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ARTICLE

# CLIMATE POLICIES AND BUSINESS CYCLES: THE EFFECTS OF A DYNAMIC CAP

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**Abstract**
Emissions are directly linked to economic output and consequently subject to business cycle fluctuations. The present study analyses the interactions between climate policies and business cycles through the lens of a New Keynesian dynamic stochastic general equilibrium model. We compare a static cap-and-trade policy with a dynamically adjusting policy in terms of macroeconomic stabilisation, welfare and emissions price dynamics. The results of the quantitative evaluation suggest that a constant policy leads to lower aggregate volatility but is associated with larger welfare costs. In contrast, under the dynamic policy emissions prices and labour markets display less variations.

**Keywords:** Macroeconomic dynamics; environmental policy; cap-and-trade; business cycles

**JEL codes:** Q52; Q58; E32

## 1. Introduction

Market-based climate policy instruments such as emissions taxes or systems of emissions trading through permits are generally viewed as central tools in the efforts to mitigate global warming. Compared to regulations such as emissions standards, these tools offer market participants the possibility to flexibly adjust their emissions. Optimally, this should channel polluting activities into the most productive uses, which bear potentially larger abatement costs. Since emissions are closely tied to economic activity, the flexibility of the instruments also promotes smoother economic adjustments in response to aggregate fluctuations, supporting macroeconomic stability. Clearly, the main focus of climate policies is to achieve the medium to long-run emissions reduction targets in order to limit global warming.

However, as emphasised by Heutel (2012) the effects of climate policies for business cycle dynamics are non-negligible and an efficient design of policy instruments has the potential to reduce the welfare costs stemming from the dynamic implications of climate policies. As shown by Doda (2014), in most economies we observe that emissions vary with the business cycle and tend to be pro-cyclical. Therefore, the question of the dynamic effects of climate policy instruments is important for policymakers worldwide. In particular, because of the cyclicality of emissions, climate policies can interact with other short-term policies such as fiscal stabilisation measures and, through the inherent price effects, with monetary policy.

Accordingly, recent research has sought to understand the dynamic interactions between climate policies and the macroeconomy. In earlier studies, Fischer *et al.* (2011) and Heutel (2012) explore the cyclical properties of climate policies within real business cycle (RBC) frameworks. They highlight that the design of policy instruments determines emissions and emissions price dynamics and discuss the resulting implications for the aggregate economy. A key finding is that climate policies, conditional on the design (e.g. price or quantity instruments), contribute to macroeconomic stabilisation. Later research by Annicchiarico and Di Dio (2015) shows that these stabilising effects crucially hinge on the assumptions regarding market imperfections and frictions. They show that at high degrees of nominal rigidities, the stabilising effects of climate policies diminish. Subsequently, Annicchiarico and Di Dio (2017) examine the optimal environmental and monetary policy mix in a New Keynesian model. Their results imply that under frictions, the optimal policy mix strikes a balance between the opposing policy objectives. This clearly highlights the importance of frictions in this context.

However, the question of how climate policies and business cycle fluctuations affect emissions dynamics is relevant beyond a macroeconomic perspective, and has also direct implications for permit markets. Business cycle-related emissions dynamics are an important driver of allowance prices and can induce potentially large fluctuations in permit markets. As discussed by Koch *et al.* (2014) fluctuations in economic activity explain a substantial share of the price drops observed in European emissions trading markets between 2008 and 2013. Generally, these fluctuations can undermine the efficiency of emissions pricing by increasing the uncertainty in allowance prices for producers. In light of the high volatility in permit markets, different reforms of the cap-and-trade system have been proposed. As discussed by Fell and Morgenstern (2010) these measures have the potential to stabilise allowance prices and could thus contribute to a stable economic environment. The central idea behind most of the proposed reforms is to increase flexibility of the cap-and-trade system, either through flexible permit reserves, or by defining a price collar for allowances. Each of these reforms will, in turn, change emissions dynamics and consequently have an impact on the overall economy.

Against this backdrop, the present study contributes to the debate about the cyclical dynamics of emissions and climate policies by examining a dynamically adjusting cap-and-trade system from a macroeconomic perspective. Specifically, we develop a New Keynesian business cycle model along the lines of Annicchiarico and Di Dio (2015) and Fischer *et al.* (2011) that incorporates emissions into a framework with market imperfections and nominal rigidities. The model includes various sources of aggregate risk and takes labour market imperfections into account. Tailored to match stylized facts of the German economy between 2000 and 2015, the quantitative predictions of the model provide some insight into the advantages and disadvantages of a dynamic cap-and-trade regulation. In particular, we observe that a constant cap-and-trade leads to lower output, consumption and investment volatility, compared to dynamic regulation. In contrast, dynamic regulation is associated with less volatile allowance prices, more stable labour markets and appears marginally favourable in terms of welfare. The differences between the instruments can be attributed to the additional emissions flexibility under dynamic regulation that partially offsets the allowance price dynamics. From a policy perspective, these results suggest that a more flexible emissions policy is suitable to dampen allowance price dynamics, in exchange for an increase in output volatility.

The remainder of this article is structured as follows. Section 2 outlines the theoretical model and presents some basic intuition about the policy instruments under examination. Section 3 presents the calibration of the model. Section 4 shows the results of the policy comparison. Section 5 presents a sensitivity analysis regarding the role of frictions. Section 6 concludes.

## 2. Model

### 2.1. Structure of the model

The first studies of climate policies in the context of business cycles, for example, Fischer *et al.* (2011) and Heutel (2012), largely abstract from economic frictions and compare policy instruments within RBC frameworks. Subsequent studies, such as Annicchiarico and Di Dio (2015) build on New Keynesian models and emphasise the importance of nominal rigidities for the evaluation of climate policy instruments. Since the presence of frictions affects the behaviour of firms under uncertainty and generally alters aggregate dynamics, a comprehensive assessment of climate policy instruments should take them into account.

Hence, to shed light on the effects and implications of dynamic climate policy instruments, we use a New Keynesian model that features nominal price-setting rigidities. In addition, to account for other types of imperfections, we introduce nominal wage-setting frictions and investment adjustment costs. In modelling emissions, we follow the approach of Fischer *et al.* (2011), such that emissions evolve on the firm level from the use of a polluting intermediate input factor. In addition, to capture the adverse effects associated with climate change, we adopt the formalisation of Heutel (2012) and assume that the emissions stock in the atmosphere causes production losses.[1] The public sector is kept rather simple and we assume that the government implements climate policy in the form of a dynamic or a static emissions trading system. Within this framework, we consider four different types of aggregate risk, namely shocks to total factor productivity (TFP), demand shocks, government spending shocks and monetary policy shocks.

