International Transmission of the Business Cycle and Environmental Policy*

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Abstract

This paper presents a baseline dynamic general-equilibrium model of environmental policy for a two-country economy and studies the international transmission of asymmetric shocks considering two different economy-wide greenhouse gases (GHG) emission regulations: a carbon tax and a cap-and-trade system allowing for cross-border exchange of emission permits. We find that international spillovers of shocks originated in one country are strongly influenced by the environmental regime put in place. The cross-border reaction to shocks is found to be magnified under a carbon tax. The pattern of trade and the underlying monetary regime influence the cross-border transmission channels interacting with the environmental policy adopted.

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1 Introduction

This paper presents a baseline general-equilibrium theoretical model with two-interdependent economies to highlight the international aspects of environmental policies. In particular, the paper addresses the following fundamental questions. What is the role of different environmental policy regimes in shaping the transmission of shocks in open economies? What is the dynamic behavior of an economy where countries are tied by international trade and by a common environmental policy regime? How does the pattern of trade interact with the underlying environmental policy? What happens if countries share the same currency?

The impact of unilateral mitigation policies and the strategic interactions between different countries committed to regulate emissions are topics largely debated among environmental economists. Computable General Equilibrium (CGE) models and Integrated Assessment Models (IAMs) are at present the main tools used to estimate costs and benefits of different policies in climate change research. Nevertheless, only recently, another class of environmental models have been emerging in macroeconomics in which a growing attention is given to the role of uncertainty and of the business cycle in influencing the performance of environmental regulation.[1]

Methodologically this strand of literature on the interaction between climate actions and the business cycle is based on dynamic stochastic general equilibrium (DSGE) models and involves the systematic application of intertemporal optimization methods and of the rational expectations hypothesis that determine the behavior of consumption, investment and factor supply for different states of the economy.[2] As proposed by Khan et al. (2019) we use the acronym E-DSGE to refer to dynamic stochastic general equilibrium models with environmental regulation.

For a long time environmental aspects have been neglected by the so-called "New Consensus Macroeconomics", as remarked by Arestis and González-Martínez (2015).[3] Relevant examples of E-DSGE models include Chang et al. (2009), Angelopoulos et al. (2013), Heutel (2012), Fischer and Springborn (2011), Bosetti and Maffezzoli (2014), Annicchiarico and Di Dio (2015) and Dissou and Karnizova (2016). However, the international dimension of climate actions has so far been neglected in the context of E-DSGE models, therefore the study of the interaction among environmental policy, international trade and economic uncertainty has still remained unexplored. As far as we know, the only exception in this direction is the contribution by

[1] For an accurate and comprehensive empirical analysis of the cyclical relationship between output and carbon dioxide emissions, see Doda (2014); for an interesting investigation on the behavior of emissions at business cycle frequency in response to different technology shocks, see Khan et al. (2019).

[2] Dynamic general equilibrium models are also fruitfully used for the study of energy and climate policies in deterministic analyses abstracting from the business cycle. See Conte et al. (2010), Annicchiarico et al. (2018, 2017), and Bartocci and Pisani (2013). This last paper is the only one exploring the international dimension of energy policies analysing the effects of both unilateral and simultaneous interventions throughout the EU.

[3] However, the role of uncertainty in shaping the performance of different environmental regulations has been widely addressed in the literature. Following the seminal paper by Weitzman (1974), several contributions study the performance of alternative environmental policies, accounting for uncertainty. See, e.g., Quirion (2005) and Jotzo and Pezzey (2007). On the relationship between economic fluctuations and environmental policy, see e.g. Kelly (2005).

Ganelli and Tervala (2011) who explore the international transmission of a unilateral implementation of a more stringent mitigation policy in the context of a New Keynesian - E-DSGE model of a global economy, however, they neither consider the international transmission of shocks commonly studied in the business cycle literature, nor the role played by the underlying environmental regime in shaping fluctuations and cross-border spillovers.[4]

With this paper we aim at filling this gap of this strand of literature, enriching the methodology based upon choice-theoretic stochastic models, by embodying New Keynesian aspects, such as nominal rigidities, imperfect competition and forward-looking price-setting, consistently with Annicchiarico and Di Dio (2015, 2017), and developing the analysis in an open economy model with two interdependent countries, Home and Foreign. With this model in hand, we are able to explore the international transmission of shocks commonly considered in the business cycle literature, and to study the role played by different environmental regimes in shaping the dynamic response of the economy. In particular, we focus on two policies for constraining emissions: a carbon tax and a cap-and trade, where emission permits are traded between countries. We explore the dynamic response of the economy to three shocks hitting only Home, namely (i) technology shocks on total factor productivity (TFP), (ii) shocks on the risk-free interest rate set by the monetary authorities and (iii) shocks on the quality of capital. The first shock directly affects the supply side of the economy (supply shock), while the second shock influences aggregate demand (demand shocks). The shock on the quality of capital, instead, is a hybrid shock, altering directly and simultaneously both the supply and the demand schedules of the economy. This shock transmits through the economy like a financial shock. To further shed light on the influence exerted by environmental policies on the international transmission channels of shocks, we also look at the spillover effects under different assumptions regarding the pattern of trade and the underlying monetary regime.

Our main results can be summarized as follows. The international transmission of shocks from one economy to another proves to be affected by the underlying environmental regime, and both the magnitude and the sign of the cross-border spillover effects crucially depend on the source of uncertainty. Contrary to what expected, the adoption of an international cap-and-trade regime does not exacerbate the international spillover of shocks. The adoption of a carbon tax, instead, tends to amplify the spillover effects. In particular, we observe major differences between the two regimes in response to monetary policy shocks. In this case cross-

[4]Yet the international dimension of climate policies has been the object of several studies in the field of environmental economics. For an overview on the relationships linking trade, economic growth and environment, see Copeland and Taylor (2003). For a survey of studies focussing specifically on environmental policy analysis in open economy, see e.g. Rauscher (2005). A substantial body of literature, mostly related to CGE models, tackle problems relative to carbon leakage, strategic behaviors (e.g. Burniaux and Martins 2012 and Babiker 2005), and the loss of competitiveness (see Carbone and Rivers, 2017). For a general overview on the relationship between environmental regulation and competitiveness, see e.g. Dechezleprêtre and Sato (2017). Furthermore the effects of climate policies in open economy have been extensively analysed and estimated, mainly by means of different simulations scenarios, in the context of integrated assessment models (IAMs). Thank to their regional or global structure these models are well suited for a study of the overall costs of different policy instruments. For an overview on global scale IAMs, see Weyant (2017).

border spillovers are still magnified under a carbon tax. However Home and Foreign outputs are positively correlated under the carbon tax regime, while the correlation turns out to be negative and stronger under the cap-and-trade regime where, the cross-border exchange of emission permits determines a reallocation of production from one country to the other.

When we solve the model assuming a trade pattern such that Home and Foreign goods are imperfect complements the international spillovers tend to be larger, as well as under a higher degree of openness. More interestingly, under both assumption we observe large differences across environmental regimes with the carbon tax always giving rise to stronger spillover effects.

Finally, we show how the role played by environmental policies in shaping the international transmission channels of asymmetric shocks changes when the economies share the same currency. In particular, we show how in response to a positive TFP shock hitting the domestic economy, the correlation between Home and Foreign output turns out to be positive under a carbon tax and less negative under a cap and trade. In response to a positive TFP shock hitting only Home monetary policy is now less accommodative for Home, but becomes expansionary for Foreign.

The remainder of the paper is organized as follows. Section 2 describes the two-country model and introduces the various sources of uncertainty giving rise to different dynamic adjustments of the economy. Section 3 summarizes the parametrization used to numerically solve the model. Section 4 presents the dynamic response of macroeconomic and environmental variables to various types of shocks, under the two alternative environmental policy regimes, accounting for the role of international trade in the propagation of disturbances between countries. Section 5 summarizes the main results and concludes.

2 The model

We model an artificial economy with two countries, Home and Foreign, open to international trade and financial capital flows. Home and Foreign are modeled symmetrically, therefore the following description holds for both economies. Foreign variables are denoted by a superscript asterisk. Each country manufactures tradable intermediate goods produced in a number of horizontally differentiated varieties by using labor and physical capital as factor inputs. The intermediate goods sector is characterized by monopolistic competition and price stickiness in the form of quadratic adjustment costs of the Rotemberg (1982) type, while labor and physical capital are immobile between countries. For convenience, we assume the existence of a perfectly competitive final good sector combining domestic and foreign intermediate goods. On the demand side, the economy is populated by households deriving utility from consumption and disutility from labor. Households supply labor and capital to domestic producers and hold two financial assets, namely domestic and foreign bonds. The economy features pollutant emissions, which are a by-product of output, and a negative environmental externality on production. Finally, we have a central bank making decisions on monetary policy and a government that sets the environmental policy.

2.1 Households

The typical infinitely lived household derives utility from consumption, C_t, and disutility from hours worked, L_t. The lifetime utility U is of the type:

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\varphi_C}}{1-\varphi_C} - \xi_L \frac{L_t^{1+\varphi_L}}{1+\varphi_L} \right), \tag{1}$$

where E is the rational expectations operator, $\beta \in (0,1)$ is the discount factor, φ_C is the coefficient of relative risk aversion, ξ_L is a scale parameter measuring the relative disutility of labor, and φ_L is the inverse of the Frisch elasticity of labor supply. Households own the stock of physical capital, K_t, and provides it to firms in a perfectly competitive rental market. The accumulated capital stock K_t is subject to a quality shock determining the level of effective capital for use in production. Therefore, the stock of capital held by households evolves according to the following law of motion:

$$K_{t+1} = I_t + (1-\delta) e^{u_{K,t}} K_t, \tag{2}$$

where I_t denotes investments, K_t is physical capital carried over from period $t-1$ and $\delta \in (0,1)$ is the depreciation rate of capital, while u_K is an exogenous process capturing capital-quality shocks. The capital-quality shock is meant to capture any exogenous variation in the value of installed capital able to trigger sudden variations in its market value and changes in investment expenditure.[5] This shock directly affects the capital in use for production and indirectly influences future investments by changing their expected return. The process $u_{K,t}$ is such that $u_{K,t} = \rho_K u_{K,t-1} + \varepsilon_{K,t}$, where $0 < \rho_K < 1$ and $\varepsilon_K \sim i.i.d.\ N(0, \sigma_K^2)$.

Investment decisions are subject to convex capital adjustment costs of the type $\Gamma_K(I_t, K_t) \equiv \frac{\gamma_I}{2}(\frac{I_t}{K_t} - \delta)^2 K_t$, $\gamma_I > 0$. We further assume that domestic residents have access to a one-period risk free bond, B_t, sold at a price R_t^{-1} and paying one unit of currency in the following period, and to a risk-free asset traded between the two countries, F_t^*, denominated in Foreign currency, sold at a price $(R_t^*)^{-1}$ and paying one unit of foreign currency in the following period. Households receive lump-sum transfers Tr_t from the government, dividends D_t from the ownership of domestic intermediate good-producing firms, and payments for factors they supply to these firms: a nominal capital rental rate $R_{K,t}$ and a nominal wage W_t.

