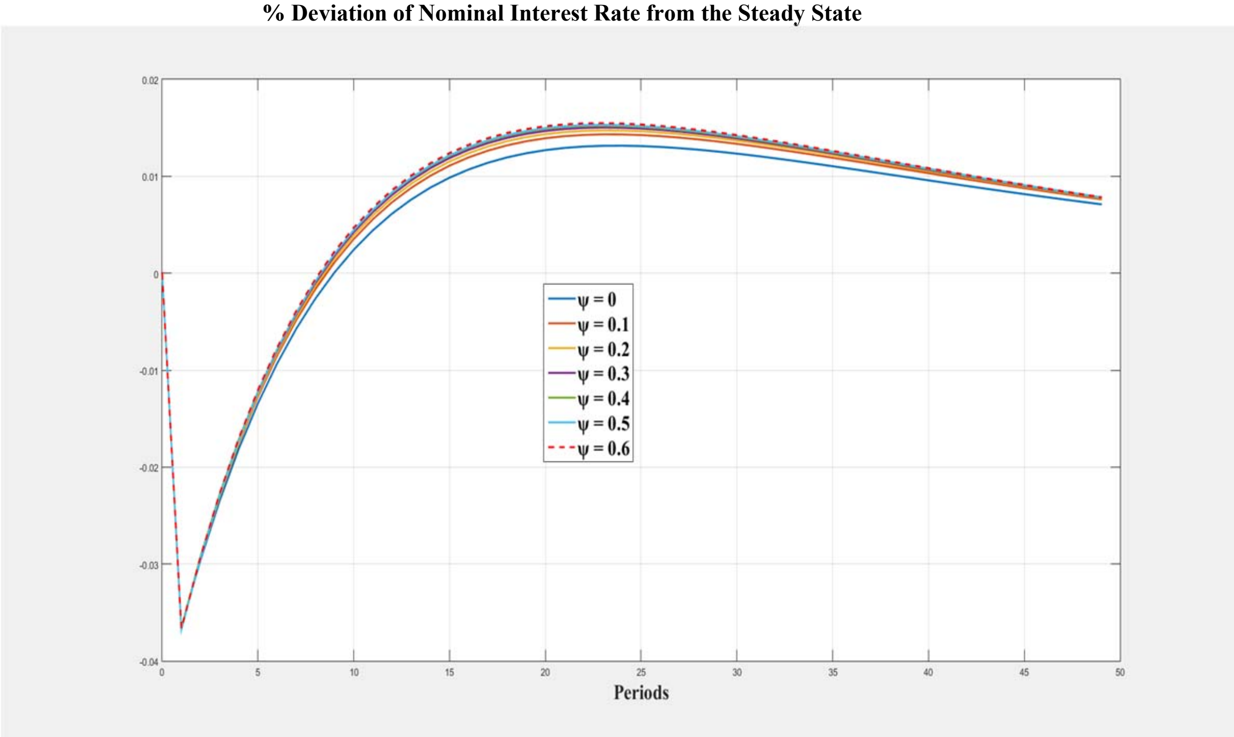


**Figure 4d: Steady State Inflation 2%**
**% Deviation of Welfare from the Steady State**