### 2.2. Households and labour markets

The economy is populated by a continuum of households $I \in [0,1]$. The representative household chooses consumption $c_t$, investment $x_t$ and labour supply $h_t$ in order to maximise expected lifetime utility:

$$E_0 \sum_{t=0}^{\infty} d_t \beta^t \left[ \frac{c_t^{1-\rho}}{1-\rho} - \psi \frac{h_t^{1+\chi}}{1+\chi} \right], \ \beta \in (0,1), \chi > 0, \tag{1}$$

where $\beta$ denotes the discount factor of households, $\psi$ denotes the disutility from labour, $\chi$ denotes the inverse Frisch elasticity and $\rho$ denotes the inverse of the elasticity of intertemporal substitution. In addition, $d_t$ represents a time preference shock that is formulated as an AR(1) process in logarithms and evolves according to $\ln(d_t) = \rho_d \ln(d_{t-1}) + \epsilon_{d,t}$, where $\epsilon_{d,t}$ denotes stochastic innovations. As explained by Gali (2013), these demand shocks are a common feature in New Keynesian models. In particular, shifts in time preferences are often used to capture fluctuations in household demand for consumption goods. Households face the following budget constraint:

$$c_t + x_t + b_t = \mathcal{W}_t h_t + R_{t-1} \frac{b_{t-1}}{\pi_t} + F_t + F_{u,t} + R_{k,t} k_t - T_t, \tag{2}$$

where $\mathcal{W}_t$ denotes the real remuneration of labour, $R_{k,t}$ denotes the real return of capital, inflation is denoted by $\pi_t = p_t / p_{t-1}$, $b_t$ denotes the stock of risk-free one-period government bonds, $R_t$ denotes the nominal interest rate and $T_t$ denotes a lump-sum tax. Households own firms and consequently receive profits $F_t$. In addition, wage markup profits from unions $F_{u,t}$ are transferred to households. As in Christiano *et al.* (2005), we introduce convex investment adjustment costs:

$$k_{t+1} = \left[ 1 - \frac{\kappa}{2} \left( \frac{x_t}{x_{t-1}} - 1 \right)^2 \right] x_t + (1-\delta) k_t. \tag{3}$$

Here, $\kappa$ captures the degree of adjustment costs and $\delta$ denotes the depreciation rate of physical capital.

The solution of the household problem yields the following first-order conditions for consumption, labour supply, bond holdings, capital and investment:

$$\lambda_t = c_t^{-\rho}, \tag{4}$$

$$\psi h_t^{\chi} = c_t^{-\rho} \mathcal{W}_t, \tag{5}$$

$$\lambda_t = \beta R_t E_t \frac{d_{t+1}}{d_t} \lambda_{t+1} \pi_{t+1}^{-1}, \tag{6}$$

[1] As explained by Fischer and Heutel (2013), there exist different approaches to incorporate emissions into dynamic stochastic general equilibrium (DSGE) models. The model developed by Fischer *et al.* (2011) abstracts from the damages of climate change and can thus be considered as a cost-effectiveness approach. In contrast, the framework of Heutel (2012) explicitly takes the adverse effects of climate change into account and provides an explicit rationale for climate policies.

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$$1 = q_t\left(1 - \frac{\kappa}{2}\left(\frac{x_t}{x_{t+1}} - 1\right)^2 - \kappa\left(\frac{x_t}{x_{t-1}} - 1\right)\frac{x_t}{x_{t-1}}\right) + \beta E_t \frac{d_{t+1}\lambda_{t+1}}{d_t\lambda_t} q_{t+1}\kappa\left(\frac{x_{t+1}}{x_t} - 1\right)\left(\frac{x_{t+1}}{x_t}\right)^2, \tag{7}$$

$$q_t = \beta E_t \frac{d_{t+1}}{d_t}\frac{\lambda_{t+1}}{\lambda_t}\left((1-\delta)q_{t+1} + R_{K,t+1}\right). \tag{8}$$

Here $\lambda_t$ denotes the marginal utility of an additional unit of consumption and $q_t$ denotes Tobin's $q$, which is defined as the value of installed capital relative to new capital. Labour market frictions are introduced through a union setup similar to Erceg *et al.* (2000). As in Sims and Wu (2021), we assume that households supply differentiated labour inputs to a continuum of unions $u \in [0,1]$. Unions sell labour inputs $h_{u,t}$to a labour packer at the price $w_{u,t}$ and remunerate households. Labour packers bundle differentiated labour inputs according To $h_{d,t} = \left(\int_0^1 h_{u,t}^{(\eta_w-1)/1} du\right)^{\eta_w/(\eta_w-1)}$. Labour packers operate under perfect competition and maximize profits, which yields the demand curves for each type of union labour relative to aggregate labour demand of the production sector $h_{d,t}$:

$$h_{u,t} = \left(\frac{w_{u,t}}{w_t}\right)^{-\eta_w} h_{d,t}, \tag{9}$$

where $\eta_w > 1$ The equation should be numbered as (9) denotes the elasticity of substitution between differentiated labour inputs and $w_t$ denotes the aggregate real wage. The aggregate real wage can be derived as ${w_t}^{1-\eta_w} = \int_0^1 w_{u,t}^{1-\eta_w} du$. Unions set wages to maximise the income of union members by maximising the transfer $F_{u,t}$ that union members receive. Wage inertia results from a nominal wage adjustment rigidity as in Calvo (1983).

Every period unions can adjust the wage with probability $1-\theta_w$. Given the chance that wages cannot adjust over a prolonged period, unions apply the stochastic discount factor of households $\Lambda_{t,t+k} = \beta\lambda_{i,t+k}/\lambda_{i,t}$ to maximise the expected present discounted value of their members' labour income. The optimal reset wage $w_t^*$ is common across unions and reads:

$$w_t^* = \frac{\eta_w}{\eta_w - 1}\frac{E_t\sum_{k=0}^{\infty}\theta_w^k\Lambda_{t,t+k}}{E_t\sum_{k=0}^{\infty}\theta_w^k\Lambda_{t,t+k}w_{t+k}^{\eta_w}p_{t+k}^{-1}h_{d,t+k}}. \tag{10}$$

Hence, in the absence of wage adjustment rigidities, unions will set wages as a constant markup $\eta_w/(\eta_w - 1)$ above the level of competitive wages. Under staggered wage setting, the aggregate real wage can be derived as a weighted average of currently adjusted and previous wages:

$$w_t^{1-\eta_w} = (1-\theta_w)w_t^{*1-\eta_w} + \theta_w\pi_t^{\eta_w-1}w_{t-1}^{1-\eta_w}. \tag{11}$$

### 2.3. Firms

Final output $y_t$ is produced under perfect competition. Final goods producers combine intermediate goods $y_{j,t}$ into final goods according to the CES aggregator $y_t = \left(\int_0^1 y_{j,t}^{(\varepsilon-1)/\varepsilon} dj\right)^{\varepsilon/(\varepsilon-1)}$, where $\varepsilon > 1$, denotes the elasticity of substitution between different varieties of intermediate goods. Profit maximisation of final goods producers yields a downward-sloping demand for intermediate goods $y_{j,t} = \left(p_{j,t}/p_t\right)^{-\varepsilon} y_t$. The demand for good $j$ is a decreasing function of the individual goods price $p_{j,t}$ relative to the overall price level of intermediate goods $p_t$. Given the functional forms, the aggregate price level is defined as $p_t = \left(\int_0^1 p_{j,t}^{1-\varepsilon} dj\right)^{1/(1-\varepsilon)}$.