Denoting the consumption price index by P_t, the period-by-period budget constraint reads

[5] This type of shock is introduced in DSGE models to mimic a recession originating from an adverse shock on the asset price. As we will see this shock is able to generate co-movement of consumption, investment, hours and output. See e.g. Gertler and Kiyotaki (2010).

as:

$$P_tC_t + P_tI_t + R_t^{-1}B_t + (R_t^*)^{-1} S_tF_t^* = W_tL_t + R_{K,t}K_t + \\ + B_{t-1} + S_tF_{t-1}^* - P_t\Gamma_K(I_t, K_t) + P_tTr_t + P_tD_t, \tag{3}$$

where S_t is the nominal exchange rate expressed as the price of Foreign currency in units of Home currency. The typical household will choose the sequences $\{C_t,\ K_{t+1},\ I_t,\ L_t,\ B_t,\ F_t^*\}_{t=0}^{\infty}$ so as to maximize (1), subject to (2) and (3).

Rewriting the budget constraint in real terms, from the households' utility maximization problem, we obtain the following set of first-order conditions:

$$C_t^{-\varphi_c} = \lambda_t, \tag{4}$$

$$q_t = \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \left[r_{K,t+1} + \gamma_I \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right) \frac{I_{t+1}}{K_{t+1}} - \frac{\gamma_I}{2} \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right)^2 \right] \right\} + \\ + \beta(1-\delta) E_t \left\{ e^{u_{K,t+1}} \frac{q_{t+1}\lambda_{t+1}}{\lambda_t} \right\}, \tag{5}$$

$$q_t - 1 = \gamma_I \left(\frac{I_t}{K_t} - \delta \right), \tag{6}$$

$$\lambda_t w_t = \xi_L L_t^{\varphi_L}, \tag{7}$$

$$\frac{1}{R_t} = \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\Pi_{t+1}} \right\}, \tag{8}$$

$$\frac{1}{R_t^*} = \beta E_t \left\{ \frac{\lambda_{t+1} S_{t+1}}{\lambda_t \Pi_{t+1} S_t} \right\}, \tag{9}$$

where λ_t denotes the Lagrange multiplier associated to the flow budget constraint (3) expressed in real terms and measures the marginal utility of consumption according to condition (4), $r_{K,t} = \frac{R_{K,t}}{P_t}$, $w_t = \frac{W_t}{P_t}$, q_t is the Tobin's q and $\Pi_t = \frac{P_t}{P_{t-1}}$ measures inflation in the final-good sector. Equations (5) and (6) refer to the optimality conditions with respect to capital and investments, (7) describes labor supply, whereas (8) and (9) are the two first-order conditions with respect to domestic and foreign assets, reflecting the optimal choice between current and future consumption, given the return on the two risk-free assets, expected inflation and the expected depreciation of the domestic currency.

2.2 Production

2.2.1 Production of Domestic Intermediate Goods

The intermediate goodw producing sector is dominated by a continuum of monopolistically competitive polluting firms indexed by $j \in [0, 1]$. Each firm charges the same price at home and abroad and faces a demand function that varies inversely with its output price $P_{j,t}^D$ and directly with aggregate demand Y_t^D for domestic production, that is $Y_{j,t}^D = \left(\frac{P_{j,t}^D}{P_t^D}\right)^{-\sigma} Y_t^D$, where $\sigma > 1$ and P_t^D is an aggregate price index defined below.

The producer of the variety j hires capital and labor in perfectly competitive factor markets to produce the intermediate good $Y_{j,t}^D$ according to a Cobb-Douglas technology, modified to incorporate a capital-quality shock and the damage from pollution, measured in terms of intermediate output's reduction:

$$Y_{j,t}^D = \Lambda_t A_t \left(u_{K,t} K_{j,t}\right)^\alpha L_{j,t}^{1-\alpha}, \tag{10}$$

where $0 < \alpha < 1$ is the elasticity of output with respect to capital, A_t denotes total factor productivity, and Λ_t is a term capturing the negative externality of pollution on production. In particular, referring to Golosov et al. (2014), we adopt the following simplified specification for the damage function Λ_t:

$$\Lambda_t = \exp[-\chi(Z_t - \overline{Z})], \tag{11}$$

where Z_t is the global stock of carbon dioxide in period t, $\overline{Z}$ is the pre-industrial atmospheric CO_2 concentration, and χ is a positive scale parameter measuring the intensity of the negative externality on production.[6] The equation describes how economic damages change in function of greenhouse gas concentration in the atmosphere. This kind of formalization is established in the literature and is an exponential version of the well-known Nordhaus damage function introduced in in the DICE/RICE family of models (see e.g. Nordhaus 1992, 2018). According to Nordhaus, there is a relationship between global temperature increase and income loss. However, whereas Nordhaus explicitly models damages in two steps, the first one mapping carbon concentration into temperature and the second one mapping temperature to damages, Golosov et al. (2014) propose a function directly mapping from the stock of carbon dioxide to economic damages. The damage effects are multiplicative as in the RICE and the DICE models, and the exponential specification turns out to be a good approximation of Nordhaus specifications, as discussed by the authors.[7] We further assume that productivity A_t is subject to shocks, that is $A_t = Ae^{u_{A_t}}$, where A denotes the steady-state productivity level, while u_{A_t}

[6] A similar specification is adopted by Annicchiarico et al. (2017). Both Home and Foreign are equally affected by the negative externality, causing a reduction of the production possibilities of the intermediate sector. This leads to a reduction of the production in the final sector as well. As a consequence, via its effect on the production possibilities of the economy, the environmental externality also has a negative effect on aggregate welfare. A commonly considered alternative formulation includes the damages from pollution directly in the utility function (see Weitzman 2010). In a decentralized economy, as the one we consider, the two modelling choices are equivalent and yield similar results. It is worth noting that this paper focuses on the short run. Capturing the effects of pollution on human health, which would be better accomplished by including pollution in the utility function, is therefore beyond the considered time span.

[7] Although the aforementioned functions represent well-established approaches to formalize climate change damages, considerable uncertainty still remains on the aggregate consequences of pollution. So far, there is no consensus on the form and the parametrization of a general climate damage function. For a discussion on the role of damage modeling in climate change literature, see Bretschger and Pattakou (2018).

is assumed to evolve as $u_{A_t} = \rho_A u_{A_{t-1}} + \varepsilon_{A,t}$, where $0 < \rho_A < 1$ and $\varepsilon_{A,t} \sim i.i.d.\ N(0, \sigma_A^2)$.

Emissions for firm are a by-product of output:

$$E_{j,t} = (1 - \mu_{j,t})\epsilon(Y_{j,t}^D)^{1-\gamma}, \tag{12}$$

where the parameter γ determines the elasticity of emissions with respect to output, ϵ is a parameter that we use to scale the emission function and $0 < \mu_t < 1$ is the abatement effort.

Firms are subject to environmental regulation and can choose to purchase emission permits on the market at the price $P_{E,t}$ (or to pay a tax in the case of price regulation), or to incur in abatement costs $AC_{j,t}$ to reduce emissions. Abatement costs, in turn, depend on firm's output and on abatement effort:

$$AC_{j,t} = \theta_1 \mu_{j,t}^{\theta_2} Y_{j,t}^D, \tag{13}$$

where $\theta_1 > 0$ and $\theta_2 > 1$ are technological parameters. However, differently from previous E-DSGE models, we assume that firms are not able to freely choose the level of environmental efficiency of their technology and propose a formalization of the abatement effort more plausible at business cycle frequencies. In particular, to account for the fact that improvements in the level of environmental efficiency are typically the results of medium-term efforts that require investments and the adoption of new technologies, we assume that firms wishing to change their abatement effort incur in adjustment costs. The abatement choice is also partially irreversible, implying that firms face a limit in their ability to reduce their effort in the attempt of minimizing the cost of mitigation over the business cycle. To introduce these features into our model we assume that the costs of changing the level of effort are represented by a linex function, say $\Gamma_{\mu_t}(\mu_t)$, such that the cost depends on both the magnitude and sign of the effort adjustment. In particular, we assume that following functional form:

$$\Gamma_{\mu_t}(\mu_t) = \gamma_\mu \frac{\exp\left(-\psi_\mu \left(\frac{\mu_t}{\mu_{t-1}} - 1\right)\right) + \psi_\mu \left(\frac{\mu_t}{\mu_{t-1}} - 1\right) - 1}{\psi_\mu^2}, \tag{14}$$

where γ_μ and ψ_μ are positive coefficients.[8] The linex function is attractive for two reasons. First, it is differentiable and strictly convex for $\gamma_\mu > 0$. Second, it implies that as μ_t increases the linear term dominates and the costs associated with the abatement effort changes tend to increase linearly. By contrast, as μ_t decreases the exponential term dominates and the costs associated with the changes in the abatement effort tend to increase exponentially. The higher ψ_μ, the more asymmetric these adjustment costs are. In particular, for $\psi_\mu \to \infty$ downward changes become prohibitive and abatement choices are completely irreversible. For $\psi_\mu \to 0$, instead, (14) boils down to a quadratic form and adjustment costs become symmetric.[9]

[8] The linex specification has been originally proposed by Varian (1974).

[9] Applying twice L'Hôpital's rule on (14), it is possible to show that for $\psi_\mu \to 0$, function $\Gamma_{\mu_t}(\mu_t)$ reduces to $\frac{\gamma_\mu}{2}\left(\frac{\mu_t}{\mu_{t-1}} - 1\right)^2$.

Let $p_{E,t} = \frac{P_{E,t}}{P_t}$ and $p_t^D = \frac{P_t^D}{P_t}$, by imposing symmetry across producers, from the solution of firm j's static cost minimization problem, we have the following optimality conditions:

$$r_{K,t} = \alpha \Psi_t \frac{Y_t^D}{K_t}, \tag{15}$$

$$w_t = (1-\alpha)\Psi_t \frac{Y_t^D}{L_t}, \tag{16}$$

$$\begin{aligned} p_{E,t}(Y_t^D)^{(1-\gamma)} &= \theta_2\theta_1\mu_t^{\theta_2-1}p_t^D Y_t^D - \gamma_\mu \frac{1}{\mu_{t-1}} \frac{\exp\left(-\psi_\mu\left(\frac{\mu_t}{\mu_{t-1}}-1\right)\right)-1}{\psi_\mu} + \\ &+\beta E_t \frac{\lambda_{t+1}}{\lambda_t}\gamma_\mu \frac{\mu_{t+1}}{\mu_t^2} \frac{\exp\left(-\psi_\mu\left(\frac{\mu_{t+1}}{\mu_t}-1\right)\right)-1}{\psi_\mu}, \end{aligned} \tag{17}$$

where equations (15) and (16) are demands for capital and labor, equation (17) is the optimal abatement choice and Ψ_t is the marginal cost component related to the use of extra units of capital and labor needed to produce an additional unit of output. It can be easily shown that the marginal cost component Ψ_t is common to all firms and is equal to $\Psi_t = \frac{1}{\alpha^\alpha(1-\alpha)^{1-\alpha}}\frac{1}{\Lambda_t A} w_t^{1-\alpha} r_{K,t}^\alpha$.

