THE GREEN METAMORPHOSIS OF A SMALL OPEN ECONOMY*

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Abstract: We develop a model of green transition for a small open economy with endogenous energy efficiency, where production combines energy and traditional factors with limited short-run substitutability. Brown energy taxes reduce energy use and improve long-run efficiency but raise costs, causing inflation and output losses in the short run. Green public investment or subsidies avoid inflation and output losses but impose significant fiscal costs, raising spreads and reducing consumption. Without policies to mitigate debt increases, these measures do not improve welfare. Mixed policies using carbon tax revenues to finance green subsidies or investment are welfare-improving.

Keywords: green transition, endogenous growth, fiscal policy

JEL classifications: E62, H23, Q43

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1 Introduction

The transition to sustainable energy sources is one of the most pressing global challenges today, particularly for small open economies. These economies, while contributing modestly to global CO_2 emissions individually, collectively play a significant role in shaping climate outcomes. We build a dynamic general equilibrium climate model for a small open economy with nominal rigidities and endogenous energy efficiency and growth to assess the role of economic policy in dealing with the green transition. We define the green transition as a transition to efficient energy use based on non-polluting and renewable sources.

Our model builds on the standard New Keynesian model for a small open economy. We incorporate an endogenous supply of green energy and allow green and brown energy to be substitutes in energy production. Departing from the existing models and following Hassler et al. (2021, 2022), we assume that intermediate goods production is characterized by low substitutability between energy and traditional inputs in the short run that firms can alter over longer periods through directed input-saving technical change. Differently from the previous authors, we consider nominal frictions to study the direct impact of the green transition on inflation as well as its indirect impact through the response of fiscal and monetary policies. Our model also captures key features of emerging economies, such as taking international prices and risk-free rates as given, facing financial constraints through external debt premiums, and experiencing higher average inflation than developed economies. Moreover, we assume a domestic exogenous supply of brown energy, a type of energy that many emerging markets may also produce and export. As such, the small open economy model that we propose is useful for understanding short- and long-term movements in macroeconomic aggregates along the green transition.

The existing literature on climate change policy has focused mainly on carbon taxes as a Pigouvian tool to reduce emissions (e.g., Golosov et al. (2014); Aghion et al. (2016); Hassler et al. (2021), and Angelopoulos et al. (2010), among others). Some studies, such as those of Acemoglu et al. (2012), emphasize the importance of combining carbon taxes with research and development (R&D) subsidies to maximize their effectiveness. However, limited attention has been given to other fiscal instruments, such as green public investment or subsidies, particularly in the context of small open economies. This paper fills this gap by evaluating the effects of these tools on both real and nominal macroeconomic variables along the transition.

We calibrate the model to Chile, a representative emerging country that has become a stable economy over the past 30 years and is taking measures towards the green transition. Chile's Climate Action Plan 2017–2022 includes a reduction in the intensity of its CO_2 emissions by at least 30% by 2030 and the advancement of non-conventional renewable energies by promoting an energy efficiency law. The plan specifies an increase in carbon taxes, moving from $5/t to at least $35/t. For expositional purposes, in the baseline scenario, we start from the initial steady state and assume a transition involving an increase in carbon taxation that is more moderate than the Chilean plan.

We define the green transition as a permanent reduction in the use of brown energy. We show that while carbon taxes can accelerate this transition, they come at the cost of inflationary pressures and output losses in the short and medium term. The mechanism works as follows: anticipating higher carbon taxes, households invest in green capital, and firms gradually reduce brown energy usage. However, as the economy builds capacity for green energy production gradually, the transition leads to price increases in both brown and green energy. To adjust, firms reallocate resources to improve energy efficiency, sacrificing traditional factor productivity. This results in lower capital demand and output. The decline in output increases country spreads, further damping investment and consumption. We also show that while monetary policy can mitigate short-run inflationary costs by responding to price pressures, it cannot alleviate the associated output losses.

Our framework includes frictions that can significantly affect the transitional dynamics as well as the initial and final steady states. As a result, we analyze the sensitivity of our findings to changes in key production function parameters. This analysis underscores that effective green transition policies must consider the specific characteristics of each economy, especially its supply-side features, which play a crucial role in shaping both the transition process and its long-term success.

Next, we explore the role of green subsidies and public investment. Relying solely on green subsidies can reduce brown energy consumption to levels similar to those achieved by carbon taxes, but only if subsidies are raised to 100%. This is because subsidies do not directly affect firms' marginal costs and may even encourage inefficient energy use. In contrast, a substantial increase in green public investment (by 3.5% of GDP) can achieve comparable reductions in brown energy consumption, though it creates significant fiscal pressures over several years. Green public investment increases green sector productivity and reduces green energy prices in the long term. Similarly, subsidies reduce the price of green energy.