Intermediate goods are produced by a continuum of intermediate goods-producing firms $j \in [0, 1]$ under monopolistic competition. As in Fischer *et al.* (2011), we assume that intermediate goods production requires a polluting input factor $m_{j,t}$, which firms buy on international markets at the price $p_{m,t}$. In particular, we assume that the Cobb–Douglas production function has constant returns to scale:

$$y_{j,t} = (1 - \Omega(s_t))A_t k_{j,t}^{\alpha} h_{j,t}^{1-\alpha-\gamma} m_{j,t}^{\gamma}, \quad 0 < \alpha < 1, \quad 0 < \gamma < 1, \tag{12}$$

where $A_t$ represents TFP. The dynamics of TFP are given by $\ln(A_t) = \rho_a \ln(A_{t-1}) + \epsilon_{a,t}$, where $\rho_a$ denotes the autocorrelation of the AR(1) process and $\epsilon_{a,t}$ denotes i.i.d. innovations in productivity that are assumed to be normally distributed. The parameters $\gamma$ and $\alpha$ denote the output elasticities with respect to the polluting intermediate input and to physical capital, respectively. The production losses associated with climate change are captured via $(1 - \Omega(s_t))$, where $s_t$ denotes the stock of pollution in the atmosphere. Here, we assume that the stock of pollution evolves according to $s_t = (1 - \delta_s)s_{t-1} + em_t + em_t^w$. The decay of atmospheric pollution is denoted by $\delta_s$, $em_t^w$ denotes emissions of the rest of the world, and for simplicity, we assume that the domestic flow of emissions $em_t$ is proportional to the aggregate utilisation of polluting inputs $em_t = m_t = \int_0^1 m_{j,t}\, dj$. With respect to the damages of climate change, we assume that the damage function is convex and given by $\Omega(s_t) = \omega_0 + \omega_1 s_t + \omega_2 s_t^2$.

Since intermediate goods-producing firms take factor prices as given, cost minimization yields the following optimality conditions for factor inputs:

$$R_{k,t} = mc_{j,t}\alpha(1 - \Omega(s_t))A_t k_{j,t}^{\alpha-1} h_{j,t}^{1-\alpha-\gamma} m_{j,t}^{\gamma}, \tag{13}$$

$$w_t = mc_{j,t}(1 - \alpha - \gamma)(1 - \Omega(s_t))A_t k_{j,t}^{\alpha} h_{j,t}^{-\alpha-\gamma} m_{j,t}^{\gamma}, \tag{14}$$

$$\widehat{p}_{e,t} = mc_{j,t}\gamma(1 - \Omega(s_t))A_t k_{j,t}^{\alpha} h_{j,t}^{1-\alpha-\gamma} m_{j,t}^{\gamma-1}, \tag{15}$$

where $mc_{j,t}$ denotes the marginal costs of the firm, specifically the cost of producing an additional unit of output. $\widehat{p}_{e,t}$ denotes the price of the polluting intermediate input including the emissions price. It is important to emphasise that we assume that individual firms ignore climate damages in their optimal choice of the polluting intermediate input. This assumption seems warranted given the coordination problem associated with the common good characteristics of global climate. Since conditions (13)–(15) are symmetric across firms, all firms choose the same capital-labour and intermediate inputs-labour ratios, so that marginal costs are the same for all firms, that is, $mc_{j,t} = mc_t$, given by:

$$mc_t = \left(\frac{1}{1 - \alpha - \gamma}\right)^{1-\alpha-\gamma} \left(\frac{1}{\alpha}\right)^{\alpha} \left(\frac{1}{\gamma}\right)^{\gamma} \frac{w_t^{1-\alpha-\gamma} R_{k,t}^{\alpha} \widehat{p}_{e,t}^{\gamma}}{(1 - \Omega(s_t))A_t}. \tag{16}$$

Intermediate goods producers set the price of intermediate goods $p_{j,t}$ in order to maximise discounted real profits. Since households own firms, they apply the stochastic discount factor of households defined as $\Lambda_{t,t+i} = \beta\lambda_{t+i}/\lambda_t$. As in Calvo (1983), we assume that every period only a fraction $(1 - \theta_p)$ of firms can adjust prices, while the other firms remain at their previously chosen prices. Hence, the optimal reset price $p_t^*$ is given by:

$$p_t^* = p_{j,t} = \frac{\varepsilon}{(\varepsilon - 1)} \frac{E_t \sum_{i=0}^{\infty} \theta_p^i \Lambda_{t,t+i} p_{t+i}^{\varepsilon} y_{t+i} mc_{t+i}}{E_t \sum_{i=0}^{\infty} \theta_p^i \Lambda_{t,t+i} p_{t+i}^{\varepsilon-1} y_{t+i}}. \tag{17}$$

In the absence of price-setting frictions ($\theta_p = 0$), firms charge a constant markup $\varepsilon/(\varepsilon - 1) > 1$ over marginal costs. For $\theta_p > 0$, the aggregate price level evolves as $p_t = \left[(1 - \theta_p)p_t^{*1-\varepsilon} + \theta_p p_{t-1}^{1-\varepsilon}\right]^{1/(1-\varepsilon)}$. This

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can be rewritten in terms of inflation as $1 = (1-\theta_p)\pi_t^{*1-\varepsilon} + \theta_p \pi_t^{\varepsilon-1}$, where $\pi_t = p_t/p_{t-1}$ and $\pi_t^* = p_t^*/p_t$. Furthermore, we can define the dispersion of intermediate goods prices as $v_t^p = (1-\theta_p)\pi_t^{*-\varepsilon} + \theta_p \pi_t^{\varepsilon} v_{t-1}^p$.

### 2.4. Environmental policies, public sector and market clearing

Finally, we turn to the implementation of environmental policies within the model. As is common, we model climate policies in a polluter-pays fashion and assume that intermediate goods-producing firms face a cap $\overline{em}$ on emissions. This implies that at the aggregate level, the utilisation of polluting intermediate inputs cannot exceed the cap, that is, $m_t \leq \overline{em}$.[2] We assume that intermediate goods producers trade permits in a perfectly competitive market. Hence, the permit price will correspond to the shadow value of an additional permit resulting from the optimization of firms under the emission constraint. From the firm's perspective, the price of the polluting intermediate input $\widehat{p}_{e,t}$ can be decomposed into the constant component $p_m$ and the environmental component $p_{e,t}$.

Since the goal of this study is to evaluate the performance of flexible emissions reduction policies, we consider a reaction function which defines a flexible emissions cap:

$$\overline{em_t} = \overline{em} + \nu_e \left( \frac{p_{e,t}}{\overline{p}_e} - 1 \right), \tag{18}$$

here $\nu_e$ denotes a reaction parameter that determines how strongly the number of emissions allowances adjusts in response to deviations of emissions prices from the price target $\overline{p}_e$. The case of $\nu_e = 0$ represents the classical fixed cap-and-trade system as modelled by Annicchiarico and Di Dio (2015) or Heutel (2012). In this situation, the number of emissions permits is constant and does not adjust in response to economic fluctuations.[3] With a dynamic adjustment of the cap ($\nu_e > 0$), emissions are still limited but allowed to vary with the economic situation. The regulation function, as depicted in (18), implies an increase in the emissions cap when the market price of permits increases above its target value $\overline{p}_e$. Conversely, the number of permits is reduced whenever the price of emissions falls below the target. This design choice corresponds to the idea proposed by Heutel (2012) to allow for pro-cyclical adjustments of the policy instruments.

