Mitigating Policies for Pollutant Emissions in a DSGE for the Brazilian Economy

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The views expressed in this paper are those of the authors and should not be interpreted as representing the positions of the Banco Central do Brasil or its board members.

Abstract

This paper examines the dynamic behavior of the Brazilian economy under policy regimes aimed at controlling pollutant emissions and limiting environmental damage. Greenhouse gas (GHG) emissions are assumed to be of two types: carbon from fossil resources burning for energy generation (i.e., thermoelectric) or carbon and non-carbon outputs from production processes (i.e., methane from cattle). Firms optimally decide on the demand for fossil and green energy, as the level of effort dedicated to abating emissions coming from production processes. Two alternative policies for emissions, which include emissions taxation (fixed cost) and emission permits trade (quantity caps), are introduced into an open-economy DSGE model for the Brazilian economy. Departing from the estimated parameters of the original version of the model, ratios in the new block of equations for the energy and emissions are calibrated using sectoral data, and some elasticities are set to reproduce the sensibility to some shocks implicit in the NGFS[2] scenarios (Net Zero 2050). Simulations indicate neither of the emissions policies can induce transition in the energy matrix without a green investment policy. The approach adopted here is a first step in building a macroeconomic model capable of challenging scenarios from more specialized models dedicated to energy and emissions by better assessing possible effects and feedback related to the iterations with macroeconomic dynamics. Despite the difficulties concerning the limited availability of data in higher frequency, results indicate those modeling approaches are sufficiently flexible to incorporate the main aspects of energy and emission, serving as valuable tools for policy analysis.

Keywords: DSGE models, environmental policy, macroeconomic dynamics, monetary policy

JEL Classification: E32, E50, Q58

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1 Introduction

The assessment of the economic implications of climate change, resulting from greenhouse gas (CHG) emissions, has been identified as one of the most challenging issues for economic modeling. Those economic implications come from physical risks that can directly damage firms' productivity and transition risks associated with implementing policies to reduce current emissions to mitigate future physical damages. The theme has attracted the interest of academic researchers and policymakers (e.g., central banks), who have been pushed to include climate issues in their research agendas and cooperate in developing new approaches to macroeconomic modeling for climate scenarios.

Experience shows the social costs of GHG emissions are more significant than the private costs incurred by the emitter, a perfect example of a negative externality. Carbon taxation is considered an effective policy instrument to reduce emissions since it can factor the external social costs of carbon emissions into private transactions, providing an incentive to reduce carbon emissions. An alternative policy framework would be to cap total emissions, allowing a limited number of emissions permits to be traded in a free market pricing environment. By directly targeting the GHG content of production, such policies incentivize innovation in greener technologies, inducing environmentally sustainable production and energy use, thus allowing for a transition to a greener economy.

Multiple factors can influence the level of the economic impact of emission price increases. Notably, the effectiveness in affecting firms' and households' investments and consumption decisions depends significantly on whether these are credibly implemented (expectations channel). Higher energy prices, a direct consequence of higher emissions costs, can primarily affect economic activity and inflation, increasing production costs and dampening domestic demand by lowering real corporate profits and household incomes.

Fiscal policy is not the focus of this paper. However, despite some budget-neutral mitigation measures (e.g., regulation), fiscal policy can be essential if emission tax revenues are used to finance transition projects. Such initiatives of subsidizing green technology can mitigate output losses from emissions tax increases more efficiently than alternative public spending measures (e.g., transferences to consumers). Since it gives rise to an output/inflation trade-off, the way emission policies propagate to the economy is also influenced by monetary policy.

Environmental economics literature is moving in the direction of exploring the macroeconomic implications of environmental regulations and their performance in dynamic stochastic general equilibrium (DSGE) models, as in Fischer and Springborn (2011), Heutel (2012), Angelopoulos et al. (2013), and Bosetti and Maffezzoli (2014). Ganelli and Tervala (2011) introduce imperfect price adjustments and lack of perfect competition designed to study the international transmission of environmental policy shocks. Annicchiarico and Di Dio (2015) develop a closed economy New Keynesian model embodying pollutant emission, abatement technology, and environmental damage to study the business cycle under alternative environmental policy regimes (i.e., cap-and-trade, carbon tax, and intensity target). They also explore the role played by nominal rigidities in shaping the macroeconomic performances of the environmental policy regime put in place. Annicchiarico and Di Dio (2017) examine the optimal environmental and monetary policy mix in a New Keynesian model, finding that the optimal response of the economy to productivity shocks is shown to depend crucially on the instruments policymakers have available, the intensity of the distortions they must address and the way they interact.

Policymakers have been interested in assessing the cyclical economic fluctuations that could result from emission policies, considering their interaction with other current macroeconomic policies (e.g., monetary policy). Brand et al. (2023) provide a model-based assessment of the macroeconomic impact, with a focus on the euro area, of a higher carbon price path that supports the transition to a low-carbon economy and address the high level of uncertainty in gauging the impact of carbon price increases. Coenen et al. (2023) assess the macroeconomic effects of transition policies aimed at reducing carbon emissions in the euro area, focusing on tax policies that raise the price of carbon emissions.

This paper seeks to contribute to the debate on climate change implications to macroeconomic fluctuations, developing an adapted version of the medium-scale DSGE model currently used by the Banco Central do Brasil (SAMBA Model) to address climate issues. In some aspects, our approach follows the one in Annicchiarico and Di Dio (2015). It uses a similar approach to model productivity damages and the firms' decisions on their optimal effort to decrease emissions to reduce the cost of their emissions. We consider two of the environmental policy regimes they have assessed, evaluating the macroeconomic implications of each one. However, the approach here differs concerning many aspects. For instance, we model brown and green energy production sectors that demand specific investments and we disaggregate emissions into two components, resulting from fossil energy and the production process.

The paper is organized as follows. Section 2 provides only an overview of the new climate block of equations (concerning energy and emissions) added to the base model. This latter is comprehensively described in Fasolo et al. (2023). Section 3 details the calibration procedure. Section 4 analyses the impulse responses of the model. Section 5 reports on some policy exercises and comparisons with the NGFS NetZero2050 scenario. The last section concludes the paper.

2 The model

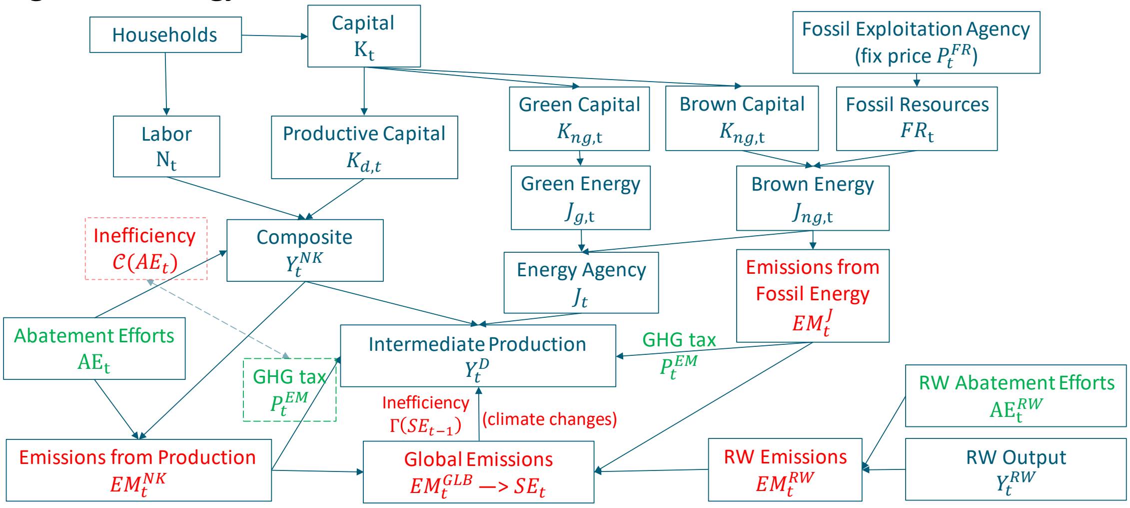
The model in this paper was built on a DSGE model structure very close to the one currently in use at the Banco Central do Brasil, known as the SAMBA model. This model, first documented by Castro et al. (2011 and 2015), is an open-economy DSGE model with a large set of nominal and real rigidities, such as wage and price stickiness, habit persistence in consumption, rule-of-thumb households and capital adjustment costs. A more recent version of the SAMBA model, which includes many additional developments, can be found in Fasolo et al. (2023). The new version brings a reformulation of the labor-market block that allows for involuntary unemployment, the direct introduction of imported goods in the final consumption bundle, and a new specification for the rest-of-the-world block based on vector autoregressions (VAR).

The subsections below detail the new structure to address climate issues added to the base DSGE model described in Fasolo et al. (2023). The new structure has the following main characteristics: green energy producers and brown energy producers dispute investments with other production sectors; an energy agency that aggregates green and brown energies in one composed energy; domestic emissions come specifically from fossil resources burning off energy and output from the production process (as a function of capital and labor use); rest of the world emission is a function of rest of world output; global emission damages domestic productivity; firms optimally decide total energy demand for production (composite of green and brown) as the level of effort to decrease emissions from production processes.