Consider now the optimal price setting problem of the typical firm j. Acting in a non-competitive setting, firms can choose their price, but they face quadratic adjustment costs *à la* Rotemberg: $\frac{\gamma_p}{2}\left(\frac{P_{j,t}^D}{P_{j,t-1}^D}-1\right)^2 P_t^D Y_t^D$, where the coefficient $\gamma_p > 0$ measures the degree of price rigidity. Formally, the firm sets the price $P_{j,t}^D$ by maximizing the present discounted value of profits subject to demand constraint $Y_{j,t}^D = \left(\frac{P_{j,t}^D}{P_t^D}\right)^{-\sigma} Y_t^D$. At the optimum we have:

$$\begin{aligned} &\left(1-\theta_1\mu_t^{\theta_2}\right)(1-\sigma) + \sigma MC_t + \\ -\gamma_p\left(\Pi_t^D - 1\right)\Pi_t^D + \beta E_t &\left\{\frac{\lambda_{t+1}}{\lambda_t}\gamma_p\left(\Pi_{t+1}^D-1\right)\left(\Pi_{t+1}^D\right)^2 \frac{Y_{t+1}^D}{Y_t^D}\frac{1}{\Pi_{t+1}}\right\} = 0, \end{aligned} \tag{18}$$

where we have imposed symmetry across producers and defined $\Pi_t^D = \frac{P_t^D}{P_{t-1}^D}$. The above equation is the New Keynesian Phillips curve, relating current inflation Π_t^D to the expected future rate of inflation Π_{t+1}^D and to the current (real) marginal cost, $MC_t = \frac{1}{p_t^D}\left[p_{E,t}(1-\gamma)(1-\mu_t)\epsilon\left(Y_t^D\right)^{-\gamma} + \Psi_t\right]$, which, in turn, depends on the available technology and the underlying environmental regime. Note that in the deterministic steady state and with no trend inflation (i.e. $\Pi = \Pi^D = 1$), the so-called New Keynesian Phillips curve (18) collapses to $MC_t = \frac{\sigma-1}{\sigma}\left(1-\theta_1\mu_t^{\theta_2}\right)$,[10] or equivalently, by defining the price markup, say MU_t, as the reciprocal of the MC_t, to

$$MU_t = \frac{\sigma}{\sigma-1}\frac{1}{1-\theta_1\mu_t^{\theta_2}}. \tag{19}$$

[10]This condition simply equates marginal cost, MC, to marginal revenues, $\frac{\sigma-1}{\sigma}\left(1-\theta_1\mu_t^{\theta_2}\right)$.

Clearly, in the absence of any environmental policy regime, the steady-state price markup will only depend on the elasticity of substitution between intermediate goods σ. In this case, instead, the price markup is shown to be increasing in the abatement effort μ_t. Market power gives firms the possibility of transferring the burden of emission abatement to households via higher markups.

2.2.2 Domestic Output Index

Each domestic producer supplies goods to the Home and to the Foreign markets. Let $Y_{j,t}^H$ and $X_{j,t}$ denote, respectively, the domestic and the foreign demand for the generic domestic variety j, then $Y_{j,t}^D = Y_{j,t}^H + X_{j,t}$. For simplicity we assume the presence of a perfectly competitive aggregator that combines domestically produced varieties into a composite Home-produced good Y_t^D, according to a CES function $Y_t^D = \left(\int_0^1 \left(Y_{j,t}^D\right)^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma}{\sigma-1}}$. Cost minimization delivers the demand schedule $Y_{j,t}^D = \left(\frac{P_{j,t}^D}{P_t^D}\right)^{-\sigma} Y_t^D$ for each variety. From the zero-profit condition, we obtain the production price index, $P_t^D = \left(\int_0^1 (P_{j,t}^D)^{(1-\sigma)} dj\right)^{\frac{1}{1-\sigma}}$, at which the aggregator sells units of each sectoral output index. Clearly, this output index is allocated in both markets, therefore $Y_t^D = Y_t^H + X_t$, where X_t represents exports of Home to Foreign.

By symmetry, we assume the existence of a perfectly competitive aggregator in the Foreign economy that combines differentiated intermediate goods into a single good to be used for local production of the final good and for exportation.

2.2.3 Production of the Final Good

Competitive firms in the final sector combine a share Y_t^H of the good index Y_t^D produced in the intermediate domestic sector with a share M_t of foreign intermediate production in order to produce the final good Y_t according to the following production function:

$$Y_t = [\kappa^{\frac{1}{\rho}} (Y_t^H)^{\frac{\rho-1}{\rho}} + (1-\kappa)^{\frac{1}{\rho}} (M_t)^{\frac{\rho-1}{\rho}}]^{\frac{\rho}{\rho-1}}, \tag{20}$$

where κ represents the share of intermediate domestic goods used in the production of final good and $\rho > 0$ is the elasticity of substitution between domestic and foreign intermediate goods. Clearly, $1-\kappa$ represents the degree of openness of the economy.

Final good producing firms sustain the following cost for inputs: $P_t^D Y_t^H + P_t^{D^*} S_t M_t$, where $P_t^{D^*}$ represents the price index of Foreign production expressed in Foreign currency. Taking as given the price index of the domestic intermediate goods, P_t^D, and the price index of the imported intermediate goods, $S_t P_t^{D^*}$, firms minimize their cost function choosing the optimal quantities of domestic and imported goods:

$$Y_t^H = \kappa \left(\frac{P_t^D}{P_t} \right)^{-\rho} Y_t, \tag{21}$$

$$M_t = (1-\kappa) \left(\frac{S_t P_t^{D*}}{P_t} \right)^{-\rho} Y_t. \tag{22}$$

From the zero-profit condition we derive the consumer price index:

$$P_t = [\kappa (P_t^D)^{(1-\rho)} + (1-\kappa)(S_t P_t^{D*})^{(1-\rho)}]^{1/(1-\rho)}. \tag{23}$$

2.3 Public Sector

2.3.1 Environmental Policy

In what follows we consider two possible environmental policies: carbon tax and cap-and-trade. Under a carbon tax regime each country imposes a tax rate per unit of emission (i.e. p_E is constant and can then be interpreted as a carbon tax). Under a cap-and-trade regime Home and Foreign pursue a common environmental policy and jointly choose an emission target. Specifically, Home and Foreign set the level of cumulative emissions that can be released ($E_t + E_t^* = \bar{E} + \bar{E}^*$). In the intermediate goods sector all firms must hold one permit for each unit of pollution they emit. Permits are sold by the government of each country and traded on a secondary international market. We rule out the possibility of grandfathering.

For simplicity we abstract from the existence of a public debt and assume that the fiscal authority runs a balanced budget at all times. In particular, we assume that the revenues from environmental policy are distributed to households as lump-sum transfers, that is

$$p_{E,t} E_t = Tr_t, \tag{24}$$

where the term $p_{E,t} E_t$ may refer to the revenues from a carbon tax policy or from the government sale of emission permits.

2.3.2 Monetary Policy

The monetary authority manages the short-term nominal interest rate R_t in accordance to the following simple interest-rate rule:

$$\frac{R_t}{R} = \left(\frac{\Pi_t}{\Pi} \right)^{\iota_\Pi} e^{u_{R,t}}, \tag{25}$$

where R and Π denote the deterministic steady-state of the nominal interest rate and of the inflation rate, ι_π is a policy parameter and $u_{R,t}$ is an exogenous process capturing the possibility of monetary policy shocks, that is: $u_{R,t} = \rho_R u_{R,t-1} + \varepsilon_{R,t}$, with $0 < \rho_R < 1$ and $\varepsilon_R \sim i.i.d.$

$N(0, \sigma_R^2)$.

2.4 Trade Block, Current Account and Real Exchange Rate

In a two-country setting imports of Home are translated into a exports of Foreign, therefore

$$X_t^* = M_t = (1-\kappa)\left(\frac{S_t P_t^{D^*}}{P_t}\right)^{-\rho} Y_t. \quad (26)$$

Likewise, exports of Home are translated into imports of Foreign

$$X_t = M_t^* = (1-\kappa)\left(\frac{P_t^D}{S_t P_t^*}\right)^{-\rho} Y_t^*. \quad (27)$$

The accumulation of Foreign assets for Home is determined by the current account relationship:

$$S_t F_t^* = R_t^* \left(S_t F_{t-1}^* + P_t^D X_t - S_t P_t^{D^*} M_t\right). \quad (28)$$

In the initial steady state F^* is set at zero, thus implying $P_t^D X_t = S_t P_t^{D^*} M_t$.

The assumption of perfect financial capital mobility between Home and Foreign implies that the nominal exchange rate is determined in the Foreign exchange market as a result of the monetary policy conduct in the two countries.[11] On the other hand, the real exchange rate, defined as $\frac{S_t P_t^*}{P_t}$ (i.e. the ratio between the Foreign price level and the Home price level, where the Foreign price level is converted into domestic currency), not only is influenced by the time path of the nominal exchange rate, but it also reflects the response of the consumption prices indexes to shocks and policy changes.

2.5 Resource Constraint and Stock of Pollution

The resource constraint of the economy can be derived by plugging the government budget constraint, along with the definition of profit of the intermediate sector and the expression for the current account position, into the household budget constraint:

$$P_t^D Y_t^D = P_t C_t + P_t I_t + P_t^D X_t + P_t^D AC_t - S_t P_t^{D^*} M_t + P_t \Gamma_K(I_t, K_t) + P_t \Gamma_{\mu_t}(\mu_t) + \frac{\gamma_p}{2}(\Pi_t^D - 1)^2 P_t^D Y_t^D. \quad (29)$$

The stock of pollution Z_t evolves according a natural decay factor $\eta \in (0,1)$, and on the basis of current period Home emissions E_t, current period Foreign emissions E_t^*, and non-industrial emissions E_t^{NI}:

$$Z_t = \eta Z_{t-1} + E_t + E_t^* + E_t^{NI}. \quad (30)$$

[11] It can be easily shown that by log-linearizing the two Euler equations (8) and (9) one obtains the familiar uncovered interest parity condition relating the rate of depreciation of Home currency to the nominal interest rate differential, which, in turn, depends on the inflation rates via the interest rate rules adopted by Home and Foreign monetary authorities.