To illustrate the general idea, it is helpful to abstract from the described frictions and to compare the constant rule (blue line) to the dynamic rule (orange line) in a static price-quantity diagram. Figure 1 depicts both regimes at three different demand levels (dashed lines). The demand schedule $D$ depicts a situation where both policies lead to the same price-quantity relation. Unsurprisingly, inelastic permit supply leads to larger price variations compared to the dynamic rule. This is evident for schedule $\overline{D}$, where the increase in the price of permits is larger under the constant rule. Since the number of permits increases under the dynamic rule, the price increase is dampened. This stylised illustration reveals that the dynamic rule can also be viewed as a cap-and-trade system with a price range that depends on the reaction parameter $\nu_e$. As emphasised by Koch *et al.* (2014), such a mechanism can potentially reduce distortions in permit markets.[4]

The government sector is kept simple: the government finances its spending $g_t$ via issuing debt $b_t$ and through lump-sum taxes $T_t$. In addition, the government receives the revenues from issuing permits $p_{e,t} em_t$. In real terms, the government flow budget constraint is given by:

$$g_t + R_{t-1} b_{t-1}/\pi_t = b_t + T_t + p_{e,t} em_t. \tag{19}$$

[2]We assume that firms must provide one unit of permits for one unit of emissions and that the cap is set so that the emissions constraint is constantly binding at the aggregate level, that is, $m_t = \overline{em}$. This means that the emissions price is determined by the excess demand of firms for emissions permits in relation to the available quantity of emissions permits.

[3]This is true, as long as the cap is strictly binding and if we exclude the option that firms can vary their abatement efforts.

[4]For further illustration, figure A.1 presents the results of numerical simulations of emission prices under both policies for 1000 periods. As can be inferred, a dynamic cap-and-trade significantly reduces price fluctuations and balances them within narrow bands.

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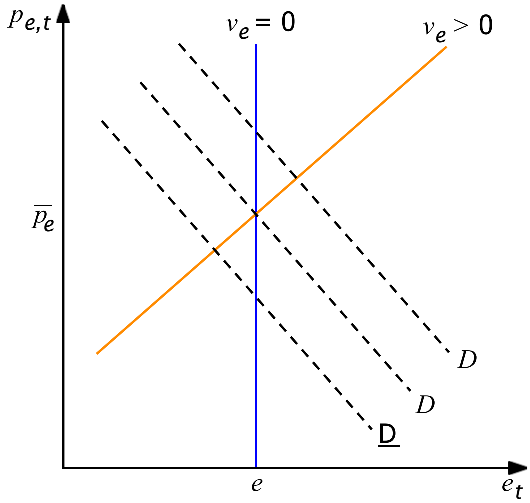


**Figure 1.** Stylised representation of the permit market under a constant cap and a dynamic cap regime.

To ensure the long-run sustainability of government debt, the government follows the fiscal rule:

$$T_t = \overline{T} + \phi_T \left( b_t - \overline{b} \right), \tag{20}$$

where $\overline{T}$ denotes steady state lump-sum taxes and $\phi_T$ captures the intensity of adjustments in taxes in response to deviations of the stock of government debt from the debt target $\overline{b}$. Similar to the formulation of Perotti (1999), government expenditures are stochastic and given by:

$$\ln\left(g_t\right) = \left(1 - \rho_g\right) \ln(\overline{g}) + \rho_g \ln\left(g_{t-1}\right) + \epsilon_{g,t}. \tag{21}$$

Here, $\overline{g}$ denotes an exogenous target of government consumption. The parameter $\rho_g$ captures the persistence of i.i.d. innovations in government consumption, denoted by $\epsilon_{g,t}$. Accordingly, government expenditures will be subject to stochastic fluctuations around the target $\overline{g}$.

Monetary policy is conducted by the central bank, which has the objective to maintain price stability and reacts to deviations of inflation from inflation target $\overline{\pi}$. We assume that the central bank applies the simple Taylor rule:

$$\frac{R_t}{\overline{R}} = \left( \frac{R_{t-1}}{\overline{R}} \right)^{\gamma_R} \left( \frac{\pi_t}{\overline{\pi}} \right)^{\gamma_\pi (1-\gamma_R)} \exp(\epsilon_{R,t}). \tag{22}$$

Here, $\gamma_\pi$ denotes the coefficient that captures the reaction of the central bank to deviations of inflation from the inflation target and $\gamma_R$ captures the persistence in nominal interest rates. The steady state nominal interest rate is denoted by $\overline{R}$ and $\epsilon_{R,t}$ denotes stochastic innovations in the nominal rate.

Finally, in equilibrium factor and goods markets clear. Clearing for capital and intermediate input markets implies: $k_t = \int_0^1 k_{j,t} dj$ and $m_t = \int_0^1 m_{j,t} dj$. Taking the demand for intermediate goods into account, integration yields $\int_0^1 y_{j,t} dj = \int_0^1 \left( \frac{p_{j,t}}{P_t} \right)^{-\varepsilon} y_t dj = y_t v_t^p$, where $v_t^p$ evolves dynamically as defined above. Aggregate final output can thus be written as:

$$y_t = (1 - \Omega(s_t)) A_t k_t^\alpha h_t^{1-\alpha-\gamma} m_t^\gamma / v_t^p. \tag{23}$$

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In equilibrium, we find that $v_t^p > 1$ if $\theta_p > 0$, which reflects the inefficiency of aggregate output associated with price rigidity. The resource constraint of the economy requires:

$$y_t = x_t + c_t + g_t + p_{m,t} m_t. \tag{24}$$

From the demand function for differentiated labour (9) in combination with aggregate labour supply given by $\int_0^1 h_{u,t}\, du = h_t$, we get $h_t = h_{d,t} v_t^w$, where $v_t^w$ denotes wage dispersion. By definition we have $v_t^w = \int_0^1 \left(\frac{w_{u,t}}{w_t}\right)^{-\eta_w} du$, such that the dynamics of wage dispersion are described by:

$$v_t^w = (1-\theta_w)\left(\frac{w_t^*}{w_t}\right)^{-\eta_w} + \theta_w \pi_t^{\eta_w} \left(\frac{w_t}{w_{t-1}}\right)^{\eta_w} v_{t-1}^w. \tag{25}$$

## 3. Solution and calibration

In total, the model outlined above consists of 33 equations in 33 unknowns. Since the model does not admit an analytic solution we employ numerical solution methods. As common in the literature, we obtain a local solution around the deterministic steady state of the model using a second-order approximation approach.[5] In this numerical exercise, we follow the conventions and specify the model parameters in line with central macroeconomic characteristics. Specifically, the underlying model parameters are set to capture key aspects of the German economy.[6] Given the focus on emissions, key parameters are set to match the German GDP share of energy expenditures, as well as the ratios of private consumption and government consumption to GDP.[7] Parameters which define preferences, frictions and the stochastic processes are adopted from recent studies of the German economy. The underlying parameter values are summarised in table 1.