2.1. Energy Producers

Figure 1 provides an overview of the new energy and emission block of the model, highlighting the main components and relations. The energy production sector comprises two separate sub-sectors: green and brown energy. For modeling simplicity, the energy sector is assumed to be capital-intensive, with no labor demand for energy production. The green energy sector uses only capital as input, and the brown sector demands capital and fossil resources, so both sectors dispute investments with the intermediate production sector. Additionally, the model includes adjustment costs of investment, which could limit the capacity to rapidly increase the green energy supply and reduce the brown energy supply. A detailed description of each component of this new block is given in the following subsections.

Figure 1 - Energy and emission block



2.1.1 Green Energy Producers

The domestic green (non-fossil) energy producer is assumed to be capital intensive and operates in perfectly competitive markets, using physical capital $K_{g,t}$ to produce the domestic green energy $J_{g,t}^D$ through a linear technology

$$J_{g,t}^D = AD_g \, Z_{g,t}^D \, K_{g,t} \tag{1}$$

where $Z_{g,t}^D$ is a domestic transitory green technology shock, and AD_g is constant.

The problem of the domestic green energy producer involves choosing optimal quantities of capital to minimize total input, subject to the technology constraint and taking as given prices of capital $R^K_{g,t}$

$$\min_{K_{g,t}} \left\{ \begin{matrix} R^K_{g,t} K_{g,t} \\ +P^E_{g,t}\left(J^D_{g,t} - AD_g Z^D_{g,t} K_{g,t}\right) \end{matrix} \right\}$$

where and $P^E_{g,t}$ is the Lagrange multiplier associated with the technology constraint. The first-order condition (FOC) of the problem above is

$$R^K_{g,t} = P^E_{g,t} AD_g Z^D_{g,t} \tag{2}$$

The equation above represents a market equilibrium condition that stablishes a direct relation between the price of the green energy, $P^E_{g,t}$, and the cost of capital, $R^K_{g,t}$, of the green energy producer. It is a necessary condition for the optimality of a strictly positive capital allocation in green energy production (otherwise, it would be zero, or infinite).

2.1.2 Brown Energy Producers

Domestic brown (fossil) energy producer operates in perfectly competitive markets, using physical capital K_t and fossil resources FR_t to produce the domestic fossil energy $J^D_{ng,t}$ through a Constant Elasticity of Substitution (CES) technology

$$J^D_{ng,t} = AD_{ng} Z^D_{ng,t} \left\{ (1-\varsigma_{ng}) \left(\frac{K_{ng,t-1}}{(1-\varsigma_{ng})} \right)^{1-\frac{1}{\eta_{ng}}} + \varsigma_{ng} \left(\frac{FR_t}{\varsigma_{ng}} \right)^{1-\frac{1}{\eta_{ng}}} \right\}^{\frac{\eta_{ng}}{\eta_{ng}-1}} \tag{3}$$

where $Z^D_{ng,t}$ is a domestic transitory technology shock, and AD_{ng} is constant.

The problem of the domestic fossil energy producer involves choosing optimal quantities of capital and fossil resources to minimize total input, subject to the technology constraint and taking as given prices of capital $R^K_{ng,t}$ and energy V^{FR}_t, to minimize costs:

$$\min_{K_{ng,t-1}, FR_t} \left\{ \begin{matrix} R^K_{ng,t} K_{ng,t-1} + V^{FR}_t FR_t \\ +P^E_{ng,t} \left(J^D_{ng,t} - AD_{ng} Z^D_{ng,t} \left\{ (1-\varsigma_{ng}) \left(\frac{K_{ng,t-1}}{(1-\varsigma_{ng})} \right)^{1-\frac{1}{\eta_{ng}}} + \varsigma_{ng} \left(\frac{FR_t}{\varsigma_{ng}} \right)^{1-\frac{1}{\eta_{ng}}} \right\}^{\frac{\eta_{ng}}{\eta_{ng}-1}} \right) \end{matrix} \right\}$$

where and $P^E_{ng,t}$ is the Lagrange multiplier associated with the technology constraint.

The FOCs of the problem above are

$$K_{ng,t} = \left(1-\varsigma_{ng}\right) \left(\frac{R^K_{ng,t}}{P^E_{ng,t}} \right)^{-\eta_{ng}} \frac{J^D_{ng,t}}{\left(AD_{ng} Z^D_{ng,t}\right)^{1-\eta_{ng}}} \tag{4}$$

and

$$FR_t = \varsigma_{ng}\left(\frac{V_t^{FR}}{P_{ng,t}^E}\right)^{-\eta_{ng}} \frac{J_{ng,t}^D}{\left(AD_{ng}Z_{ng,t}^D\right)^{1-\eta_{ng}}} \tag{5}$$

The two equations above determine the optimal demand for inputs (capital and fossil resources) from the brown energy firm, given the inputs prices, the brown energy price, and the total supply of brown energy. Note that, since $\eta_{ng} > 0$, the demands for inputs decrease when inputs prices increase.

2.2 Capital stock and investment

The total capital stock of the economy, K_t , is the sum of the capital allocated to the green and brown energy sectors, $K_{g.t}$ and $K_{ng.t}$, and $K_{d.t}$ used as input for the intermediate good production

$$K_t = K_{g.t} + K_{ng.t} + K_{d.t} \tag{6}$$

The three capital stocks follow the same type of accumulation rule, which is costly and subject to investment-specific innovations, as described by the following law of motion for capital

$$K_{s.t+1} = (1-\delta)K_{s.t} + \left[1 - \frac{\vartheta}{2}\left(\frac{I_{s.t}}{Z_{s,t}^I I_{s.t-1}}\right)^2\right] I_{s.t} \tag{7}$$

where $s = g,\ ng$, or d refers to each specific sector, δ is the capital depreciation rate, $\left[1 - \frac{\vartheta_s}{2}(.)^2\right]$ is a convex adjustment cost function, with $\vartheta_s > 0$, $I_{s.t}$ is the sectoral investment and $Z_{s,t}^I$ is an investment-specific technology shock of sector s. As usual, the adjustment cost helps to match the empirical volatility of investment. For consistency, each shock $Z_{s,t}^I$ affects the efficiency of the newly installed investment in the sector s by shifting its growth rate, not its level.

2.3. Energy sector agency

An agency of the energy sector aggregates differentiated qualities of energy resources according to their environmental impacts (brown/fossil and green/non-fossil), producing homogeneous primary energy (J_t), which is then supplied to produce domestic goods. We assume the energy agency combines the differentiated energy resources qualities through a Dixit-Stiglitz aggregator:

$$\mathrm{J_t} = \left(\alpha_g\left(\frac{\mathrm{J_{g,t}}}{\alpha_g}\right)^{\frac{\epsilon_g-1}{\epsilon_g}} + (1-\alpha_g)\left(\frac{\mathrm{J_{ng,t}}}{(1-\alpha_g)}\right)^{\frac{\epsilon_g-1}{\epsilon_g}}\right)^{\frac{\epsilon_g}{\epsilon_g-1}} \tag{8}$$

where $\epsilon_g > 1$ is the elasticity of substitution between fossil and non-fossil energy.

The optimization problem of the energy agency is given by

$$\max_{J_{g,t},J_{ng,t}} \left\{ V_t^J \left(\alpha_g \left(\frac{J_{g,t}}{\alpha_g} \right)^{\frac{\epsilon_g - 1}{\epsilon_g}} + (1-\alpha_g) \left(\frac{J_{ng,t}}{(1-\alpha_g)} \right)^{\frac{\epsilon_g - 1}{\epsilon_g}} \right)^{\frac{\epsilon_g}{\epsilon_g - 1}} - V_t^g J_{g,t} - V_t^{ng} J_{ng,t} \right\}$$

where V_t^g and V_t^{ng} are prices of non-fossil and fossil energy, respectively.

From the FOCs, the solution to the problem faced by the energy agency implies the following demand for differentiated energy quality:

$$J_{g,t} = \alpha_g \left(\frac{V_t^g}{V_t^J} \right)^{-\epsilon_g} J_t \quad \text{and} \quad J_{ng,t} = (1-\alpha_g) \left(\frac{V_t^{ng}}{V_t^J} \right)^{-\epsilon_g} J_t \tag{9}$$

The break-even condition for the energy agency pins down the aggregate cost of energy resources exploitation index

$$V_t^J = \left(\alpha_g (V_t^g)^{1-\epsilon_g} + (1-\alpha_g)(V_t^{ng})^{1-\epsilon_g} \right)^{\frac{1}{1-\epsilon_g}} \tag{10}$$

Therefore, aggregated demand for primary energy satisfies $\bar{J}_t = J_t\, \vartheta_t^g$ where ϑ_t^g is the energy cost dispersion, defined as

$$\vartheta_t^g := \alpha_g \left(\frac{V_t^g}{V_t^J} \right)^{-\epsilon_g} + (1-\alpha_g) \left(\frac{V_t^{ng}}{V_t^J} \right)^{-\epsilon_g} \tag{11}$$

2.4. Emissions and intermediate production

A new specification for the technology of the domestic input producer was introduced, different from the original in Fasolo et al. (2023), to include the demand for composite inputs of other types of energy, in addition to a composite of capital and labor. The producer operates in perfectly competitive markets, using energy J_t and composite Y_t^{KN} of physical capital and labor to produce the domestic input Y_t^D through a Constant Elasticity of Substitution (CES) technology:

$$Y_t^D = \left(1 - \Gamma(SE_{t-1})\right) Z_{d,t}^D \left\{ (1-\varsigma)(Y_t^{KN})^{1-\frac{1}{\eta_e}} + \varsigma (J_t)^{1-\frac{1}{\eta_e}} \right\}^{\frac{\eta_e}{\eta_e - 1}} \tag{12}$$

where the process $Z_{d,t}^D$ is a domestic transitory technology shock and SE_t represents the stock of global emissions, and

$$\Gamma(SE_t) = \beta_{se} \,.\, SE_t^{\alpha_{se}} \tag{13}$$

is an increasing function of the stock of global emissions SE_t, where $\alpha_{se} > 0$ and $\beta_{se} > 0$ are technological parameters.