3 Parametrization

The model is calibrated for the world economy and time is measured in quarters. We adopt the following parametrization as a benchmark for our positive analysis, in line with the aim of the paper to provide an understanding of the dynamic effects of different environmental policies in open economy.[12] Standard parameters, related to the New Keynesian formalization of the model, follow the existing literature. See, e.g., Galí (2015). The discount factor β is set at a value consistent with a real interest rate of 4% per year, that is $\beta = 0.99$. The inverse of the Frisch elasticity of labor supply ϕ_L is equal to 1. By assuming that the time spent working at the steady state is 0.3, we obtain an implied value for ξ_L, the scale parameter related to the disutility of labor, of 3.8826**.** The depreciation rate of capital δ is set at 0.025 and the capital share α at 1/3. The degree of price rigidities, the parameter γ_p, is consistent with a Calvo pricing setting with a probability that price will stay unchanged of 0.75 (i.e. average price duration of three quarters), namely $\gamma_p = 58.25$. The inverse of the intertemporal elasticity of substitution φ_C is equal to 1.2, the parameter for capital adjustment costs γ_I is set at 1.5. Regarding the goods market, we set the elasticity of substitution among intermediate good varieties σ equal to 6 and the intratemporal elasticity of substitution between domestic and foreign intermediate goods ρ equal to 1.5, implying that domestic and foreign varieties are imperfect substitute. In line with the average values of the import/GDP ratio observed for the world economy in period 2010-2015 according to World Bank data, we assume a propensity to import of 0.3, that implies a share of domestic intermediate goods used in the final sector κ equal to 0.7. The steady-state target inflation is equal to zero ($\Pi = 1$), while the relative price of intermediate goods and the real exchange rate, p^D and S^R, are both normalized to 1. Turning to parameter related to monetary policy, we set the interest rate response to inflation, ι_Π, at 1.5.

With regards to the environmental part of the model, we refer to previous environmental DSGE models and Integrated Assessment Models for climate change, in order to obtain plausible values for environmental parameters. We set the elasticity parameter of emissions to output γ at 0.304 as in Heutel (2012), the pollution decay factor η at 0.9979, following Reilly and Richards (1993), and the parameter of the abatement cost function θ_2 at 2.8 as in Nordhaus (2008), while θ_1 is normalized to 1. The parameter determining the size of the adjustment cost of abatement changes, γ_μ, is set at 1.5, consistently to the one determining the size of the capital adjustment costs, while the parameter governing the asymmetry of these costs, ψ_μ, is set at 10. To obtain the steady state level for emissions, we refer to the policy runs of the RICE-2010 model, in detail to the simulation results for year 2015. We take the level of global carbon emissions, and the level of global industrial emissions, both measured in gigatons of carbon (GtC) per year, then we assume that Home and Foreign contribute in equal way to output

[12] However, a more specific parametrization could be designed to adapt the analysis to specific countries of interest.

and emissions in the region. Through these data we are able to recover the level of global non-industrial emissions, emissions for domestic and foreign country, and the steady state level of output in the intermediate goods sector. Finally, by looking at the RICE model, we know that abatement costs, measured as fraction of output, are equal to 0.00013. This calibration strategy delivers implicit values for the pollution stock in model units, emission intensity and the scale parameter ϵ. Regarding the negative externality on production, we calibrate Λ on the basis of the total damage for year 2015, measured as fraction of output, that amounts to 0.0030. Estimating that the pre-industrial atmospheric CO_2 concentration ($\overline{Z}$) represents 3/4 of the total pollution stock, we obtain a value for the intensity of negative externality on output χ and for the total factor productivity A.

Finally, for the stochastic processes of the model we assume a high degree of autocorrelation for the exogenous shocks by setting ρ_A and ρ_K at 0.85, while ρ_R is set at 0.5. Table 1 lists all the parameters of the model.

4 International Transmission of Shocks and Environmental Policies

In this Section we analyze the international transmission of asymmetric shocks under two alternative environmental regimes, namely a carbon tax and a cap-and-trade. We analyze the effects of three temporary shocks hitting only Home: (i) a positive productivity shock increasing the TFP, (ii) a negative shock on the quality of capital, and (iii) a positive shock on the risk-free interest rate set by the monetary authorities.

In what follows we focus our attention on a selection of macroeconomic and environmental variables. Results are reported as percentage deviations from the initial steady state over 20 quarters, with the exception of the trade balance which is reported in percentage points.[13]

4.1 TFP Shock

Figures 1 and 2 show the economy's response to a one percent increase of productivity hitting only Home. Continuous lines refer to the dynamic response of the economy under a carbon tax, while dashed lines report the response under a cap-and-trade policy.

In response to a positive shock on the TFP, domestic consumption and investment immediately increase.[14] Output increases as well, and all these positive effects are magnified under a carbon tax regime because the environmental-related cost component borne by firms tends to

[13]The model is solved with Dynare. For details, see http://www.dynare.org/ and Adjemian et al. (2011).

[14]It can be shown that in response to a positive technology shock labor is countercyclical, as usual in New Keynesian models. Nominal rigidities do not allow an immediate adjustment of prices and this has a negative impact on the labor market. This result is also consistent with empirical studies that point out how a positive technology shock leads to a temporary decline in employment: firms take advantage of the productivity's increase by reducing labor demand. See e.g. Galí (1999).

increase by less than under a cap and trade. The shock gives rise to a depreciation of the domestic currency and deteriorates Home terms of trade. On impact the effects on the trade balance are negative and negligible but, starting from the second period, we observe an improvement of the trade balance, no matter the kind of environmental policy implemented. A typical J-curve effect arises: in the first periods after the shock the price effect dominates, imports are costlier than exports and this deteriorates the trade balance. At later stages quantities adjust: the volume of export starts to rise because of the higher Foreign demand for domestic goods that are relatively low-priced. At the same time domestic consumers reduce their demand for more expensive Foreign goods. At the earlier stages of the adjustment we also observe a deterioration in the foreign asset position of Home, followed by a steady increase.[15] The improvement in the Foreign terms of trade increases Foreign consumption that remains above the steady state levels along all the considered time horizon.

Looking at Foreign investment and output we note that they behave very differently in the two environmental regimes. Under a carbon tax domestic firms pollute more than under a cap and trade and output expands by more, while abatement costs do not change significantly. This is because firms facing a constant carbon tax per unit of emissions do not have to sustain higher marginal cost per unit of emissions when their production expands. The greater expansion of Home output then explains the initial positive spillover effects on Foreign output and investments. However, these positive effects already fade away after two quarters, because of the lower demand for foreign goods.

Under a cap-and-trade regime, instead, both Foreign output and investments decline immediately after the shock and remain under their steady state level all along the simulation period. The asymmetric shock determines an outflow of emission permits from Foreign to Home allowing domestic firms to pollute more, while the price of emission permits, determined in the international market, increases sharply. In Foreign this outflow of emission permits, along with the sharp increase in the permit price explain the reduction of output and investment, and the dampened reaction of Foreign consumption. The cross-border reallocation of permits reflects on the time path of emissions in the two countries, while the expansion of output in Home explains the sharp increase in the international price of permits.

4.2 Monetary Policy Shock

In Figures 3 and 4 we consider the response of the economy to a monetary policy shock. In detail, we assume an increase of 0.50% in the innovation $\varepsilon_{R,t}$ implying a restrictive monetary shock hitting Home. The rise in the interest rate reduces investment and consumption, triggering a fall of output in Home. In addition the domestic currency appreciates, so that we observe

[15]The response of trade balance and of net external asset position of Home crucially depends on the elasticity of substitution ρ between domestic and foreign goods. It can be shown that in the case of imperfect complementarity (i.e. $0 < \rho < 1$), in fact, Home trade balances never improve during the adjustment process, while we observe a stronger depreciation of the domestic currency.

a short-lived improvement in the trade balance. The price effect on imports dominates the volume effect on net exports which materializes only at later stages. Consistently, the external asset position first improves and then worsens.

The main Home macroeconomic variables show the same patterns in the regimes, although the immediate response to the shock is different in magnitude. In particular, a carbon tax amplifies the effects induced by the contractionary shock, while a cap and trade policy reduces the impact on output, investment and consumption.

Looking at the Foreign macroeconomic variables the differences generated by the two environmental regimes are remarkable. Under the carbon tax regime the domestic demand channel depresses Foreign output that follows the decline of Home imports. On impact we observe a negative reaction of Foreign consumption and investment. In the following periods the expenditure switching effect prevails and these variables recover quickly, following the movement of the trade balance. Emissions follow the same pattern of production in both countries, while abatement costs do not change significantly.

Under the cap-and-trade regime, instead, Foreign output increases, and so consumption and investments. The tightening of monetary policy generates a contraction of Home production and a decline in the Home demand for permits. The price of carbon decreases sharply and we observe a reallocation of permits in favor of Foreign. The fall in the price of permits makes abatement extremely uncompetitive. Foreign emissions then increase along with a sharp fall in abatement costs. The reduced abatement costs and of permit prices free up resources for firms and translate into higher production and investments for Foreign. Foreign consumption instead slightly declines as a result of the worsening in the terms of trade of this country.

4.3 Quality of Capital shock

We now focus the attention on the economy's response to a one percent negative shock on the quality of capital. The negative shock decreases the capital value, and, at the same time, the effective quantity of capital available for production. See Figures 5 and 6. This shock depresses demand and supply at the same time, since it implies a reduction of investments and an increase in the marginal cost of firms that suffer a deterioration of their production capacity. Since the shock is temporary, households find it optimal to decrease investment immediately in response to the shock, given the lower marginal product of capital, while consumption follows a hump-shaped dynamics. In general, we observe a negative co-movement of the main real variables: consumption, investment and output.

The real exchange rate slightly increase in the first period, then appreciates. The trade balance improves on impact, but it starts to deteriorate already from the second period. On the other hand, in Foreign the value of capital is relatively higher and firms decide to invest more. Foreign output increases, while consumption decreases as a consequence of the deterioration of the terms of trade. Considering the dynamic implications of the underlying environmental policy, we notice that, under the cap-and-trade regime, the decline of Home production is milder than in the case of carbon tax. As in the case of a recessionary monetary policy shock, we observe a reallocation of permits from Home to Foreign and a fall in the their price. The fall in the emission permits price alleviates the negative effects of the capital quality shock for Home producers. Foreign producers, in turn, take advantage of the lower price of emissions on the market by buying permits, reducing the abatement and increasing emissions.

4.4 International Spillovers, Pattern of Trade and Monetary Regime

In this Section we explore the role played by the pattern of trade and by monetary policy in the transmission of the business cycle across different environmental policy regimes. In particular, we solve the model under three different assumptions in turn: (i) domestic and foreign bundles of goods are imperfect complements, rather than imperfect substitutes, (ii) higher degree of openness to international trade, (iii) currency union. To address these points in a parsimonious way we look at the standard deviations for Home and Foreign output and at their correlation. Both statistics are computed using stochastic simulations considering each shock in turn. In this way we are able to measure the magnitude and the sign of international spillovers under different sources of uncertainty for the two environmental regimes.[16]

We start by considering the benchmark case, where the model is solved under the baseline calibration of Table 1. Results are reported in Table 2, where σ_{Y^D} and $\sigma_{Y^{D*}}$ denote the standard deviations of Home and Foreign output, while $\rho(\cdot,\cdot)$ is the coefficient of correlation between variables. We notice what follows.

First, the volatility of Home output and the relative standard deviation of Foreign output are found to be larger under a carbon tax regime. The higher volatility of domestic output under a carbon tax is just the result of the facts that under a cap and trade the emission permit price is procyclical and therefore tends itself to stabilize output in response to shocks. In addition, a carbon tax amplifies the magnitude of the international spillovers, in particular when the economy is hit by a monetary policy shock for which we note a much higher relative standard deviation of Foreign output than that observed under a cap and trade.