In accordance with the average capital share in Germany between 1991 and 2019, we set $\alpha = 0.3$. In order to calibrate the production elasticity of polluting intermediate inputs, we follow Fischer *et al.* (2011) and set $\gamma = 0.1$, which corresponds to the average total energy supply relative to GDP as reported by the International Energy Agency (IEA) for the German economy over the period from 1991 to 2019. The quarterly depreciation rate of physical capital is set to $\delta = 0.025$. The parameters which capture household preferences are adopted from Hristov (2016). Hence, we set the discount factor of households to $\beta = 0.998$, the inverse of the elasticity of intertemporal substitution to $\rho = 2$ and the inverse of the Frisch elasticity of labour supply to $\chi = 1.5$. Labour disutility denoted by $\phi$ is set in order to reach an average working time of $\overline{h} = 0.33$ in the deterministic steady state. The steady-state levels of government debt $\overline{b}$ and government consumption $\overline{g}$ are set to match a debt-to-GDP ratio of 0.6 and a government consumption to GDP ratio of 0.19.[8] Based on Drygalla *et al.* (2020), the parameter $\phi_T$ that captures the strength of the reaction of lump-sum taxes to deviations of government debt from target is set to 0.38. With respect to monetary policy, we follow the same study and set $\gamma_\Pi = 1.47$. The degree of interest rate smoothing is set to $\gamma_R = 0.91$.[9]

[5]Note that in order to apply the solution method, we have to rewrite (9) and (16) in a recursive fashion. For this purpose, we need to define additional auxiliary variables.

[6]Note that the aim of the present study is to understand the effects and implications of dynamic emissions pricing policies. Therefore, the model abstracts from several empirically relevant features that are not directly related to the research question. While this limits the model's ability to fit empirical data, it allows for a comprehensive and transparent assessment of the topic.

[7]The respective data series are obtained from the Federal Statistical Office of Germany (destatis) and cover the period between 1991 and 2019. Data on the total energy supply, defined as domestically produced energy in metric tons of oil equivalent (toe) relative to GDP, cover the period 1991–2019 and are obtained from the International Energy Agency (IEA).

[8]The debt ratio is set in accordance with the Maastricht criteria and the share of government consumption relative to GDP matches the German data between 1991 and 2019.

[9]This choice is broadly comparable with other studies. However, as pointed out by a referee, in light of a common monetary policy in the Euro Area, a higher interest rate persistence appears warranted to limit the monetary policy reactions to domestic inflation. Hence, as a robustness check, we set $\gamma_R = 0.99$ and scale the standard deviation of interest rate shocks accordingly. While this affects the quantitative differences between a constant and a dynamic policy, the qualitative results in terms of volatility and welfare do not change. The corresponding results are available upon request.

**Table 1.** Summary of model parameter values

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Households: | | | |
| $\beta$ | 0.998 | $\psi$ | 55.8 |
| $\chi$ | 1.5 | $\rho$ | 2 |
| $\theta_w$ | 0.83 | $\eta_w$ | 4 |
| Firms: | | | |
| $\delta$ | 0.025 | $\kappa$ | 3.90 |
| $\gamma$ | 0.10 | $\theta_p$ | 0.86 |
| $\alpha$ | 0.30 | $\varepsilon$ | 6 |
| Policy: | | | |
| $\gamma_{\Pi}$ | 1.47 | $\gamma_R$ | 0.91 |
| $\overline{\Pi}$ | 1.01 | $\phi_T$ | 0.38 |
| $\frac{b}{y}$ | 0.6 | $\frac{g}{y}$ | 0.19 |
| Environment: | | | |
| $\delta_s$ | 0.0021 | $\omega_0$ | 1.3950*e*-3 |
| $\omega_1$ | −6.6722*e*-6 | $\omega_2$ | 1.4647*e*-8 |
| Stochastic processes: | | | |
| $\sigma_a$ | 0.0049 | $\rho_a$ | 0.87 |
| $\sigma_d$ | 0.0033 | $\rho_d$ | 0.85 |
| $\sigma_g$ | 0.0039 | $\rho_g$ | 0.70 |
| $\sigma_R$ | 0.0011 | | |

As shown by Annicchiarico and Di Dio (2015) frictions and especially nominal rigidities play an important role for the evaluation of climate policies. To address this, we employ commonly used parameter values in the baseline specification, and later assess the parameter sensitivity with respect to price-setting frictions. In the baseline specification, parameters that capture price markups and pricing frictions are set in accordance with Jondeau and Sahuc (2008), such that $\theta_p = 0.86$ and $\epsilon = 6$, which corresponds to a markup of 1.2. Based on Gadatsch *et al.* (2016), the wage-setting frequency of unions $\theta_w$ is set to 0.83 and the elasticity of substitution between labour types is set to $\eta_w = 4$. This implies a wage markup in the deterministic steady state of 1.33. In line with the estimation results of Drygalla *et al.* (2020), we set the investment adjustment cost parameter to $\kappa = 3.9$. The parameters capturing the dynamics of the emissions stock and the associated damages from climate change are taken from Heutel (2012). The decay rate of pollution is set to $\delta_s = 0.0021$, the parameters of the damage function are $\omega_0 = 1.3950e-3$, $\omega_1 = -6.6722e-6$ and $\omega_2 = 1.4647e-8$.[10] The German economy is responsible for roughly 2 per cent of global emissions, we set $em^w$ accordingly and assume that global emissions are constant. Lastly, the stochastic processes are specified based on the estimation results of Drygalla *et al.*

[10]As explained in Heutel (2012), the decay rate corresponds to a half-life of atmospheric carbon dioxide of 83 years and the damages are specified based on the DICE-2007 model.

**Table 2.** Deterministic steady state, percentage changes relative to the no-policy scenario

| Scenario | $y$ (Δ%) | $c$ (Δ%) | $x$ (Δ %) | $h$ (Δ %) | $e$ (Δ %) | $s$ (Δ %) | $\Omega$ (Δ%) |
|---|---|---|---|---|---|---|---|
| No-policy | 0.375 | 0.215 | 0.058 | 0.333 | 0.031 | 745.291 | 0.005 |
| Policy | 0.370 | 0.213 | 0.057 | 0.333 | 0.028 | 743.800 | 0.005 |
| | (−1.38) | (−0.58) | (−1.38) | (−0.09) | (−10.00) | (−0.20) | (−0.50) |

Note: Parameter values correspond to table 1.

(2020) and Hristov (2016). Accordingly, we set $\rho_d$= 0.85, $\rho_a$= 0.87 and $\rho_g$ = 0.70 with the corresponding standard errors $\sigma_d$ = 0.0033, $\sigma_a$ = 0.0049, $\sigma_g$ = 0.0039 and $\sigma_R$ = 0.0011.

## 4. Business cycle dynamics

In order to understand the effects of climate policies and to assess the implications of a dynamic instrument, we model a 10 per cent emissions reduction relative to the no-policy scenario and compare the static to the dynamic instrument. In the policy scenarios, we assume that the revenues from emissions permits are redistributed lump-sum to households, which corresponds to a reduction in lump-sum taxes. In all computations, we set $\nu_e$= 0.01, all other parameter values are reported in table 1. We begin with a brief assessment of the steady-state effects of emissions reductions. Afterwards, we study the model dynamics in terms of impulse response functions. This exercise provides an intuition for the underlying emissions dynamics and illustrates the differences between supply-side and demand-side induced fluctuations. Finally, we examine how policy instruments affect macroeconomic volatility and welfare and assess the sensitivity of these results to parameter variations.