The dynamic of the stock of global emissions is given by

$$SE_t = (1-\delta_{se}) SE_{t-1} + EM_t^{glb} \tag{14}$$

where the global emission $EM_t^{glb} = EM_t + EM_t^{rw}$ is the sum of the domestic emissions EM_t and the rest of the world emissions EM_t^{rw}.

The total domestic emissions

$$EM_t = EM_t^J + EM_t^{KN} \tag{15}$$

is the sum of the emissions from burning fossil fuels, $EM_t^J = J_{ng,t}$, and the use of a composite of capital and labor, $EM_t^{KN} = (1 - AE_t)\beta_{em}(Y_t^{KN})^{\alpha_{em}}$, where $\beta_{em} > 0$ and $\alpha_{em} > 0$ are constants.

The cost of reduction of emissions from the production process is

$$\mathcal{C}(AE_t) = \beta_{ae}(AE_t)^{\alpha_{ae}} \tag{16}$$

where $\alpha_{ae} > 1$ and $\beta_{ae} > 0$ are technological parameters.

Analogously, the current level of emission of the rest of the world is a function of the output:

$$EM_t^{rw} = (1 - AE_t^{rw})\beta_{em}^{rw}(Y_t^{RW})^{\alpha_{em}^{rw}} \tag{17}$$

where $\beta_{em}^{rw} > 0$ and $0 < \alpha_{em}^{rw} < 1$ are constants; and $AE_t^{rw}$is the emission reduction effort.

The producer operates in perfectly competitive markets, using physical capital K_t and labor N_t to produce the composite Y_t^{KN} through a Constant Elasticity of Substitution (CES) technology:

$$Y_t^{KN} := (1 - \mathcal{C}(AE_t))\left[\alpha(K_t)^{1-\frac{1}{\eta}} + (1-\alpha)\left(Z_t\left(N_t - \overline{N}\right)\right)^{1-\frac{1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \tag{18}$$

where $\overline{N}$ is overhead labor, which we assume is constant over time, and Z_t is a stochastic trend embodying permanent technological shifts.

The problem of the domestic input producer involves choosing optimal quantities of capital K_t,, labor N_t, energy J_t and emissions abatement effort AE_t to minimize the total cost, including cost of inputs and the cost of emission permits, subject to the technology constraints and taking as given lump-sum transfer T_t^D and prices of capital R_t^K, wages W_t, price of energy V_t and price of emission permits P_t^{EM}:

$$\min_{K_t, N_t, Y_t^{KN}, J_t, AE_t} \left\{ \begin{array}{c} R_t^K K_t + W_t N_t + V_t^J J_t + P_t^{EM} EM_t - T_t^D \\ +P_t^{KN}\left(Y_t^{KN} - (1 - \mathcal{C}(AE_t))\left\{\alpha(K_t)^{1-\frac{1}{\eta}} + (1-\alpha)\left(Z_t\left(N_t - \overline{N}\right)\right)^{1-\frac{1}{\eta}}\right\}^{\frac{\eta}{\eta-1}}\right) \\ +P_t^D\left(Y_t^D - \left(1 - \Gamma(SE_{t-1})\right)Z_t^D\left\{(1-\varsigma)(Y_t^{KN})^{1-\frac{1}{\eta_e}} + \varsigma(Z_t^E J_t)^{1-\frac{1}{\eta_e}}\right\}^{\frac{\eta_e}{\eta_e-1}}\right) \end{array} \right\}$$

where P_t^{KN} and P_t^D are the Lagrange multipliers associated with the technology constraints.

Solving the optimization problem above (FOCs), we obtain the optimal demands for capital, labor, energy and abatement effort:

$$K_t = \alpha^{\eta}\left(\frac{R_t^K}{P_t^{KN}}\right)^{-\eta}\frac{Y_t^{KN}}{\left((1-\mathcal{C}(AE_t))\right)^{1-\eta}} \tag{19}$$

$$N_t - \overline{N} = (1-\alpha)^{\eta}\left(\frac{W_t}{P_t^{KN}}\right)^{-\eta}\frac{Y_t^{KN}}{\left((1-\mathcal{C}(AE_t))Z_t\right)^{1-\eta}} \tag{20}$$

$$Y_t^{KN} = (1-\varsigma)^{\eta_e}\left(\frac{P_t^{KN}+\mathcal{C}_t^{KN}}{P_t^D}\right)^{-\eta_e}\frac{Y_t^D}{\left((1-\Gamma(SE_{t-1}))Z_t^D\right)^{1-\eta_e}} \tag{21}$$

$$J_t = \varsigma^{\eta_e}\left(\frac{V_t^J+\mathcal{C}_t^J}{P_t^D}\right)^{-\eta_e}\frac{Y_t^D}{\left(Z_t^E(1-\Gamma(SE_{t-1}))Z_t^D\right)^{1-\eta_e}} \tag{22}$$

and

$$P_t^{EM}.EM_t^{KN}\frac{AE_t}{(1-AE_t)} = \alpha_{ae}.P_t^{KN}.Y_t^{KN}\frac{\mathcal{C}(AE_t)}{(1-\mathcal{C}(AE_t))} \tag{23}$$

where $EM_t^{KN} = EM_t - J_{ng,t}$ is the level of emissions from production processes, and the marginal cost of emissions from production $\mathcal{C}_t^{KN}$ and from energy use $\mathcal{C}_t^J$ are defined by $\mathcal{C}_t^{KN} := \alpha_{em}\frac{P_t^{EM}EM_t^{KN}}{Y_t^{KN}}$ and $\mathcal{C}_t^J \coloneqq \frac{P_t^{EM}J_{ng,t}}{J_t}$.

Combining the equations above, the Lagrange multipliers turn out to be the cost of a unit of product:

$$R_t^K K_t + W_t\left(N_t - \overline{N}\right) = P_t^{KN}Y_t^{KN} \tag{24}$$

and

$$P_t^{KN}Y_t^{KN} + V_t^J J_t + P_t^{EM}EM_t = P_t^D Y_t^D \tag{25}$$

Substituting the optimal demand equations above into the technology constraint equation, we obtain the unit cost of the composite of capital and labor:

$$P_t^{KN} = (1-\mathcal{C}(AE_t))^{-1}\left\{\alpha\left(\frac{R_t^K}{\alpha}\right)^{1-\eta} + (1-\alpha)\left(\frac{W_t}{(1-\alpha)Z_t}\right)^{1-\eta}\right\}^{\frac{1}{1-\eta}} \tag{26}$$

which is a function of the cost of capital and wage. Analogously, we obtain the price index for intermediary input:

$$P_t^D = \left((1-\Gamma(SE_{t-1}))Z_t^D\right)^{-1}\left\{(1-\varsigma)\left(\frac{P_t^{KN}+\mathcal{C}_t^{KN}}{(1-\varsigma)}\right)^{1-\eta_e} + \varsigma\left(\frac{V_t^J+\mathcal{C}_t^J}{\varsigma}\right)^{1-\eta_e}\right\}^{\frac{1}{1-\eta_e}} \tag{27}$$

which is a function of the prices of the inputs plus the respective marginal cost of emission.

2.4. Exogenous processes and measurement errors

The gap between the emission abatement effort AE_t^{rw} and its steady-state level AE_{ss}^{rw} follows an AR(1) process

$$\ln\left(\frac{AE_t^{rw}}{AE_{ss}^{rw}}\right) = \rho_{ae}^{rw} \ln\left(\frac{AE_{t-1}^{rw}}{AE_{ss}^{rw}}\right) + \varepsilon_{ae}^{rw} \quad (28)$$

where $0 < \rho_{ae}^{rw} < 1$ and $\varepsilon_{ae}^{rw} \sim N(0, (\sigma_{ae}^{rw})^2)$.

The gap between the unitary cost of fossil resources V_t^{FR} and its steady-state level also follows similar exogenous dynamics:

$$\ln\left(\frac{V_t^{FR}}{V_{ss}^{FR}}\right) = \rho_q^{fr} \ln\left(\frac{V_{t-1}^{FR}}{V_{ss}^{FR}}\right) + \varepsilon_q^{fr} \quad (29)$$

where $0 < \rho_q^{fr} < 1$ and $\varepsilon_q^{fr} \sim N\left(0, \left(\sigma_q^{fr}\right)^2\right)$.