Second, the underlying environmental regime alters the sign of the relationship between output of the two countries in response to a monetary policy shock. In particular, we observe that in response to technology and capital quality shocks Home and Foreign output are negatively correlated, both under a carbon tax and a cap-and-trade, while in the case of a monetary policy shock, the relationship is positive under a carbon tax and negative under a cap-and-trade policy. Under the carbon tax policy shocks hitting Home through demand affect Foreign output only through international trade. Therefore positive shocks translate into positive effects on Foreign output. By contrast, under a cap and trade regime shocks occurring in Home affect

[16] Given the optimal decision rules, for each shock we draw 200 realizations of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.001.

Foreign also through the exchange of emission permits, reverting the sign of the relationship between Foreign and Home output.

Finally, the size of the correlation between Home and Foreign output is magnified under an international cap-and-trade regime in response to all the shocks considered. The mechanisms behind the permits market, the increase or decrease of permits price, as well as the allocation of permits from one country to another, reflect strongly on the production of both countries.[17]

Table 3 reports the results assuming that foreign and domestic bundles of goods are imperfect complements rather than imperfect substitutes, in particular, we set the elasticity of substitution ρ in equation (20) at 0.5. The Home economy is now less volatile, but international spillovers are greater. We note in fact that the standard deviation of Home output, σ_{Y^D}, is lower than in the benchmark case, while the relative standard deviation of Foreign output is larger. Therefore, the effects of the shocks are shared more intensively with Foreign. The only exception is observed for monetary policy shocks under a cap-and-trade regime, where the relative standard deviation of Foreign output is slightly lower compared to the baseline model. As discussed above, under a cap-and-trade, following a monetary policy shock hitting only Home, there will be an inflow or an outflow of emission permits able to generate an opposite reaction of Foreign output from that observed for Home output. In Table 3 however, this cross-border reallocation of production is weakened by the hypothesis of imperfect complementarity.

Table 4 presents the results under the assumption that the share of imported varieties,κ, in the final good production function is equal to 0.5 instead of 0.3. We observe that with a higher degree of openness the relative standard deviation of Foreign output is higher that in the benchmark case, while the volatility of Home output is lower. Under a cap-and-trade regime, a higher degree of openness sharply mitigates the (negative) correlation between Home and Foreign output. The propensity to import is now higher, therefore changes in Home income will reflect at a greater extent on import demand and so on Foreign output, partially offsetting the effects derived from the exchange of emission permits.

Finally, Table 5 presents the results under the assumption that Home and Foreign share the same currency, therefore the two countries are subject to the same monetary policy which now responds to an average of the two inflation rates. In response to the TFP shock under the carbon tax the correlation between Home and Foreign output turns out to be positive and much less negative under a cap and trade.Following a positive TFP shock hitting Home, the monetary authority will react to the price decline of Home by reducing the nominal interest rate in the currency union. This expansionary monetary policy will induce an expansion also of Foreign. On the other hand, under a cap-and-trade regime, where the possibility of importing emission permits from abroad diminishes the positive spillover effects on Foreign output induced by the

[17]In Appendix B we reproduce our results under the assumption that firms are able to fully adjust their abatement effort and under the assumption of symmetric adjustment costs (i.e. reversibility of abatement technology). We note that, while in the first case the difference between regimes are minor than in the benchmark case of Table 2, with costly abatement adjustment the relative standard deviation of Foreign output is always significantly higher under a carbon tax.

common monetary policy, the correlation remains negative, but the intensity of the relationship is weaker.

5 Conclusions

Climate change and global warming are among the greatest pressing current policy issues. A clear understanding of the economic aspects of the policy undertaken is needed, that is why environmental issues have been recently raising the hurdles also for DSGE modeling. In this respect, the paper presents a stylized but rigorous framework to study the international dimension of climate actions in a two-country fully interdependent economy with uncertainty. With this tool in hand, we are able to convey the some ideas about the role played by environmental regimes in shaping the propagation of shocks between countries.

Our results show how the international transmission mechanism of uncertainty is influenced by the policy tool chosen to stabilize greenhouse gas concentrations in the atmosphere. Unexpected shocks hitting a country may generate spillover effects, whose sign and intensity depend not only on the nature of uncertainty, but also on the underlying environmental regime. Under a carbon tax the cross border spillover effects are always magnified, especially when it comes to monetary shocks. On the contrary, under a cap and trade regime, in which countries can exchange emission permits, we observe less cross-border pressure on output. This is because under an international cap-and-trade the outflow of permits toward an economy experiencing an expansion reduces the positive spillover effects from the international trade channel. Similarly, the inflow of emission permits from an economy in recession lessens the negative cross-border effects from international trade and may revert the sign of the spillover. The degree of openness, the trade pattern and the underlying monetary policy regime are shown to play a non-trivial role in this interplay between economic and environmental policy variables.

The model studied in this paper leaves out a number of features that have been identified as potentially important for understanding the economic implications of climate actions in open economy. First, the model does not allow for international mobility of labor and physical capital. Clearly, this poses a limit to the re-allocation of production activity resulting from asymmetric and persistent shocks. Second, the importance of the pattern of trade in determining the propagation mechanism is only touched upon in this paper and deserves further and deeper investigation in a context where firms structure their production through outsourcing and offshoring of activities within so-called global value chains. Third, in this paper the economy is composed by two identical economies. Similar investigations should be carried out allowing for a certain degree of asymmetry in technology and size between countries. Finally, a further step to advance this analysis should regard a thorough analysis of the interaction between stabilization policies and economy-wide emission regulations. We leave these issues for future research.

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Declarations of Interest

None.

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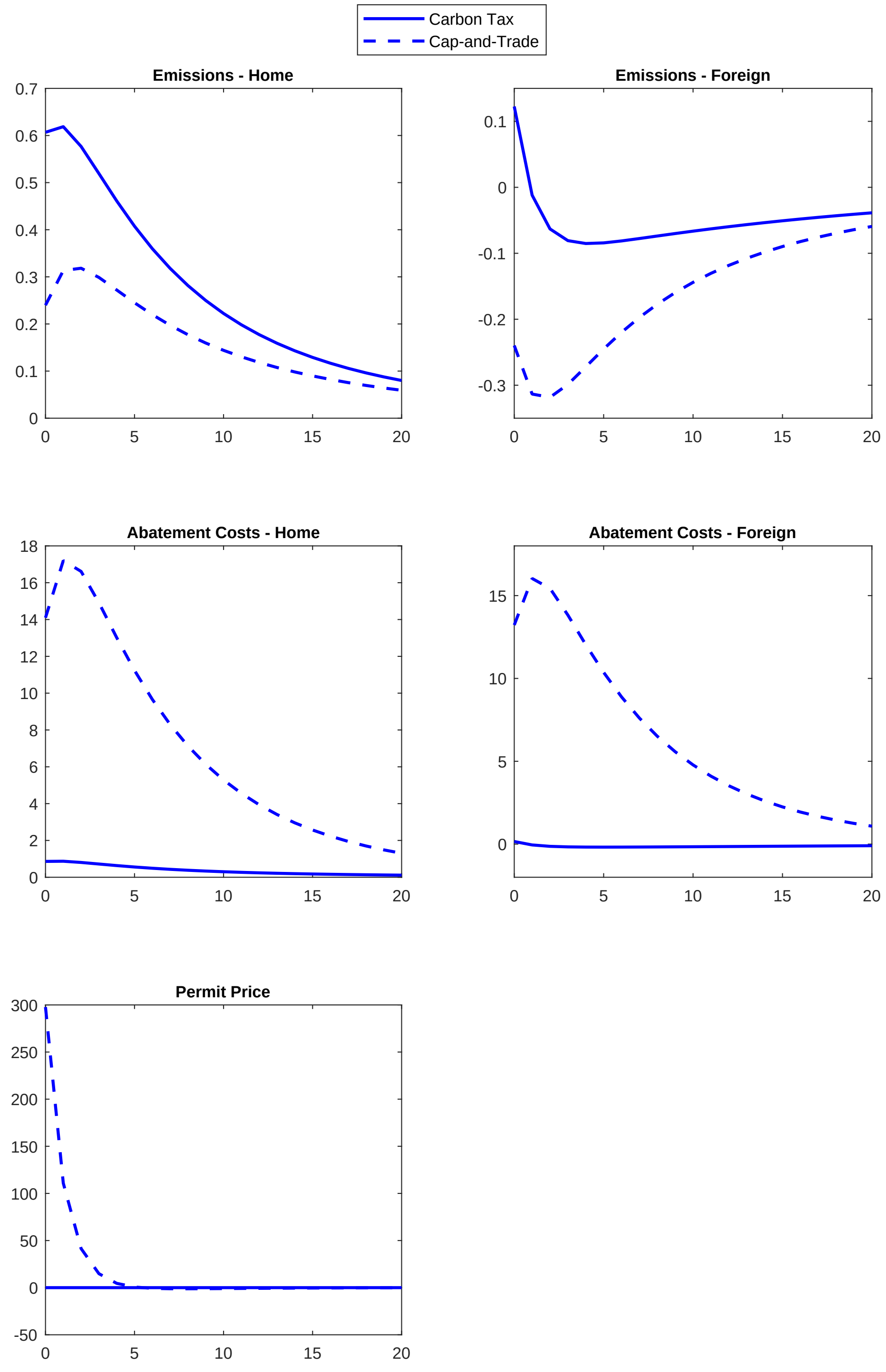
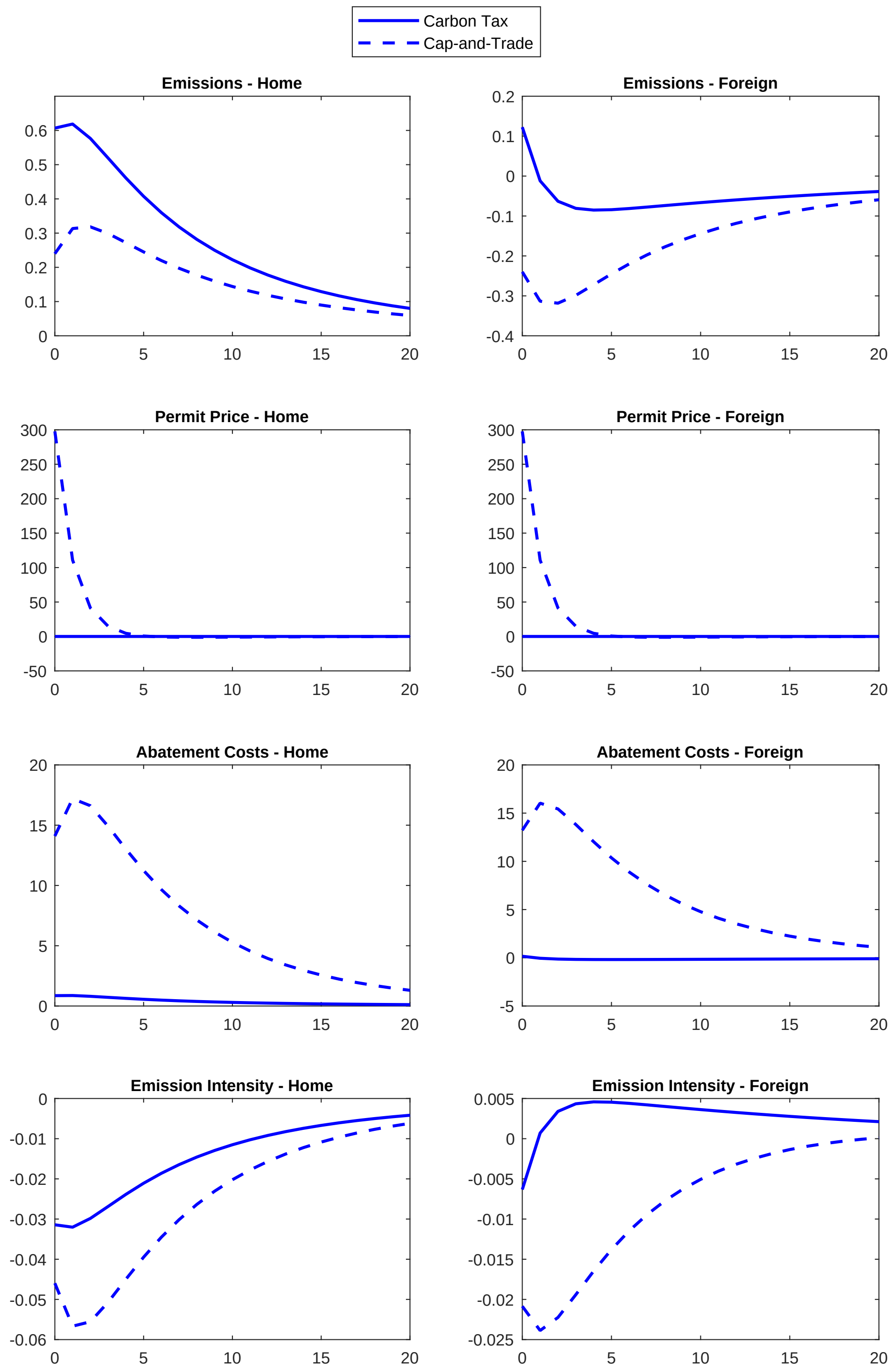
Figure 1: Dynamic Response to a 1% TFP Shock - Macroeconomic Variables