Table 2 presents the changes in aggregates of the deterministic steady state for a 10 per cent emissions reduction relative to the no-policy scenario. The static effects do not differ between the two policies and we observe a decline in aggregate output of around 1.4 per cent. This output decline implies a decline in aggregate consumption of around 0.6 per cent and a decline of aggregate investment of 1.4 per cent. Labour hours are marginally reduced by about 0.1 per cent. As can also be inferred, in the long run the emissions stock reduces by 0.2 per cent, which mitigates the damages from climate change by around 0.5 per cent. While the implementation of climate policy yields the desired emissions reduction, it overall exerts adverse economic effects. This observation is generally not too surprising. Since the emissions share of Germany is relatively small, the unilateral emissions reduction is insufficient to significantly mitigate damages from climate change. Using similar frameworks, Annicchiarico and Di Dio (2015) and Heutel (2012) report comparable results for the United States, a country with a substantially larger emissions share. Furthermore, one must bear in mind that the results crucially hinge upon the concrete specification of the damage function.

While both policy instruments perform identically in a static environment, their implications for aggregate dynamics differ. To examine these differences, we next compare the impulse response functions under both policies. Figure 2 depicts the impulse response functions for a one standard deviation TFP shock over a 20-quarter horizon.[11] In general, the implementation of climate policies dampens aggregate dynamics compared to the no-policy scenario. Furthermore, there are no qualitative differences in aggregate dynamics between the constant policy (solid line) and the dynamic policy (dashed line). However, we observe quantitative differences in the development of macroeconomic aggregates between the policies. First, note that output, consumption, investment and the stock of physical capital display slightly stronger dynamics under the dynamic policy. Second, we observe that the

[11]Due to the high serial correlation of the TFP shock and the presence of adjustment frictions, the depicted series do not fully converge within 20 quarters.

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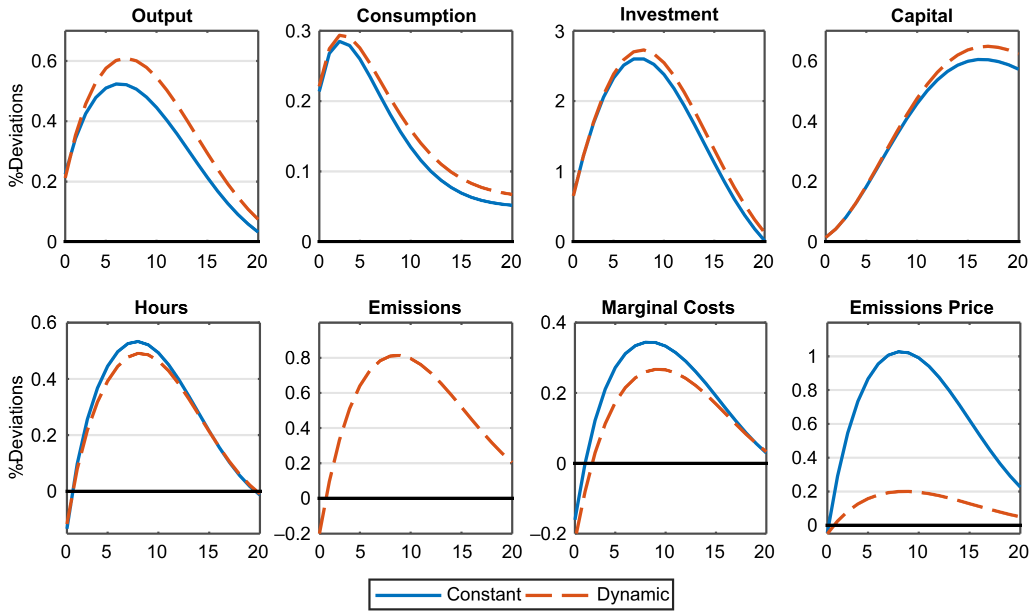


**Figure 2.** Impulse responses to a one standard deviation TFP shock, in percentage deviations from the stochastic steady state of the model. The underlying parameter values correspond to table 1.

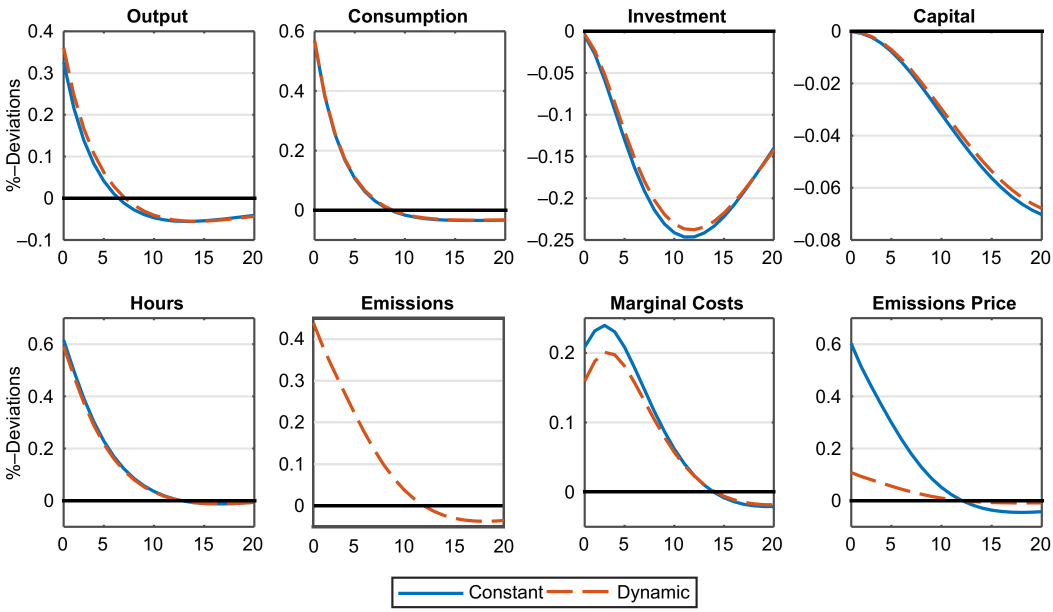


**Figure 3.** Impulse responses to a one standard deviation preference shock, in percentage deviations from the stochastic steady state of the model. The underlying parameter values correspond to table 1.

responses of hours worked, emissions prices and marginal costs are more pronounced under the constant policy.

These differences in aggregate dynamics between the policies result from the dampened increase in the emissions price under the dynamic policy. The temporary increase in productivity reduces the marginal costs of goods production, which induces firms to lower goods prices and expand output.

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However, due to price rigidities goods prices cannot fully adjust and remain at a sub-optimally high level, which dampens the increase in aggregate demand. The smaller increase in emissions prices under the dynamic policy translates into a smaller increase in marginal costs, such that firms are better able to deal with the nominal inefficiencies. Hence, the reaction of output, consumption, investment and consequently the capital stock is stronger. In contrast, labour hours react more strongly under the constant policy because firms cannot adjust the utilisation of polluting intermediate inputs.