The domestic transitory technology shocks $Z_{d,t}^D$, $Z_{g,t}^D$ and $Z_{ng,t}^D$, as the investment-specific technology shocks $Z_{d,t}^I$, $Z_{g,t}^I$ and $Z_{ng,t}^I$, evolve according to similar $AR(1)$ processes:

$$\log\left(\frac{Z_{m,t}^k}{Z_{m,ss}^k}\right) = \rho_m^k \log\left(\frac{Z_{m,t-1}^k}{Z_{m,ss}^k}\right) + \varepsilon_{m,t}^k \quad (30)$$

where $m = g,\ ng$ or d refers to each specific sector; $k = D$ or I refers to each specific type of shock, respectively, technology or investment; $Z_{m,ss}^k$ refers to the steady-state level of the shock; $0 < \rho_m^k < 1$ and $\varepsilon_{m,t}^k \sim N(0, (\sigma_m^k)^2)$.

The stochastic trend Z_t, as in Fasolo et al. (2023), is a random walk with stochastic growth factors:

$$Z_t^Z = Z_t / Z_{t-1} \quad (31)$$

such that gap to their steady-state Z_{ss}^Z follows an AR(1) process

$$log\left(\frac{Z_t^Z}{Z_{ss}^Z}\right) = \rho_Z log\left(\frac{Z_{t-1}^Z}{Z_{ss}^Z}\right) + \varepsilon_t^Z \quad (32)$$

where $0 < \rho_Z < 1$ and $\varepsilon_t^Z \sim N(0, (\sigma_Z)^2)$.

3 Data and Calibration

In addition to the historical data already used as input to the Bayesian estimation of the base model described in Fasolo et al. (2023), five new energy and emissions-related data were used to help calibrate this extended model. The new data available include quantities of fossil and non-fossil energy; the price of fossil energy; and domestic and global emissions. Historical data for Brazil and the World were obtained from the Network for Greening the Financial System (NGFS) data service (phase III revision) as data from NGFS' climate scenarios (e.g., NetZero 2050). The sample period of historical data is from 2006 to 2022, and future scenarios data are from 2023 to 2050. It is important to emphasize that no one of those climate data series is available quarterly, as the base model data, but only in annual or five-year frequency, which impairs our capacity to estimate the model.

Table 1 – Calibrated parameters of the climate block

EM_{ss}/EM_{ss}^{glb}	0.03	emissions / global emissions (s.s. values)
EM_{ss}^{J}/EM_{ss}	0.23	fossil energy emissions / total emissions (s.s. values)
$J_{ng,ss}/J_{ss}$	0.50	fossil energy / total energy (s.s. values)
η	0.95	elasticity of substitution of intermediary firms (capital x labor)
η_e	0.40	elasticity of substitution of intermediary firms (energy x KN composites)
η_{ng}	0.40	elasticity of substitution of brown energy firms (capital x fossil resources)
ϵ_g	2.50	elasticity of substitution of energy agency (green x brown energy)
AE_{ss}	0.05	abatement effort (s.s. value, proportion of production processes emissions)
α_{ae}	1.30	elasticity of the abatement cost to abatement effort
β_{ae}	0.002	multiplicative constant of the abatement cost function
$C(AE_{ss})$	0.00004	abatement cost (s.s. value, proportion of intermediary output)
C_{ss}^{J}	0.005	cost of emissions per unit of total energy / energy price (s.s. value)
C_{ss}^{KN}	0.0003	cost of emissions per unit of KN composite / composite price (s.s. value)
α_{em}	0.30	elasticity of emission with respect to the demand for capital&labor composite
β_{em}	0.11	multiplicative constant of the production processes emissions function
α_{em}^{rw}	0.30	elasticity of RW emissions with respect to RW output
β_{em}^{rw}	4.58	multiplicative constant of the RW emissions function
AE_{ss}^{rw}	0.05	RW abatement effort (s.s. value, proportion of total RW emissions)
δ_{se}	0.20	depreciation rate of the global stock of emission (carbon sequestration)
SE_{ss}	22.4	emissions cost (s.s. value, proportion of KN composite)
α_{se}	0.0001	elasticity of the emission cost to global stock of emissions
β_{se}	0.05	multiplicative constant of the global emissions cost function
$\Gamma(SE_{ss})$	0.05	emissions cost (s.s. value, proportion of KN composite)

Considering the limitation of climate data and the lower frequency of the few available series, the alternative was to adopt a pragmatic strategy for calibration of the extended climate model while keeping awareness of the high degree of uncertainty involved in any case. First, all the parameters in the base model, without the new climate block of equations, are all set to the original estimated values, as described in Fasolo et al. (2023). Second, the parameters of the new block of equations, as defined in the previous section, were all calibrated. Those set of parameters include proportions of domestic emissions and fossil energy; production technology parameters (CES elasticities); marginal costs of emissions; emissions abatement effort levels and costs; depreciation rates; AR coefficients and standard deviations of errors (see Table 1).The steady-state shares, elasticities, and other structural parameters related to the use and production of energy were calibrated using observed data, drawing on the available evidence in the literature and obtaining emissions paths compatible with NGFS NetZero2050 scenario in response to emission tax policy shocks and green investment.

Regarding the emissions and energy-related steady-state shares, reported in Table 1, the share of domestic emission to global emission, EM_{ss}/EM_{ss}^{glb}, is set at a value of

3%, close to the GHG emissions data of 2020[3]. The ratio of fossil energy emissions to total emissions, EM^J_{ss}/EM_{ss}, was calibrated at 23%, which is the number for 2020[4]. The fossil energy emissions as a proportion of total emissions, $J_{ng,ss}/J_{ss}$, was calibrated at 50%, close to the share of renewables of the energy mix, reported in Brazilian Energy Balance 2023, issued by the Empresa de Pesquisa Energética[5].

The elasticity of substitution between capital and labor, η, was calibrated at 0.95, as estimated in the base model. The elasticity of substitution between energy and composite of capital and labor, η_e, was set at 0.4, following Bodenstein et al. (2013) and Coenen et al. (2023), which was the same value that we adopted for the elasticity of substitution of capital and fossil resources, η_{ng}. The evidence from the literature is relatively scarce regarding the elasticity of substitution between green and brown energy, ϵ_g, which was calibrated at 2.5, higher than the 1.8 adopted in Coenen et al. (2023), but inside the interval between 1.8 and 3 estimated by Papageorgion et al. (2017). The elasticity of the cost of reduction with respect to the level of effort to reduce emissions, α_{ae}, was calibrated at 1.3 to reproduce the specific intensity of the effect of the increase in taxation (from 0 to 12 percent, in the ratio between emission price and fossil energy price) on the emission from the production process (decrease of 35% with respect to steady-state level), as observed in the first five years (from 2020 to 2025) of the NGFS NetZero2050 scenario (see Figure 5).

The steady-state value for the ratio between the marginal cost associated with emission from energy and the price of energy, $\mathcal{C}^J_{ss}$, was set at 0.5%, an arbitrarily low level, reflecting the fact that no emission tax policy has been in place in Brazil. The value for the ratio between the marginal cost associated with emission from the production process and the price of the intermediate product, $\mathcal{C}^{KN}_{ss}$, was set at an even lower level of 0.03%, which is compatible with an elasticity of domestic emission from production, α_{em}, equal to 0.3, and a multiplicative constant, β_{em}, equal to 0.11. The steady-state values for the domestic and rest of the World abatement efforts, AE_{ss} and AE^{rw}_{ss}; as the stock of global emissions and its cost, SE_{ss} and $\Gamma(SE_{ss})$; were all set at an arbitrarily low value of 5%. The compatible steady state value that we obtained for the abatement cost, $\mathcal{C}(AE_{ss})$, equals 0.00004. The elasticity of the emission cost to the global stock of emissions, α_{em}, was set at 0.0001, a value very close to zero, so assuming, for simplify, as in Coenen et al. (2023), that the resulting physical damages from failing to implement effective climate policies are economically negligible, at least in a short-run analysis like the one in this paper.