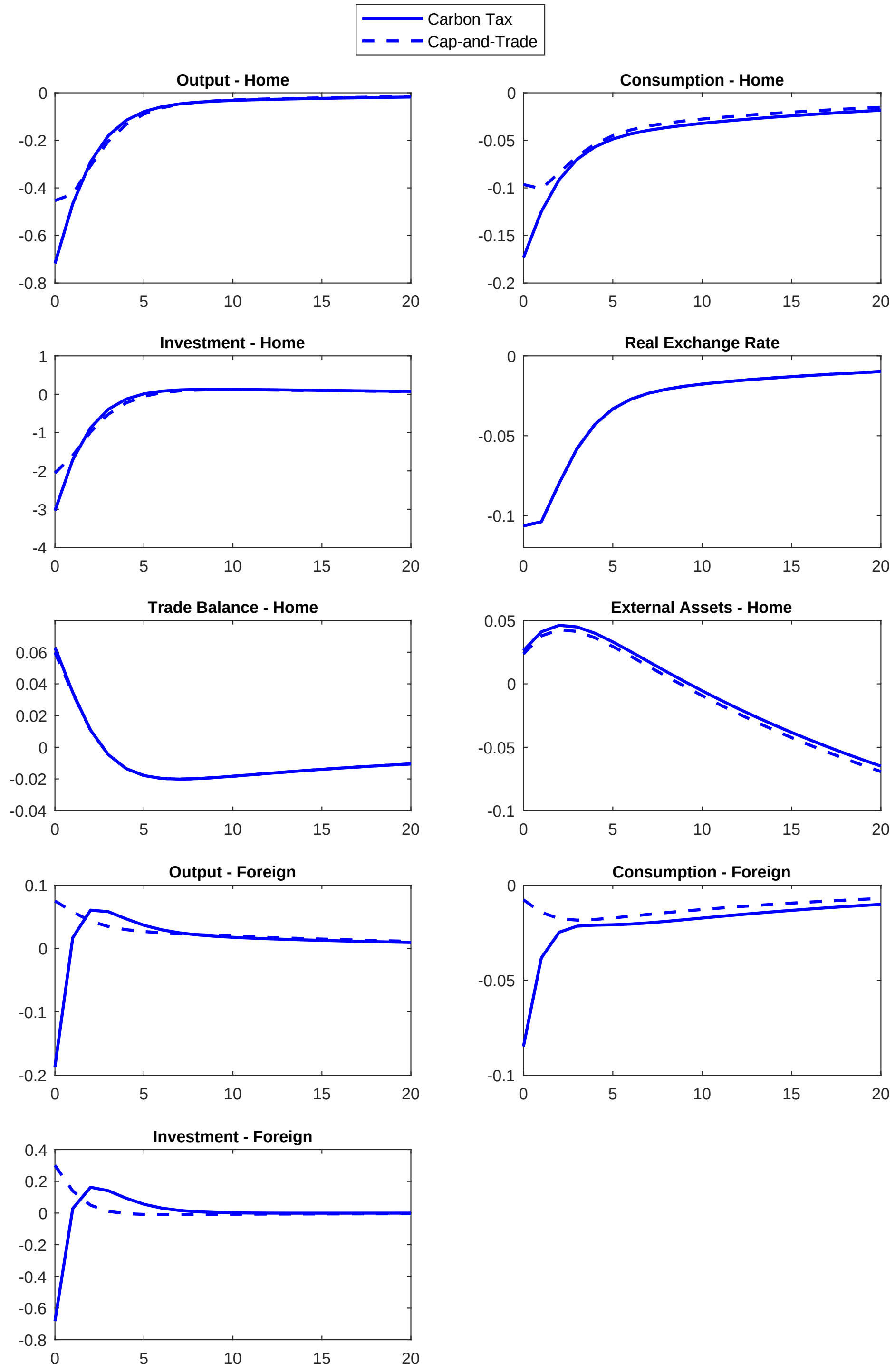
Note: the figure plots the impulse responses to a positive shock to TFP for a 20-quarter time horizon; results are reported as percentage deviations from the initial steady state with the exception of trade balance which is reported in percentage points.

Figure 2: Dynamic Response to a 1% TFP Shock - Environmental Variables



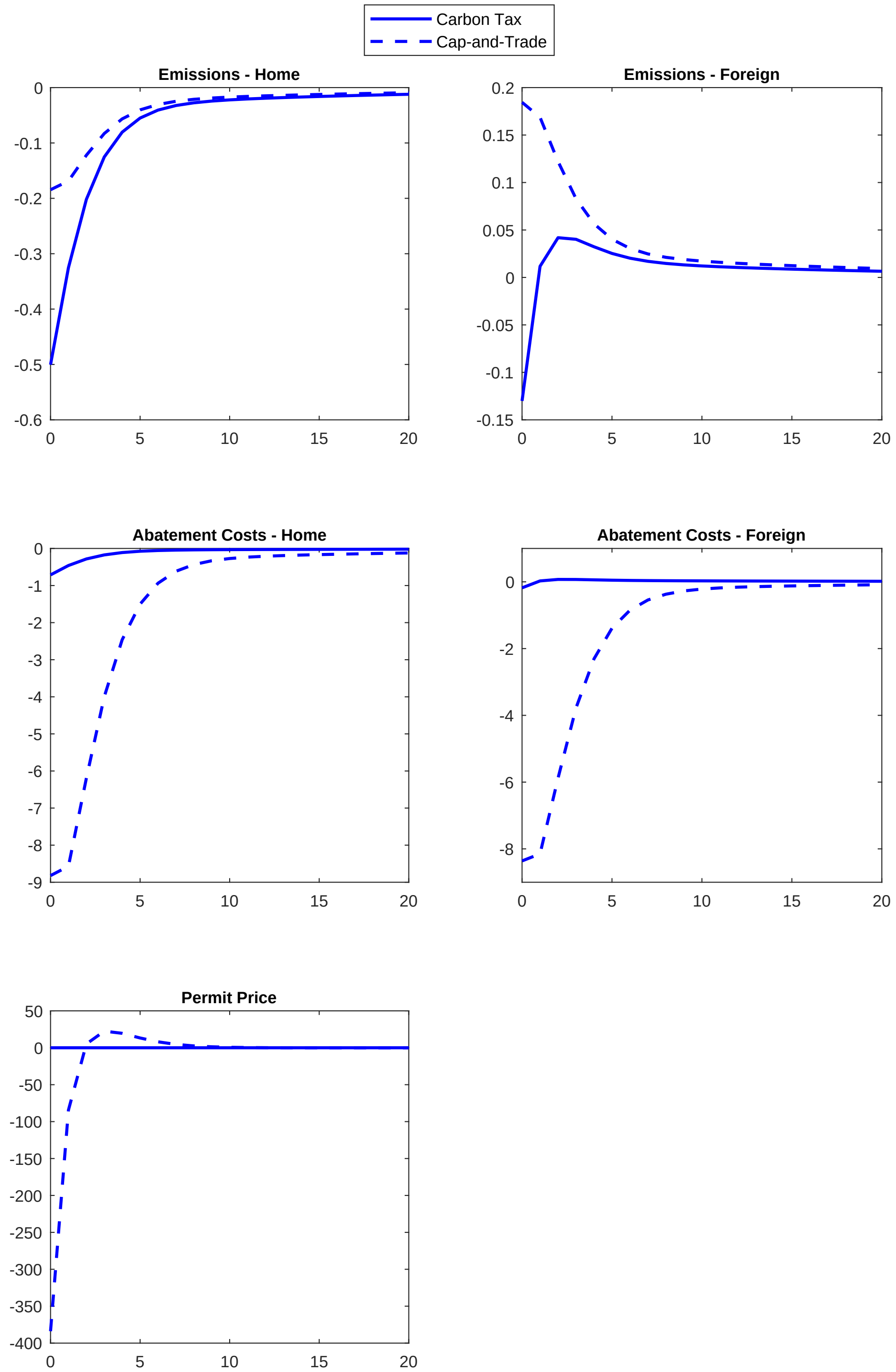
Note: the figure plots the impulse responses to a positive shock to TFP for a 20-quarter time horizon; results are reported as percentage deviations from the initial steady state.