To corroborate further on this, we now turn to a demand-side shock. Figure 3 shows the impulse response functions of the model to a one standard deviation time preference shock over a 20-quarter horizon. The ordering of variables is identical to the previous figure. The main difference compared to the supply-side shock is an immediate increase in the demand for intermediate inputs on the firm level in response to the increase in household demand. To meet the additional demand, firms have to rapidly expand production and therefore immediately employ additional labour. We observe that the increased consumption demand of households leads to an increase in output on impact. This increase is somewhat larger under the dynamic policy. The observed consumption dynamics do not differ between the two policies, but the decline in investment and the capital stock is slightly larger under the constant policy. We also observe a slightly stronger reaction of hours worked under the constant policy. These differences can again be rationalised by the differences in emissions and emissions price dynamics. While the dynamic policy allows firms to accommodate the expansion by utilising additional intermediate inputs, the constant rule does not. This mirrors in emissions price dynamics, with a substantially larger price increase under the constant rule, which ultimately explains the less pronounced output dynamics. The graphical examination generally confirms the intuition gained earlier that a dynamic cap- and-trade system significantly dampens the dynamics of emissions prices in response to aggregate shocks. The dynamic policy gives firms an additional margin of adjustment, such that firms are better able to increase output and are less reliant on adjustments in labour and capital markets. This generally amplifies output dynamics and tends to dampen labour market dynamics under the dynamic rule. To quantify these differences, we now compare the unconditional moments generated by the model. Table 3 presents the

**Table 3.** Comparison of macroeconomic aggregates and welfare between the constant and the dynamic policy for a 10 per cent emissions reduction (relative to no-policy scenario)

| **Scenario** | $y$ (Δ %) | $c$ (Δ %) | $x$ (Δ %) | $h$ (Δ %) | $e$ (Δ %) | $s$ (Δ %) | $\Omega$ (Δ %) |
|---|---|---|---|---|---|---|---|
| No-policy | 0.3740 | 0.2138 | 0.0578 | 0.3333 | 0.0312 | 745.2395 | 0.0046 |
| Constant | 0.3688 | 0.2125 | 0.0570 | 0.3330 | 0.0281 | 743.7533 | 0.0045 |
| | (−1.39) | (−0.60) | (−1.41) | (−0.07) | (−10.00) | (−0.20) | (−0.49) |
| Dynamic | 0.3688 | 0.2125 | 0.0570 | 0.3330 | 0.0281 | 743.7532 | 0.0045 |
| | (−1.38) | (−0.58) | (−1.38) | (−0.09) | (−10.00) | (−0.20) | (−0.49) |
| **Scenario** | $\sigma_y$ | $\sigma_c$ | $\sigma_x$ | $\sigma_h$ | $\sigma_e$ | $\sigma_p$ | **Δ Welfare** |
| No-policy | 0.0191 | 0.0128 | 0.0655 | 0.0164 | 0.0438 | 0.0000 | |
| | (1.00) | (0.67) | (3.42) | (0.86) | (2.29) | (0.00) | |
| Constant | 0.0142 | 0.0113 | 0.0583 | 0.0160 | 0.0000 | 0.0406 | −0.41% |
| | (1.00) | (0.80) | (4.10) | (1.13) | (0.00) | (2.86) | |
| Dynamic | 0.0179 | 0.0125 | 0.0640 | 0.0162 | 0.0343 | 0.0085 | −0.39% |
| | (1.00) | (0.70) | (3.58) | (0.90) | (1.92) | (2.27) | |

Note: Welfare effects are reported in terms of consumption equivalent variations (in %). Standard deviations and relative standard deviations of macroeconomic variables are based on a second-order approximation of the HP-filtered theoretical moments of the model. Parameter values correspond to table 1.

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mean, volatility and the relative volatility of aggregate variables, as well as the unconditional welfare, for both policy regimes. The underlying figures are obtained from the approximated theoretical moments of the model. The welfare effects are expressed in terms of consumption equivalent variations relative to the no-policy scenario.

As can be inferred from the upper part of the table, differences between the policies with regards to changes in output, consumption, investment and hours are relatively small. In general, the decline tends to be a magnitude smaller under the dynamic rule. For example, the decline in output is roughly 0.01 percentage points smaller and the decline in consumption and investment is about 0.02 percentage points smaller. Even though these differences are not large, they reveal that the dynamic rule reduces output and consumption losses in a stochastic environment. Since both policy rules yield identical emissions reductions, the differences clearly result from the different dynamics in emissions and emissions prices. The dynamic rule gives firms the ability to adjust more flexibly in response to shocks, which helps to stabilise output and consumption.

With regards to the effects on aggregate volatility, the differences between the two rules are larger. As expected, both policies reduce emissions volatility and by construction, the constant rule fully eliminates fluctuations in emissions. As a consequence, the volatility of emissions prices is substantially lower under the dynamic rule than under the constant rule. This finding confirms the earlier reasoning and indicates one potentially important argument in favour of a dynamic cap-and-trade system. Furthermore, we find that both policies stabilise output, consumption and investment relative to the no-policy scenario. The finding that the implementation of a cap-and-trade system dampens aggregate volatility is in line with previous studies, for example, Annicchiarico and Di Dio (2015) or Fischer *et al.* (2011). While the dampening effect on macroeconomic volatility is stronger under the constant policy, a different picture emerges with respect to relative volatility. Generally, we find that the volatility of consumption and investment relative to the volatility of output is smaller under the dynamic policy. This indicates that the stabilising effect on investment and consumption is comparably stronger under the dynamic policy.

Lastly, the welfare losses compared to the no-policy scenario amount to roughly 0.4 per cent, with a 0.02 percentage points smaller welfare loss under the dynamic rule. The small welfare difference between the two policies results from the additional flexibility of firms adjustments under the dynamic policy. While this figure appears relatively small, the difference translates into roughly 320 million Euros per year measured in terms of real private consumption in Germany in 2015. However, given this number, one must bear in mind that the analysis abstracts from any costs associated with the implementation of the dynamic policy. Since such a policy requires at least active monitoring of permit markets, the implementation costs would generally be higher than under the constant rule.

## 5. Sensitivity analysis

Finally, as argued by Annicchiarico and Di Dio (2015) the possibility to adjust goods prices plays a crucial role in assessing the welfare effects of climate policy instruments. As laid out above, the observed welfare differences between the two policy rules are due to their different effects on emission prices and overall dynamics and reflect how goods-producing firms can adapt to climate policies. The extent to which more flexible emissions and less volatile emissions prices affect welfare therefore depends crucially on the ability of firms to respond to aggregate shocks. Hence, to better understand the observed welfare effects, it is helpful to examine the role of nominal rigidities in more detail. To this end, we conduct a sensitivity analysis and compute the welfare effects of a 10 per cent emissions reduction for both policies with a varying degree of nominal price and wage rigidities, namely $\theta_p = \theta_w \in [0, 0.88]$.