For simplifying reasons, in the absence more information on the energy sector, all standard deviations and auto-regressive coefficients of technological shock, energy

[3] As reported in Our World in Data based on emissions data from Jones et al. (2023) at https://ourworldindata.org/greenhouse-gas-emissions

[4] See page 15 of the 6ª edition (2022) of "Estimativas Anuais de Emissões de Gases de Efeito Estufa no Brasil" at https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/estimativas-anuais-de-emissoes-gee/arquivos/6a-ed-estimativas-anuais.pdf; or emissions of GHG by sector of the National Emissions Registration System (SIRENE) at https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/emissoes/emissoes-de-gee-por-setor-1

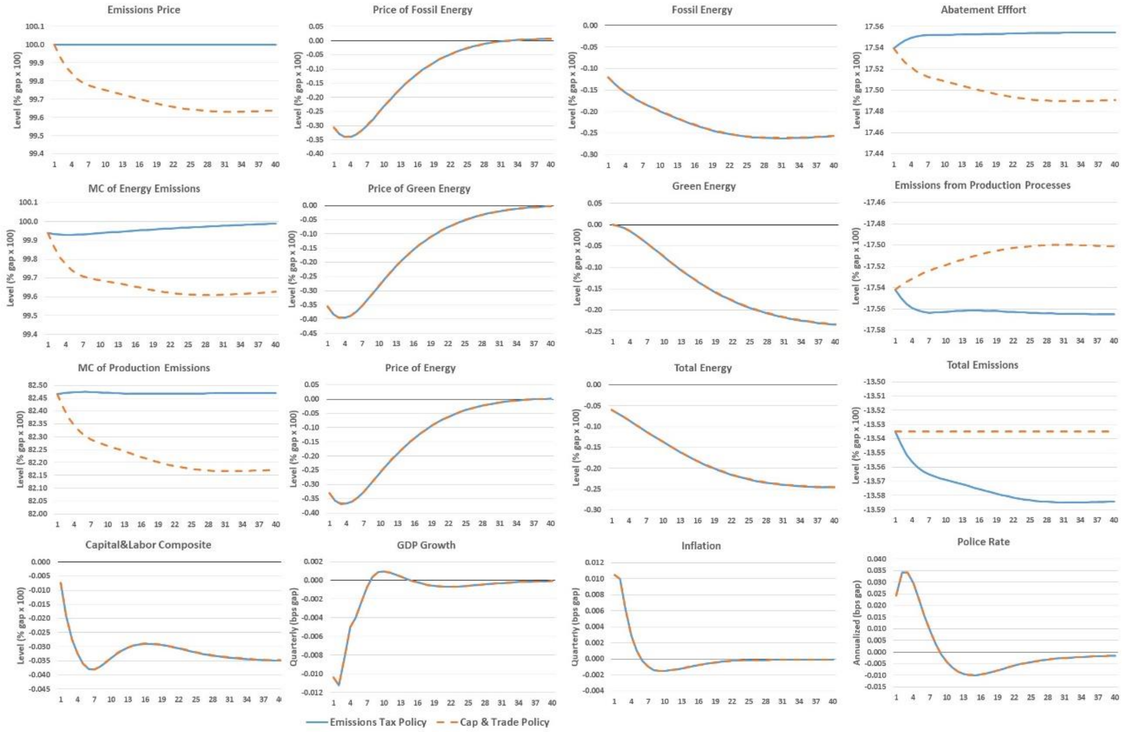
[5] See page 12 at https://www.epe.gov.br/sites-en/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-253/BEN_S%C3%ADntese_2023_EN.pdf

investments, are assumed to have the same correspondent value estimated in the base model ($\sigma_g^k = \sigma_{ng}^k = \sigma_d^k$ and $\rho_g^D = \rho_{ng}^D = \rho_d^D$).

4 Impulse responses

This section provides impulse response analysis, comparing two versions of the model, which differ according to the emission policy implemented. In the first (primary) version, the emission price (carbon price) is fixed, and the quantity of emissions comes out in equilibrium, what is called an “Emissions Tax Policy”. In a second version, the emission quantity is fixed, while the emission (permit) price is the outcome of the economy's equilibrium, called “Cap & Trade Policy”. An assessment of the responses of main model variables to shocks to emission policies, green investment, and green energy productivity is provided below.

Figure 2 - Shock to emission policies



Note: The pictures above illustrate the deviations from the steady state in a horizon of 10 years (40 quarters) and for a set of selected variables as a response to a temporary (first quarter only) exogenous shock to the emission policy instrument. In the tax policy version of the model, the shock size was calibrated to impose an increase of +1% on the emissions price in the first quarter. In the model's cap & trade policy version, the shock to the level of emissions was calibrated to generate the same reduction in total emissions, in the first quarter, obtained in the tax policy version (-0.13%).

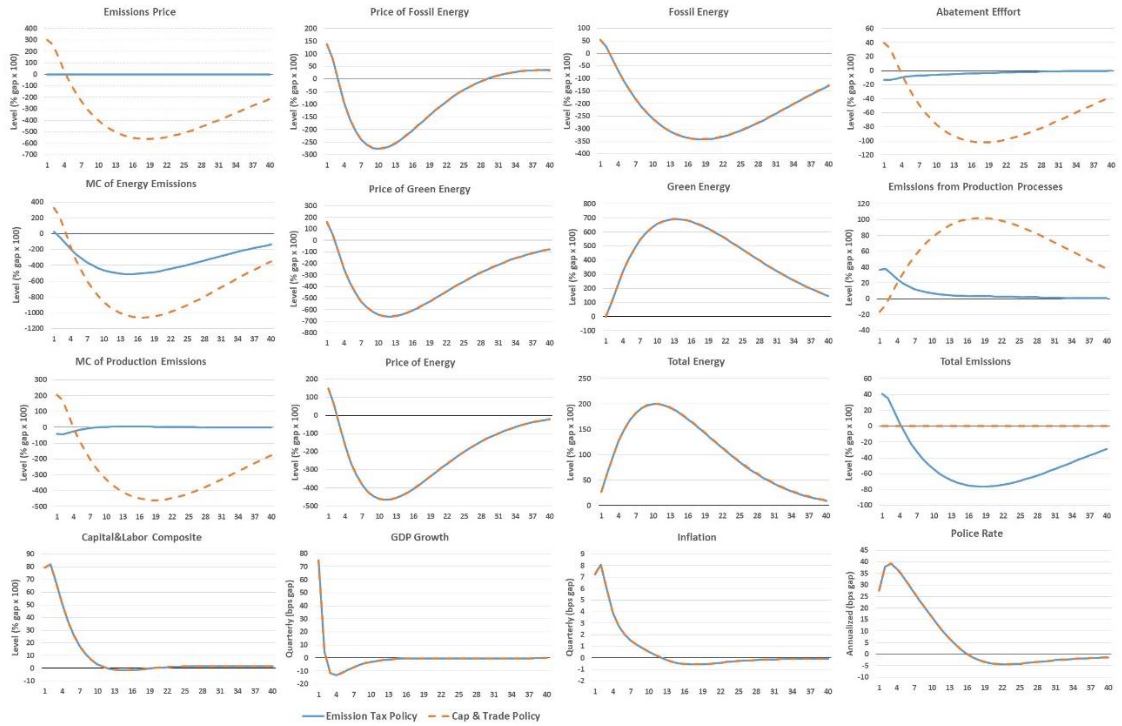
In the first simulation, shown in Figure 2, both policy regimes are perturbed in a very particular way to facilitate the comparison. In the “Emission Tax Policy” scenario, there is a mild deviation of emission prices of 1% from the steady-state value during the simulation horizon (10 years). In the “Cap & Trade Policy” scenario, the total emission level is fixed at the initial value resulting from the “Emission Tax Policy” scenario, close to -0.16% from steady state.

Note that the equilibrium level of emission price, as both marginal costs of emission, oscillate below (but very close) to the fixed price. The lower price in the “Cap & Trade Policy” scenario is compatible with reducing the abatement effort and increasing emissions from production processes, which compensates for the reduction in fossil energy, since the total emissions remain fixed.

As a consequence of those endogenous adjustments in the abatement effort and emission prices in the “Cap & Trade Policy” version, both scenarios show the same trajectories for relative prices and quantities of energy (the same occurs with shocks to green investment and productivity below). Energy prices reduce immediately to their lowest values but gradually return to the steady state until the end of the simulation horizon; energy quantities show decreasing trajectories that decelerate along the horizon.

Concerning the macroeconomic variables, GDP is negatively affected as a consequence of the low productivity related to the abatement efforts, returning to the steady-state level in 8 quarters; the positive impact on inflation results from the increase of the marginal costs associated with emissions, but lasting only five quarters because of the monetary policy reaction.