Figure 3: Dynamic Response to a 0.5% Monetary Policy - Macroeconomic Variables



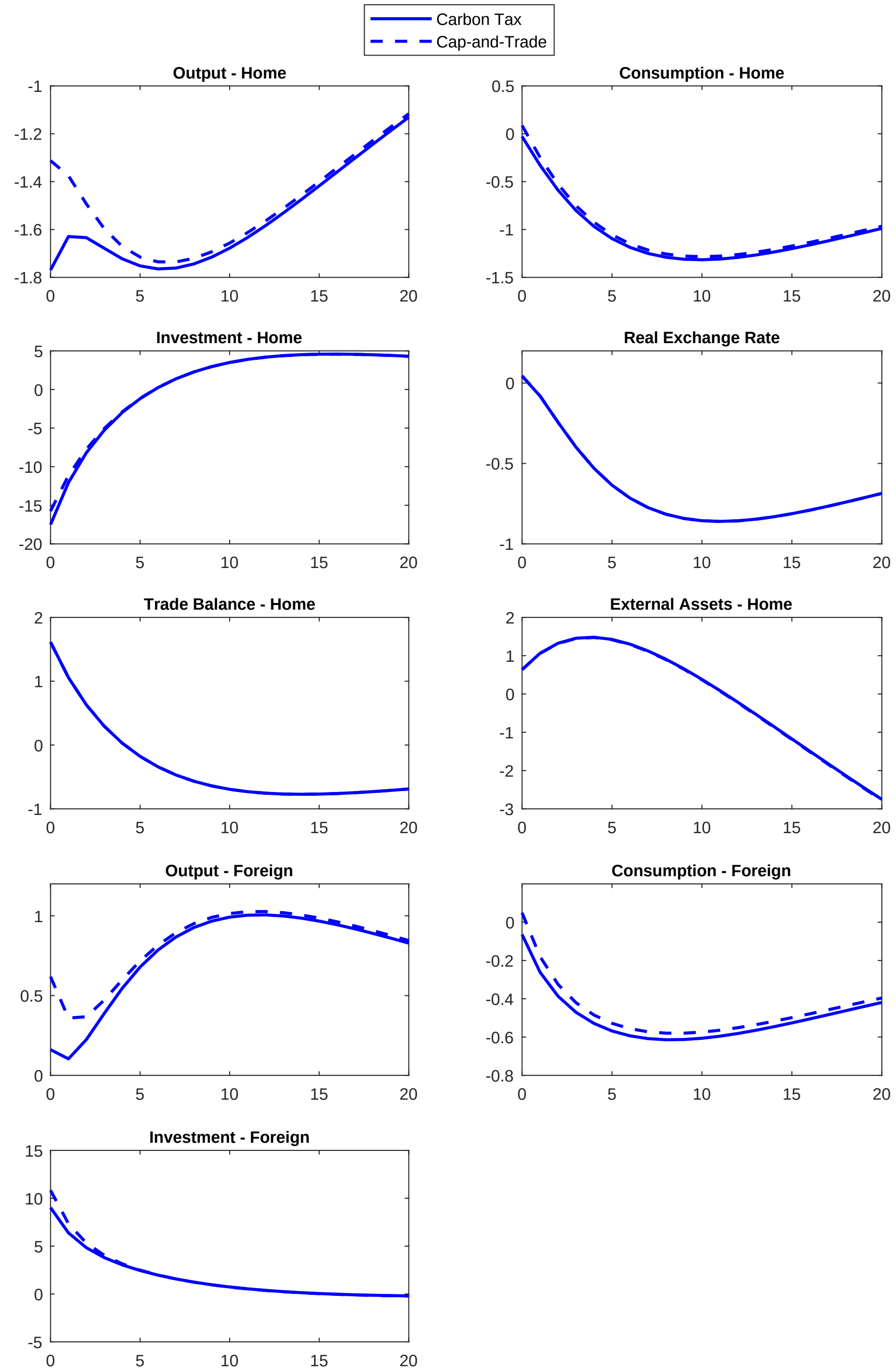
Note: the figure plots the impulse responses to a positive shock to the risk-free interest rate for a 20-quarter time horizon; results are reported as percentage deviations from the initial steady state with the exception of trade balance which is reported in percentage points.

Figure 4: Dynamic Response to a 0.5% Monetary Policy - Environmental Variables



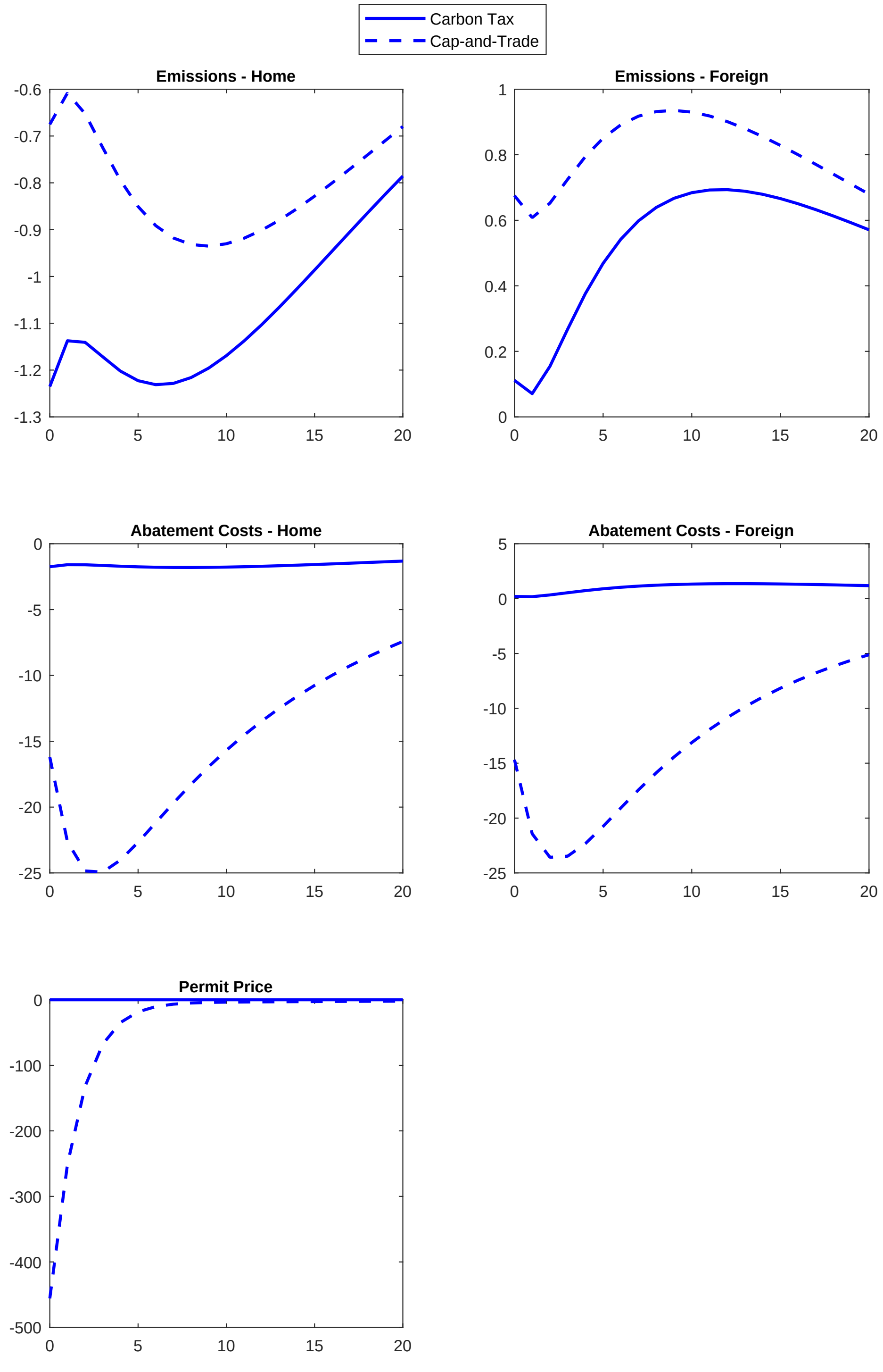
Note: the figure plots the impulse responses to a positive shock to the risk-free interest rate for a 20-quarter time horizon; results are reported as percentage deviations from the initial steady state.

Figure 5: Dynamic Response to a -1% Capital-Quality Shock - Macroeconomic Variables



Note: the figure plots the impulse responses to a negative shock to quality of capital for a 20-quarter time horizon; results are reported as percentage deviations from the initial steady state with the exception of trade balance which is reported in percentage points.

Figure 6: Dynamic Response to a -1% Capital-Quality Shock - Environmental Variables



Note: the figure plots the impulse responses to a negative shock to quality of capital for a 20-quarter time horizon; results are reported as percentage deviations from the initial steady state.

Table 1: Parametrization

Parameter	Value	Description
α	1/3	technology parameter
β	0.99	quarterly discount factor
$1-\gamma$	1-0.304	elasticity of emissions to output
γ_I	1.5	parameter for capital adjustment costs
γ_p	58.25	degree of price rigidities
γ_μ	1.5	parameter for abatement adjustment costs
ψ_μ	10	degree of asymmetry of abatement adjustment costs
δ	0.025	quarterly capital depreciation rate
ϵ	0.3829	emissions scale parameter
$1-\eta$	1-0.9979	pollution decay rate
θ_1	1	abatement cost function parameter
θ_2	2.8	abatement cost function parameter
ι_Π	1.5	Interest rate rule: inflation coefficient
κ	0.70	share of domestic goods used in the final sector
ξ_l	3.8826	disutility of labor parameter
ρ	1.5	elasticity of substitution between Home and Foreign goods
ρ_A	0.85	persistence of productivity shock
ρ_K	0.85	persistence of quality of capital shock
ρ_R	0.5	persistence of monetary policy shock
σ	6	elasticity of substitution between good varieties
ϕ_c	1.2	coefficient of relative risk aversion
ϕ_l	1	inverse of the Frisch elasticity of labor supply
χ	2.3069e-06	intensity of negative externality on output
A	13.2581	total factor productivity - TFP

Table 2: International Transmission of Shocks - Benchmark Case (%)

	σ_{Y^D}	$\sigma_{Y^{D*}}/\sigma_{Y^D}$	$\rho(Y^D, Y^{D^*})$
Carbon Tax			
TFP	4.664	17.990	-15.311
monetary	5.215	20.282	46.026
capital quality	8.292	37.828	-20.342
Cap-and-Trade			
TFP	4.204	16.103	-96.869
monetary	4.396	10.052	-95.775
capital quality	7.685	35.299	-54.485

Note: the table reports moments generated by the model for 200 realizations of shock sequences of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.1%.

Table 3: International Transmission of Shocks - Imperfect Complementarity between Home and Foreign Goods (%)

	σ_{Y^D}	$\sigma_{Y^{D*}}/\sigma_{Y^D}$	$\rho(Y^D, Y^{D^*})$
Carbon Tax			
TFP	4.243	25.190	-8.099
monetary	4.776	27.544	57.832
capital quality	7.813	41.831	-23.163
Cap-and-Trade			
TFP	3.843	19.051	-81.260
monetary	3.999	8.454	-42.918
capital quality	7.187	40.427	-56.139

Note: the table reports moments generated by the model for 200 realizations of shock sequences of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.1%.