The results of this exercise are depicted in figure 4. In general, the observed welfare losses range from 0.39 to 0.41 per cent, which is in the order of magnitude of the effects reported for the baseline specification. Under fully flexible prices $\theta_p = \theta_w = 0$, the welfare losses under both policies are virtually identical. In this case, which is relatively close to a standard RBC model with investment adjustment

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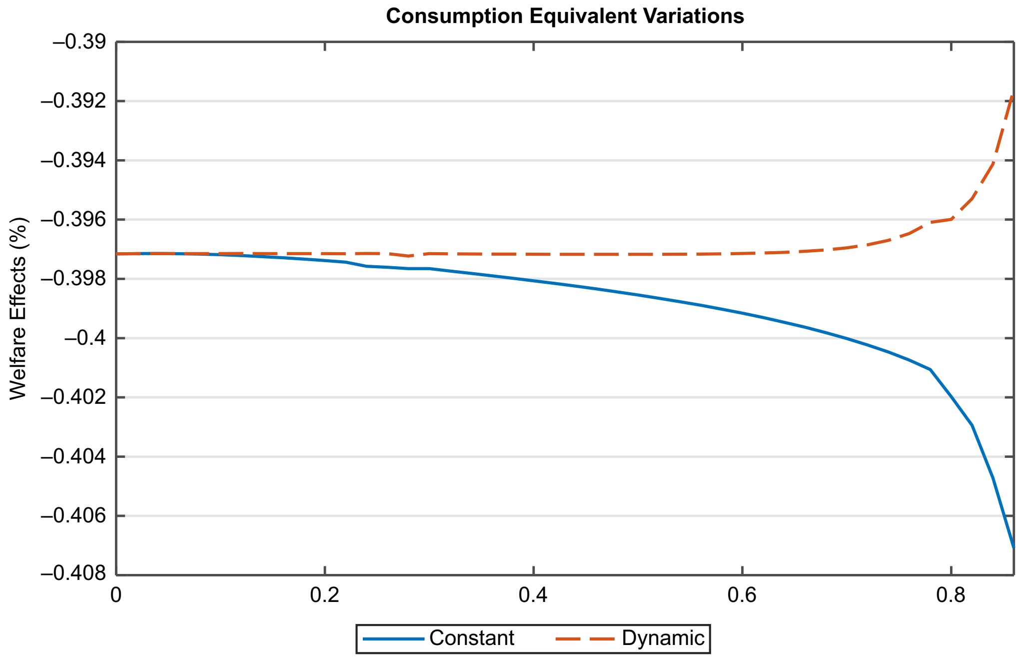


**Figure 4.** Welfare effects of a 10 per cent emissions reduction for $\theta_p = \theta_w \in [0, 0.88]$, the remaining parameter values correspond to table 1. Welfare effects are reported in terms of consumption equivalent variations (in per cent) relative to the no-policy scenario.

costs, firms are able to respond to shocks via adjustments of goods prices. Hence, the additional flexibility under the dynamic policy yields no additional welfare gains. However, with increasing degrees of price and wage rigidities, firms' ability to adjust the utilisation of polluting intermediate inputs becomes more important. At around values of $\theta_p = \theta_w \approx 0.18$, welfare losses under the constant policy begin to increase, while welfare losses under the dynamic policy remain relatively constant. At values of $\theta_p = \theta_w \approx 0.80$ the welfare difference between the two policies approach the effects as reported in table 3. Hence, the observed welfare differences can clearly be attributed to the presence of nominal rigidities in the present model. Nevertheless, since parameter values within this range have generally broad empirical support and also reflect recent estimates for the Germany economy, the mechanism depicted here highlights potentially important aspects for the design of climate policy instruments.

## 6. Conclusion

More and more countries are implementing market-based climate policy instruments to mitigate global warming. These instruments have systemic effects on the macroeconomy, affecting both long-term and short-term dynamics. A central concern about market-based policies is the potential fluctuations in emissions prices in response to aggregate shocks. During recessions, the market price of emissions might drop substantially below the desired target, while during an expansion prices might rise too fast. Large fluctuations in emissions prices reflect fundamental economic uncertainties and can undermine the efficiency of climate policies. Therefore, different reform concepts, that promise to stabilise permit markets, have been proposed. These concepts directly address the dynamic interactions between the state of the economy and emissions dynamics and propose specifically designed dynamic rules for climate policy adjustments. These dynamic rules inevitably affect aggregate dynamics and influence macroeconomic stability.

Given these dynamic interactions, the present study examines how dynamic climate policy rules affect emissions price dynamics and the aggregate economy. Based on a New Keynesian DSGE model with several sources of uncertainty and various types of frictions, we compare the economic performance of constant and dynamic policy rules. According to the results of our numerical simulations, a constant cap-and-trade system is associated with lower volatility in output, consumption, investment and emissions. On the contrary, we observe that a dynamic cap-and-trade system leads to lower volatility in labour markets and allowance prices. This confirms that the desired stabilisation of permit markets can be achieved through dynamic rules. Moreover, a welfare comparison indicates a small advantage in favour of dynamic rules.

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## A. Appendix

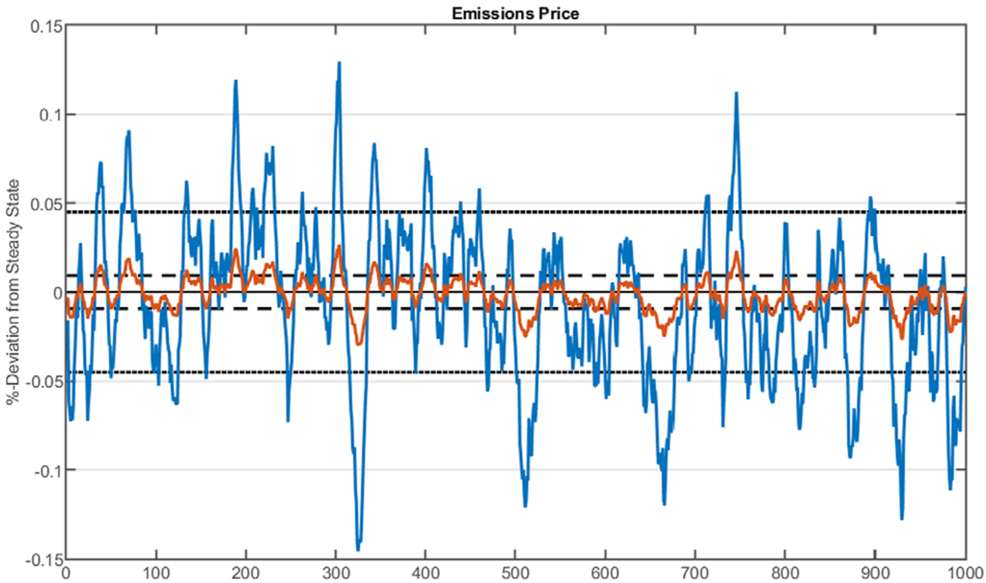


**Figure A.1.** Simulated time paths of emissions prices for 1000 periods under a constant cap-and-trade (blue) and a dynamic cap-and-trade (orange). The dotted lines indicate the standard deviation under the constant rule. The dashed lines indicate the standard deviation under the dynamic rule

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