Figure 3 - Shocks to green energy investments



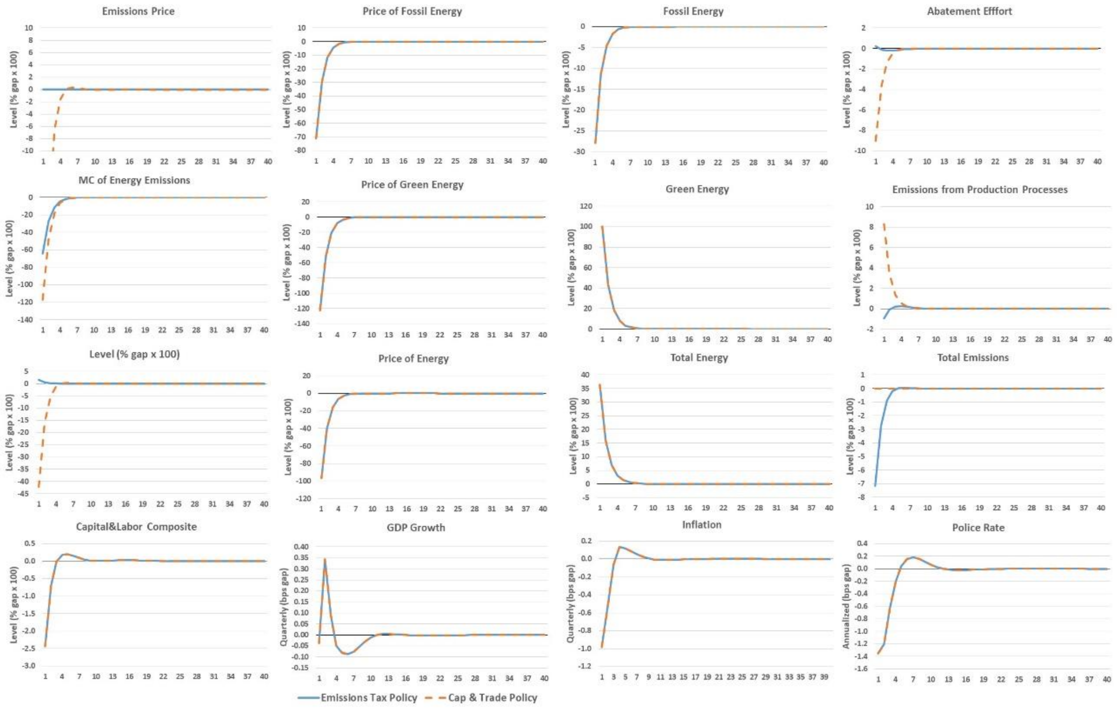
Note: The pictures above illustrate the deviations from the steady state in a horizon of 10 years (40 quarters) and for a set of selected variables as a response to a temporary (first quarter only) exogenous shock to investments in the green energy sector. In each model version, shock size was calibrated to impose an increase of +1% on green energy in the second quarter (by construction, the effects of investment decisions have a delay of one quarter).

The second simulation, shown in Figure 3, imposes shocks to green investment on both model versions that result in an increase of 1% in the steady-state level in the subsequent period (by hypotheses, investment affects capital stock with a quarter delay). The autoregressive parameter of the shock to investment (0.27) plays a role in determining the persistent behavior of the green energy demand, which has its peak after 13 quarters, at 7% above its steady-state level.

The high elasticity substitution between green and brown energy allows for a reduction (-3.5%, after 18 quarters) in the demand for fossil energy. The total energy increases during the first ten quarters since the marginal cost of emission from the energy sector reduces after the investments in green energy. The higher energy use is compatible with the observed increase in economic activity and inflation despite the monetary policy reaction.

In the case of a productivity shock in the production of green energy, shown in Figure 4, the shock size is calibrated to increase the demand for green energy to 1% above the steady-state level. The effects of this shock are short-lived, most of those vanishing after seven quarters. As in the investment shock, higher productivity changes the composition of green and brown energy and increases the aggregate energy supply. Prices of both types of energy decrease in equilibrium, which is responsible for a decline in inflation, followed by a monetary policy easing and a temporary increase in economic activity in the first four quarters.

Figure 4 - Shocks to green energy productivity



Note: The pictures above illustrate the deviations from the steady state in a horizon of 10 years (40 quarters) and for a set of selected variables as a response to a temporary (first quarter only) exogenous shock to productivity in green energy production. In each version of the model, shock size was calibrated to impose an increase of +1% on green energy demand in the first quarter.

In the "Emissions Tax Policy" case, after a positive green productivity shock (+1% in green energy), total emissions reduced (-0.15%) as a consequence of the lower use of fossil (-0.27%) and a slight reduction of the emissions from production. However, note that in the case of the "Cap & Trade Policy," emission prices decrease, reducing incentives to lessen emissions, compensating for all the reduction in fossil energy use. In other words, only in the case of "Emissions Tax Policy," when emissions price is maintained fixed, is a productivity shock in the green energy sector reflected in a total emission reduction.

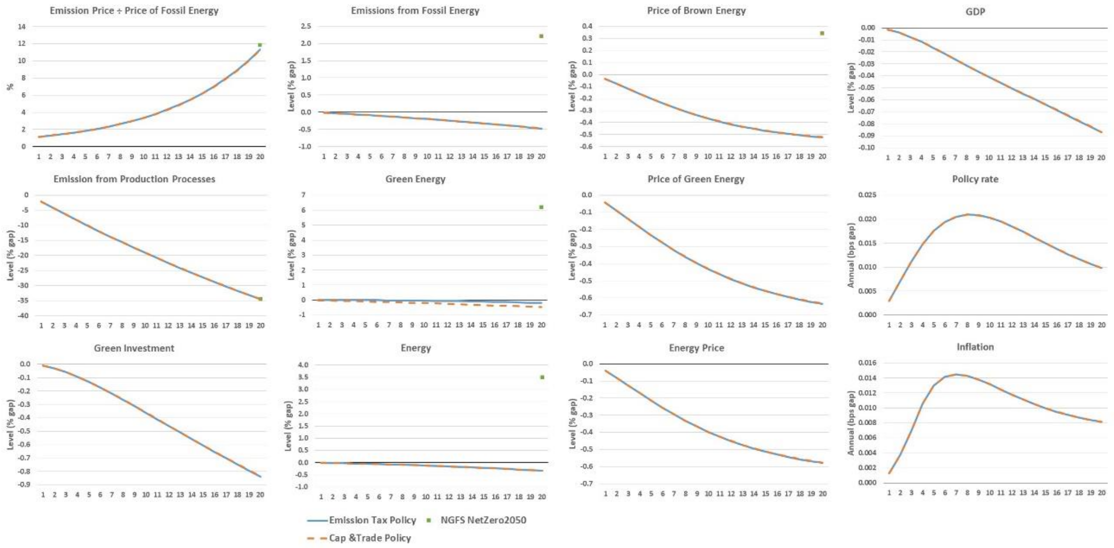
5 Policy exercises

This section provides a simple first approach to assess the capacity of this model to simulate transition scenarios by executing a set of simple simulations aimed at generating exercises that can be minimally comparable with the NGFS's Net Zero 2050 scenario[6].

[6] Scenario for Brazil from the model GCAM 5.3 (Phase 3).

In the first two exercises, respectively, the short-term target (5 years) of the NGFS scenario for the level of emissions taxation is used as a reference to calibrate a sequence of equally sized emission policy shocks, and the target for the increase of green energy demand is used to calibrate a succession of green investment shocks of the model. The last simulation combines both shocks to hit the NGFS targets in a horizon of 15 years, which allows a first simple approach to assess the long-term effects of the transition on the macroeconomic variables, considering the interaction with the monetary policy rule of the model.

Figure 5 – Shock to emission tax versus NGFS scenario



Note: The pictures above illustrate the deviations from the steady state in a horizon of 5 years (20 quarters) and for a set of selected variables, as a response to a sequence of permanent exogenous shocks to emissions policy (equal sized shocks are applied in all quarters). The elasticity of the abatement cost function of the model and the shock sizes were calibrated to get a reduction of 35% in emissions from the production process after five years as a consequence of an increase in emissions price to a level of 12% of the fossil energy price, as anticipated in the NGFS Net Zero scenario (squared points correspond to Phase 3 NGFS data, from GCAM for Brazil).

Considering the five-year target for the emissions tax, in Figure 5, a sequence of equal shocks to the taxation is calibrated to generate a reduction of 35% in five years in the emissions from production processes as a consequence of an increase in the emission price to a level that represents 12% of the price of the fossil energy (after changing scales appropriately)[7]. We know from the impulse responses exercise that the “Emissions Tax Policy” reduces emissions but does not induce a green transition in the energy sector. The model also does not indicate a significant cost in terms of GDP or a relevant impact on inflation.

In Figure 6, a sequence of equally sized shocks to the green investments was calibrated to hit the five-year target to increase green energy use by 6% in the NFGS scenario. Note such shock has a significant but small positive impact on GDP (+0.3%) but minimal effects on annual inflation[8] (+0.2 bps) and policy rate (+0.1bps).

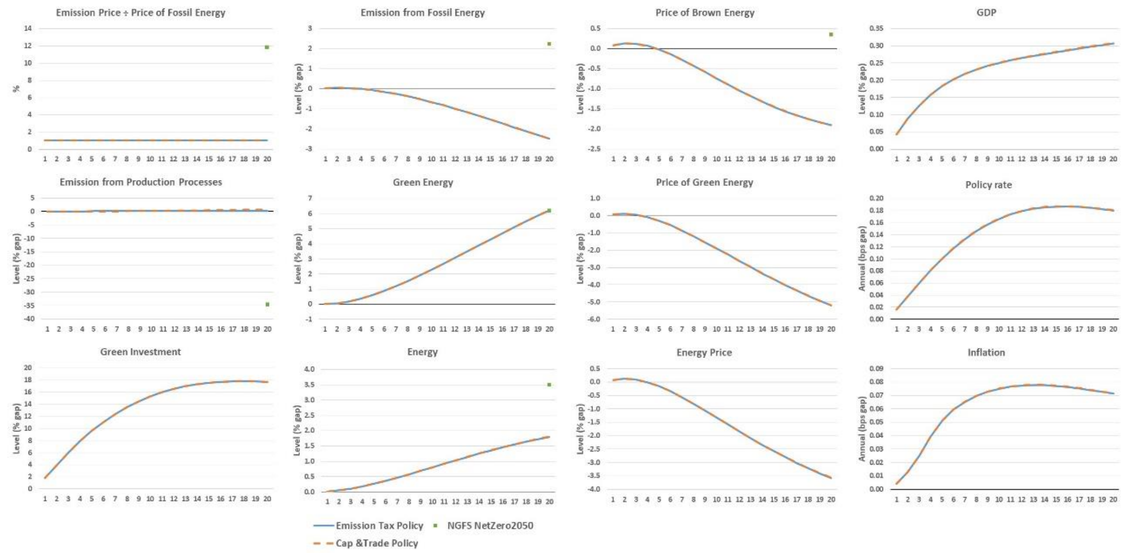
In the last simulations, shown in Figure 7, sequences of shocks to the emissions prices (taxation) and green investments are combined to obtain the same variations in emissions price and demand for green energy, as observed in the NGFS scenario (NetZero 2050). Two different simulations are implemented: the dashed lines represent the

[7] Note that, as described in the calibration section above, the elasticity of the cost of abatement with respect to the level of effort was calibrated to reproduce this specific intensity of the effect of the taxation on the emission from production process.