Table 4: International Transmission of Shocks - High Degree of Openness (%)

	σ_{Y^D}	$\sigma_{Y^{D*}}/\sigma_{Y^D}$	$\rho(Y^D, Y^{D^*})$
Carbon Tax			
TFP	3.977	33.880	-14.481
monetary	4.335	38.529	46.638
capital quality	6.9560	88.080	-48.752
Cap-and-Trade			
TFP	3.642	26.197	-72.073
monetary	3.678	18.326	-17.040
capital quality	6.912	77.995	-67.898

Note: the table reports moments generated by the model for 200 realizations of shock sequences of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.1%.

Table 5: International Transmission of Shocks - Currency Union (%)

	σ_{Y^D}	$\sigma_{Y^{D*}}/\sigma_{Y^D}$	$\rho(Y^D, Y^{D^*})$
Carbon Tax			
TFP	4.3440	26.622	22.468
monetary	6.364	100	100
capital quality	7.926	33.771	-2.210
Cap-and-Trade			
TFP	3.911	13.853	-54.836
monetary	4.402	100	100
capital quality	7.223	33.228	-37.401

Note: the table reports moments generated by the model for 200 realizations of shock sequences of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.1%.

Appendix A

Equilibrium Conditions

Let define $B_t^* = \frac{S_t B_t^*}{P_t}$, $S_t^R = \frac{S_t P_t^*}{P_t}$ and $\frac{S_t}{S_{t-1}} = 1 + s_t$, the following equations describe the decentralized competitive equilibrium of the model. Since we assume that the structure of the Foreign economy is isomorphic to that of the Home, we present only the equations for the Home economy and common equations.

$$C_t^{-\varphi_C} = \lambda_t, \tag{A-1}$$

$$\begin{aligned} q_t &= \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \left[r_{K,t+1} + \gamma_I \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right) \frac{I_{t+1}}{K_{t+1}} - \frac{\gamma_I}{2} \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right)^2 \right] \right\} + \\ &\quad + \beta(1-\delta) E_t \left\{ e^{u_{K,t+1}} \frac{q_{t+1}\lambda_{t+1}}{\lambda_t} \right\}, \end{aligned} \tag{A-2}$$

$$-\xi_L L_t^{\varphi_L} + \lambda_t w_t = 0, \tag{A-3}$$

$$\gamma_I \left(\frac{I_t}{K_t} - \delta \right) = q_t - 1, \tag{A-4}$$

$$\frac{1}{R_t} = \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\Pi_{t+1}} \right\}, \tag{A-5}$$

$$K_{t+1} = I_t + (1-\delta) e^{u_{K,t}} K_t, \tag{A-6}$$

$$r_{K,t} = \alpha \Psi_t \frac{Y_t^D}{K_t}, \tag{A-7}$$

$$w_t = (1-\alpha) \Psi_t \frac{Y_t^D}{L_t}, \tag{A-8}$$

$$\begin{aligned} p_{E,t}(Y_t^D)^{(1-\gamma)} &= \theta_2 \theta_1 \mu_t^{\theta_2 - 1} p_t^D Y_t^D - \gamma_\mu \frac{1}{\mu_{t-1}} \frac{\exp\left(-\psi_\mu \left(\frac{\mu_t}{\mu_{t-1}} - 1\right)\right) - 1}{\psi_\mu} + \\ &\quad + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \gamma_\mu \frac{\mu_{t+1}}{\mu_t^2} \frac{\exp\left(-\psi_\mu \left(\frac{\mu_{t+1}}{\mu_t} - 1\right)\right) - 1}{\psi_\mu}, \end{aligned} \tag{A-9}$$

$$Y_t^D = \Lambda_t A_t \left(e^{u_{K,t}} K_t\right)^\alpha L_t^{1-\alpha}, \tag{A-10}$$

$$\begin{aligned} &\left(1 - \theta_1 \mu_t^{\theta_2}\right)(1-\sigma) + \sigma MC_t + \\ &- \gamma_p \left(\Pi_t^D - 1\right) \Pi_t^D + \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \gamma_p \left(\Pi_{t+1}^D - 1\right) \left(\Pi_{t+1}^D\right)^2 \frac{Y_{t+1}^D}{Y_t^D} \frac{1}{\Pi_{t+1}} \right\} = 0, \end{aligned} \tag{A-11}$$

$$MC_t = \frac{p_{E,t}}{p_t^D}(1-\gamma)(1-\mu_t)\epsilon(Y_t^D)^{-\gamma} + \Psi_t \frac{1}{p_t^D}, \tag{A-12}$$

$$Y_t = [\kappa^{\frac{1}{\rho}}(Y_t^H)^{\frac{\rho-1}{\rho}} + (1-\kappa)^{\frac{1}{\rho}}(M_t)^{\frac{\rho-1}{\rho}}]^{\frac{\rho}{\rho-1}}, \tag{A-13}$$

$$Y_t^H = \kappa Y_t \left(\frac{1}{p_t^D}\right)^{\rho}, \tag{A-14}$$

$$Y_t^D = Y_t^H + X_t, \tag{A-15}$$

$$M_t = (1-\kappa)\left(\frac{1}{p_t^{D^*}}\frac{1}{S_t^R}\right)^{\rho} Y_t, \tag{A-16}$$

$$\Pi_t = \frac{p_{t-1}^D}{p_t^D}\Pi_t^D, \tag{A-17}$$

$$Tr_t = p_{E,t}E_t, \tag{A-18}$$

$$X_t = (1-\kappa)\left(\frac{S_t^R}{p_t^D}\right)^{\rho} Y_t^*, \tag{A-19}$$

$$p_t^D Y_t^D = C_t + I_t + p_t^D AC_t + p_t^D X_t - S_t^R p_t^{D^*} M_t + P_t\Gamma_K(I_t, K_t) + P_t\Gamma_{\mu_t}(\mu_t) + \frac{\gamma_p}{2}(\Pi_t^D - 1)^2 p_t^D Y_t^D, \tag{A-20}$$

$$\frac{R_t}{R} = \left(\frac{\Pi_t}{\Pi}\right)^{\iota_\Pi} e^{u_{R,t}}, \tag{A-21}$$

$$E_t = (1-\mu_t)\epsilon(Y_t^D)^{(1-\gamma)}, \tag{A-22}$$

$$AC_t = \theta_1 \mu_t^{\theta_2} Y_t^D, \tag{A-23}$$

$$u_{K,t} = \rho_K u_{K,t-1} + \epsilon_{K,t}, \tag{A-24}$$

$$u_{A_t} = \rho_A u_{A_{t-1}} + \varepsilon_{A,t}, \tag{A-25}$$

$$u_{R,t} = \rho_R u_{R,t-1} + \epsilon_{R,t}. \tag{A-26}$$

Common equations determine the time path of the depreciation rate of the domestic currency s_t, the net external asset position f_t^*, the real exchange rate S_t^R, the stock of pollution Z_t in the atmosphere and the related damage Λ_t:

$$\frac{1}{R_t^*} = \beta E_t\left\{\frac{\lambda_{t+1}(1+s_{t+1})}{\Pi_{t+1}\lambda_t}\right\}, \tag{A-27}$$

$$f_t^* = \frac{R_{t-1}^*(1+s_t)}{\Pi_t} f_{t-1}^* - S_t^R p_t^{D*} M_t + p_t^D X_t, \tag{A-28}$$

$$S_t^R = S_{t-1}^R(1+s_t)\frac{\Pi_t^*}{\Pi_t}, \tag{A-29}$$

$$Z_t = \eta Z_{t-1} + E_t + E_t^* + E_t^{NI}, \tag{A-30}$$

$$\Lambda_t = \exp[-\chi(Z_t - \overline{Z})]. \tag{A-31}$$

The overall economy is then described by 24 variables related to Home, $\{C_t,\ E_t,\ I_t,\ K_t,\ L_t,\ M_t,\ MC_t,\ p_t^D,\ p_{E,t},\ q_t,\ R_t,\ r_{K,t},\ Tr_t,\ w_t,\ X_t,\ Y_t,\ Y_t^D,\ Y_t^H,\ AC_t,\ \lambda_t,\ \mu_t,\ \Pi_t,\ \Pi_t^D,\ \Psi_t\}$, 24 variables related to Foreign $\{C_t^*,\ E_t^*,\ I_t^*,\ K_t^*,\ L_t^*,\ M_t^*,\ MC_t^*,\ p_t^{D^*},\ p_{E,t}^*,\ q_t^*,\ R_t^*,\ r_{K,t}^*,\ Tr_t^*,\ w_t^*,\ X_t^*,\ Y_t^*,\ Y_t^{D*},\ Y_t^{H*},\ AC_t^*,\ \lambda_t^*,\ \mu_t^*,\ \Pi_t^*,\ \Pi_t^{D*},\ \Psi_t^*\}$, and 5 common variables, $\{f_t^*,\ s_t,\ S_t^R,\ Z_t, \Lambda_t\}$.

Note that under a national cap-and-trade regime, $E_t = \bar{E}$ and $E_t^* = \bar{E}^*$ with $\bar{E} = \bar{E}^*$; under a carbon tax $p_{E,t} = p_E$ and $p_{E,t}^* = p_E^*$, with $p_E = p_E^*$; under international cap-and-trade regime, $E_t + E_t^* = \bar{E} + \bar{E}^*$ and $p_{E,t} = p_{E,t}^*$.

Appendix B

Table B-1 reports simulation results under the assumption that firms are able to freely choose the level of environmental efficiency of their technology, i.e. we set $\gamma_\mu = 0$ so that $\Gamma_{\mu_t}(\mu_t) = 0$. Table B-2 reports simulation results under the assumption that firms face symmetric adjustment costs when changing the level of environmental efficiency of their technology μ, i.e. we set $\psi_\mu = 0$ so that $\Gamma_{\mu_t}(\mu_t) = \frac{\gamma_\mu}{2}\left(\frac{\mu_t}{\mu_{t-1}} - 1\right)^2$.

Table B-1: International Transmission of Shocks - No Adjustment Costs on Abatement Changes (%)

	σ_{Y^D}	$\sigma_{Y^{D*}}/\sigma_{Y^D}$	$\rho(Y^D, Y^{D^*})$
Carbon Tax			
TFP	4.6637	17.9899	-15.3102
monetary	5.2153	20.2816	46.0240
capital quality	8.2917	37.8275	-20.3422
Cap and Trade			
TFP	4.5775	18.5293	-25.4343
monetary	5.1418	19.8351	40.4153
capital quality	8.1324	38.4456	-25.9909

Note: the table reports moments generated by the model for 200 realizations of shock sequences of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.1%.

Table B-2: International Transmission of Shocks - Symmetric Adjustment Costs on Abatement Changes (%)

	σ_{Y^D}	$\sigma_{Y^{D*}}/\sigma_{Y^D}$	$\rho(Y^D, Y^{D^*})$
Carbon Tax			
TFP	4.6637	17.9901	-15.3106
monetary	6.9743	19.3162	21.8797
capital quality	9.4931	34.1524	-18.6353
Cap and Trade			
TFP	4.2043	16.1028	-96.8690
monetary	6.0514	13.1904	-94.0298
capital quality	8.7428	31.8529	-57.2250

Note: the table reports moments generated by the model for 200 realizations of shock sequences of size 10,000, dropping the first 100 observations from each realization. We set the standard deviations of all shocks to 0.1%.