[8] In the figures 5, 6 and 7, annual inflation refers to the accumulated inflation of the last 12 months.

simulated scenario such that sequences of exogenous shocks of the same size (equal surprises each quarter) are applied to hit the endpoints (variation after 15 years) of the NGFS scenario for the emissions price (50% of the fossil energy price) and the demand for green energy (+45% with respect to the steady state); and the solid lines correspond to the scenario such that the sizes of all shocks are selected to reproduce a interpolated trajectory crossing all (three) points of the NGFS scenario for both emissions prices and demand for green energy.

Figure 6 – Shock to green investment versus NGFS scenario



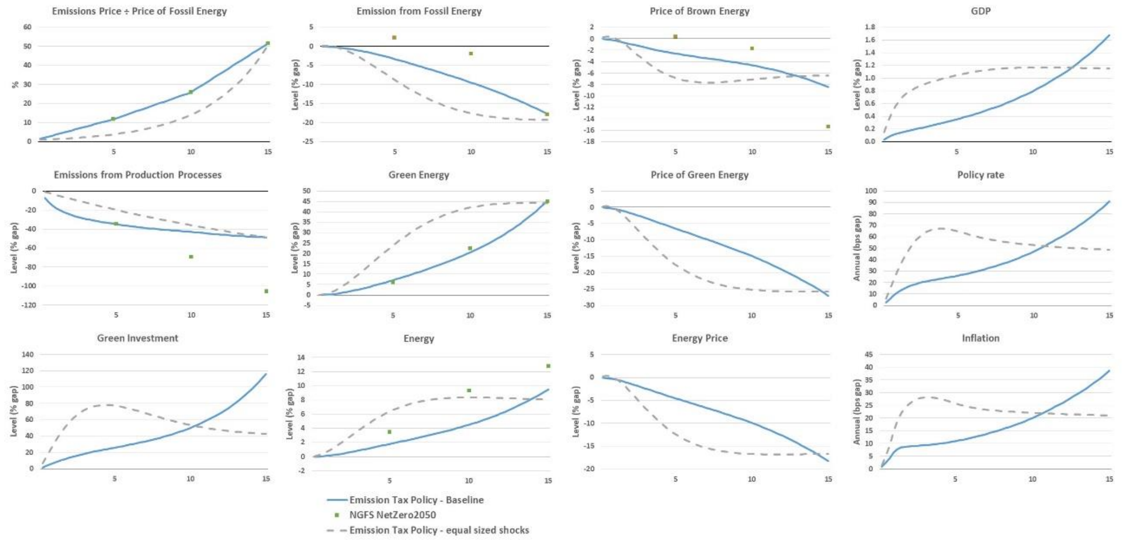
Note: The pictures above illustrate the deviations from the steady state in a horizon of 5 years (20 quarters) and for a set of selected variables, as a response to a sequence of permanent exogenous shocks to green investments (equal sized shocks are applied in all quarters). In each model version, shock size was calibrated to obtain an increase of +6% on green energy after five years, as anticipated in the NGFS Net Zero scenario (squared points correspond to Phase 3 NGFS data from GCAM for Brazil).

In both scenarios, the cost of green capital drops due to the increase in the supply of green investments, so the transition to green energy is induced by the reduction in green energy prices (-25% after 15 years). Because the energy market is assumed to be competitive, the brown energy prices also reduce (between -6% and -8%). Still, it is a smaller reduction than observed in green energy prices. As a result, not only does the smaller energy price stimulate economic activity, but reducing the emissions from fossil energy open space decreases the abatement efforts at the side of the emission from the productive process, thus improving productivity by reducing the cost of abatement. Despite the lower energy prices, higher demand for labor puts pressure on wages, and the reallocation of capital from intermediate production to the green energy sector increases the cost of capital of production. The net effect of those price movements results in higher marginal costs of the intermediate output and higher inflation, inducing a monetary policy reaction (higher interest rates).

More specifically, in the simulation with equal-sized shocks (dashed lines), the emissions prices increase more gradually than in the NGFS scenario. Conversely, the equal-sized shocks to the green investment increase the use of green energy faster than in the NGFS scenario. In the combined scenario, applying both sequences shocks simultaneously, the positive effect on GDP level is significant (peak +1.2% after ten years), as the effect on the inflation (peak of +28bps in 4 years) and on the policy rate (rise of +68 bps in 15 years).

On the other side, in the simulation that interpolates the intermediary points of the NGFS scenario (solid line), the emissions price increases are sufficient to achieve the levels of 12%, 26%, and 50% of the fossil energy price after 5, 10 and 15 years, respectively. Additionally, the shocks to the green investment are enough to increase the use of green energy by 6%, 22%, and 45% in the same three simulation horizons. In the combined scenario, GDP, inflation, and policy rate show a more gradually increasing trajectory than in the other scenario (with equal shocks) but hit higher peaks at the end of the projection horizon. A gradual increase in green investments at the beginning is more realistic (viable), attenuating the short-term macroeconomic effects. Still, the more accelerated pace at the end (to get the target) could intensify the long-term impacts. More specifically, the positive impact observed on the GDP level peaks at a higher level than in the other scenario (+50bps higher, peak of +1.7% after 15 years), as well as the impact on the inflation (+11bps higher, peak of +39bps in 15 years) and on the policy rate (+23 bps, peak of +91 bps in 15 years).

Figure 7 – Combining green investment and carbon taxation



Note: The pictures above illustrate the deviations from the steady state in a horizon of 15 years and for a set of selected variables as a response to a sequence of exogenous shocks to both the emissions tax policy and the green investments. The solid lines correspond to a scenario in which shocks of different sizes are applied to reproduce the trajectories (5, 10, and 15 years ahead) for both the emission prices and the demands for green energy, as anticipated in the NGFS Net Zero scenario (squared points correspond to Phase 3 NGFS data, from GCAM for Brazil). Emissions data from the NFGS scenario represent only to CO2 emissions, while the emissions in the model are considered to represent the total GHG emissions, so the scenarios from the model implicitly assume that the CO2 emissions are being tracked (same percentage change) by emissions from other types of GHGs. The dashed lines correspond to a scenario in which equal-sized shocks are applied to get only the end levels (15 years ahead), as in the same NGFS scenario, for the emission price and the green energy demand.

It is important to note that the simulated increases in the emissions costs, as observed in the NGFS scenario, are insufficient to reduce the simulated emissions from the production process to levels close to the endpoint of the NGFS scenario. The NetZero 2050 scenario for Brazil assumes the country's net emissions would be negative 15 years ahead, meaning it will contribute by sequestrating emissions from the rest of the world. The model's behavior reflects a limitation of the functional form adopted here for the emission technology, which is a positive increasing function of the output, not allowing for negative values for emissions. This limitation indicates it would be necessary to find an alternative specification to better model the investments in carbon sequestration activities as a separate sector in the economy.

A robustness test were carried out, see appendix below, where alternative scenarios are simulated using different substitution elasticities of the energy agency (ϵ_g) and of the intermediary firms (η_e). The alternative simulations give us some sensitivity on how the simulated scenarios are affected by those elasticities, indicating that the hypothesis for ϵ_g are more relevant to the macroeconomic impact than the one of η_e.

6 Conclusion

An adequate assessment of the emissions targets' viability, considering the impacts of their implementation on macroeconomic and financial stability, is crucial to coordinate efforts to guarantee a smoother transition to a green economy. The main goal of this kind of modeling is to challenge the common sense that recognizes that transition policies for mitigating pollutant emissions aimed at inducing abatement efforts can harm productivity if not implemented gradually and could impact the stability of the macroeconomic environment in the short run, as can impair household's welfare in the long run. The modeling provided here is one first step to approach those issues, which tries to adapt a specific DSGE developed in Banco Central do Brasil, naturally focused on macroeconomic modeling of the business cycle using higher frequency data (quarterly), aiming to understand better the impacts of a transition to a green economy. This first approach gives us a good understanding of the size of the challenge and how the high level of modeling uncertainty can impair the correct assessment of the implications of the transition and, consequently, the adequate proposition of public policies.

The simulations in this paper help to understand how capable DSGE models are to reproduce, in a simplified way, scenarios for the green and brown energy sectors and for the efforts of firms to lessen emissions, which are generated by more specialized modeling (i.e., IAMs[9]). The approach here can challenge such specialized models by complementing the analyses by better assessing possible effects and feedback concerning the iterations with macroeconomic dynamics. Despite the difficulties concerning the limited availability of data and very low frequency, the simplified calibration strategy adopted here and preliminary results indicate those modeling approaches are sufficiently flexible to incorporate the main aspects of energy and emission, serving as a valuable tool for policy analysis.

As illustrated in our simulations, the incapacity of the emissions policies evaluated here (taxation or "cap & trade") to induce transition, at least if not accompanied by green investment policies, reinforces the indication that maybe there is an essential role for alternative fiscal policies that are capable to canalize revenues from emissions taxation to green investments and technological innovations to boost productivity in green energy production. Therefore, this issue is of significant relevance for future research.

Another essential feature of the model is the strict focus on the production side of the economy combined with the absence of externalities to households. The transition from brown to green energy affects households' decisions as long as the relative prices of production inputs are transmitted to the price of final goods and real wages affect labor-leisure choices. From this perspective, the model does not offer an explicit reason for the economy to move to or from a green energy framework. One natural extension of the model is to incorporate externalities from the excessive use of brown energy – a consequence of pollution, as an example. Dynamic models with public goods that affect the households' utility can provide an exciting starting point for these extensions.

[9] Integrated assessment models (IAMs) are simplified representations of complex physical and social systems, focusing on the interaction between economy, society and the environment.

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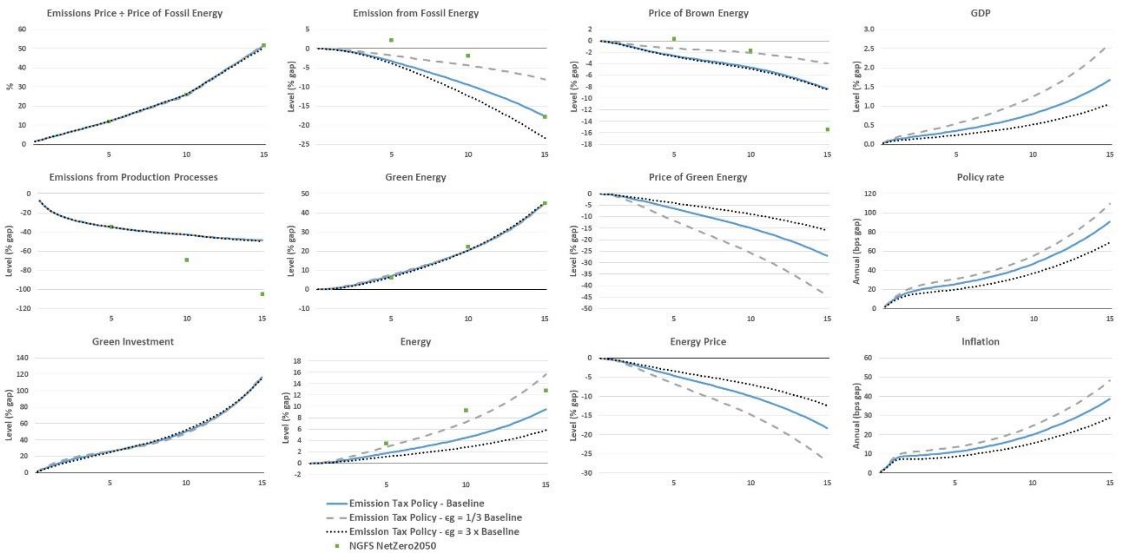
Appendix

Considering the relevance, in this new model structure, of the elasticities of substitution of inputs related to energy, whether in the energy agency (ϵ_g) or in the intermediary firm (η_e), and taking into account the uncertainty regarding their calibrated values, robustness tests with respect to both parameters may be useful. In this sense, alternative simulations are implemented in order to get some sensitivity on how our simulated scenarios are affected by the two elasticities that have a more direct influence on the demand of energy.

Figure A1 shows alternative scenarios for different elasticities of substitution of inputs in the energy agency (ϵ_g), where the shocks (tax policy and green investment) were adjusted appropriately to obtain the same trajectories (close to the NGFS scenario) for emissions price ratio and demand for green energy. Notice that higher the elasticity of substitution between the two types of energy, higher is the price of the green energy, lower is the price of brown energy, and higher is the price of the total energy. A higher price of the brown energy reduces the demand for fossil energy, reducing the respective emissions. The demand for energy reduces as the price of the total energy increases, as the GDP growth is attenuated, resulting in smaller pressures on inflation, and a lower policy rate.

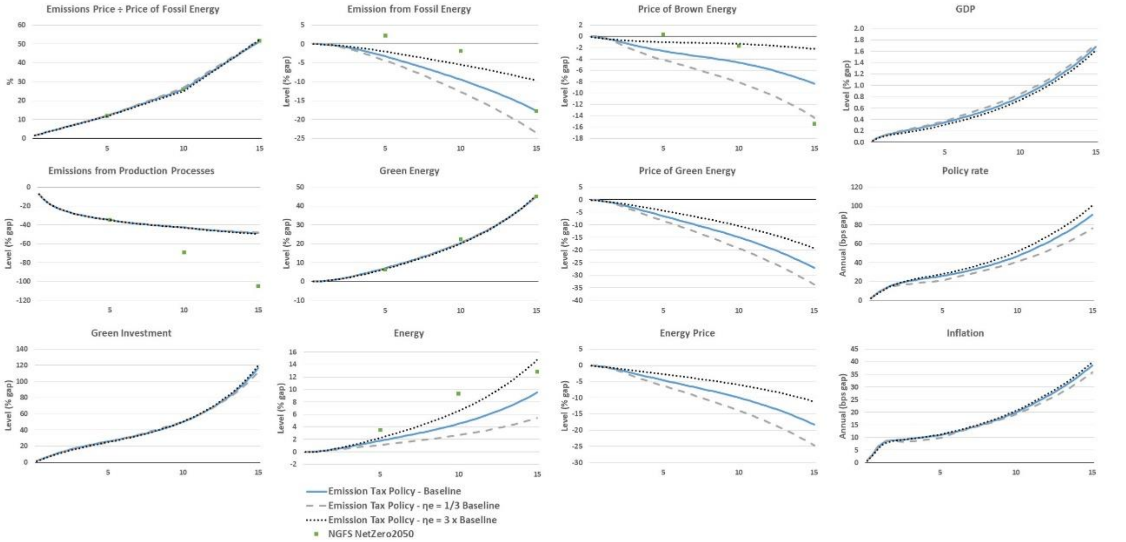
Figure A1 – Sensitivity to ϵ_g: the elasticity of substitution between green and brown energy



Note: The pictures above illustrate the deviations from the steady state in a horizon of 15 years and for a set of selected variables as a response to a sequence of exogenous shocks to both the emissions tax policy and the green investments. The solid lines correspond to a scenario in which shocks of different sizes are applied to reproduce the trajectories (5, 10, and 15 years ahead) for both the emission prices and the demands for green energy, as anticipated in the NGFS Net Zero scenario (squared points correspond to Phase 3 NGFS data, from GCAM for Brazil). Emissions data from the NFGS scenario represent only to CO2 emissions, while the emissions in the model are considered to represent the total GHG emissions, so the scenarios from the model implicitly assume that the CO2 emissions are being tracked (same percentage change) by emissions from other types of GHGs. The dashed and dotted lines correspond to scenarios in which the elasticity ϵ_e is different from the baseline value (2.5), respectively, equal to one third (0.83) and three times (7.5) the baseline value.

In Figure A2, analogous alternative simulations are implemented, this time changing the elasticities of substitution between inputs in the intermediary firm (η_e). Notice that the greater the elasticity, the greater the demand for energy and the higher the prices of both types of energy. The resulting higher inflation induces higher policy rates, implying a loss of GDP growth.

Figure A2 – Sensitivity to η_e: the elasticity of substitution between energy and the composite of capital and labor



Note: The pictures above illustrate the deviations from the steady state in a horizon of 15 years and for a set of selected variables as a response to a sequence of exogenous shocks to both the emissions tax policy and the green investments. The solid lines correspond to a scenario in which shocks of different sizes are applied to reproduce the trajectories (5, 10, and 15 years ahead) for both the emission prices and the demands for green energy, as anticipated in the NGFS Net Zero scenario (squared points correspond to Phase 3 NGFS data, from GCAM for Brazil). Emissions data from the NFGS scenario represent only to CO2 emissions, while the emissions in the model are considered to represent the total GHG emissions, so the scenarios from the model implicitly assume that the CO2 emissions are being tracked (same percentage change) by emissions from other types of GHGs. The dashed and dotted lines correspond to scenarios in which the elasticity η_e is different from the baseline value (0.4), respectively, equal to one third (0.13) and three times (1.2) the baseline value.

The results above suggest that the calibrated value for the elasticity of substitution between inputs in the energy agency (ϵ_g) are more relevant in affecting the level of the macroeconomic variables than the value for the elasticity of substitution between inputs in the intermediary firm (η_e).