In the medium term, expectations of higher future productivity prompt firms to invest more in traditional factors, driving up capital demand and output. This results in a deflationary and expansionary transition. However, both policies entail short-term consumption costs. Although green subsidies and public investment increase the long-term growth trajectory of the economy, they also create substantial fiscal pressures, raising the debt-to-GDP ratio. For small open economies facing financial frictions, this fiscal strain leads to higher spreads, which, in turn, reduce consumption. To be effective, these policies must be paired with measures that alleviate fiscal stress. In our simulations, cutting wasteful government spending helps ease this burden. Debt instruments designed to manage the debt load during the transition could also have similar effects.

We compute welfare metrics for the different fiscal policies considered using consumption equivalent measures. The green transition is welfare improving only when subsidies or green public investment can be financed by reductions in the fiscal deficit that ensure that the debt-to-GDP ratio can return to its original steady state after the transition. Although effective in decreasing brown energy usage and improving energy efficiency, carbon taxes imply welfare costs that can be reduced if one uses carbon taxation revenues to finance green subsidies or green public infrastructure investments. Carbon taxes are generally well accepted in countries with significant experience thereof, but there is still public resistance to raising them. Ewald et al. (2022) show that the lack of trust in the government and the belief in the Pigouvian mechanism are important determinants of the opposition of protesters. Given the documented resistance against increases in carbon taxes, our results suggest that policy mixes that combine a moderate increase in carbon taxation with increases in green subsidies or green public investment can attain similar reductions in brown energy usage with lower welfare costs.

Our model belongs to the class of general equilibrium models with environmental features often tagged as E-DSGE models (see, e.g., Annicchiarico and Di Dio (2015, 2017), Carattini et al. (2021), and Economides and Xepapadeas (2019), among others). Yet we are interested in analyzing transitional dynamics. Many recent studies use E-DSGE models to investigate the role of monetary policy along the green transition (see, e.g., Nakov and Thomas (2023), Olovsson and Vestin (2023), Coenen et al. (2023), Del Negro et al. (2023), and Sahuc et al. (2024)) and price dynamics (see, e.g., Ferrari and Landi (2022)). Apart from focusing on the role of fiscal policy relative to the existing studies, our model economy incorporates energy efficiency in the production function and allows firms to react to relative energy price movements, adjusting available resources to improve energy efficiency, resulting in possible non-monotone medium-run transitional dynamics. In other words, in our proposed model, changes in the fiscal policy instruments induce supply-side effects that the existing studies do not assimilate. Moreover, unlike in the existing studies, in our model, we can evaluate the effectiveness of different policies in improving energy efficiency, providing an angle of analysis that is absent in other studies of the green transition.

The rest of the paper is organized as follows: Section 2 presents the model. Section 3 discusses the calibration and solution method. Section 4 presents the transitional dynamics and offers sensitivity analysis when analyzing a transition based solely on increases in carbon taxes. Section 5 discusses alternative policy tools and different policy experiments. Section 6 quantifies welfare along the green transition. Finally, section 7 concludes.

2 The model

We extend a small open economy New Keynesian model by incorporating energy efficiency in production, directed technological change, and green energy production. The domestic economy consists of households, final goods producers, intermediate goods firms, green energy producers, a fiscal authority, and a monetary authority setting interest rates. Energy efficiency reduces the energy intensity of intermediate goods, while directed technological change drives improvements in energy-efficient technologies.

The government environmental policy determines taxes on brown energy, subsidies to green energy production, and investment in green infrastructure to support a cleaner economy. The budget is balanced with lump-sum taxes and debt issuance.

The rest of the world demands final goods, and supplies (or demands) brown energy at international prices. Additionally, the economy has access to international capital markets, where it trades a risk-free asset with a spread reflecting country-specific risk.

2.1 Households

The representative household in the domestic economy allocates a fixed portion of its time, denoted by $\bar{h}$, to labor.[1] The household allocates resources among consumption, c_t, purchases of a domestic public bond, B_{t+1}, yielding a nominal return R_t after one period, and a foreign bond, B^*_{t+1}, which offers a return in foreign currency of $R^*_t \Phi^A_{t+1}(\tilde{A}^f_{t+1})$, where $\Phi^A_{t+1}(\tilde{A}^f_{t+1})$ represents the spread on domestic bonds. Additionally, the household chooses green investment i^G_t, traditional investment i_t, that increase the green capital stock s^G_{t+1}, and traditional capital stock k_{t+1}, respectively. The household pays lump-sum taxes, τ_t, and receives profits, Γ_t, from the firms in the economy. Hence, the household's problem is to maximize

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U\left(c_t\right), \tag{1}$$

where β is the household's discount factor, subject to the following constraints:

$$i^G_t + i_t + c_t + \frac{B_{t+1}}{P_t} + FX_t \frac{B^*_{t+1}}{P_t} = \frac{B_t}{P_t} R_{t-1} + FX_t \frac{B^*_t}{P_t} R^*_{t-1} \Phi^A_t(\tilde{A}^f_t) + w_t \bar{h} + \frac{R^k_t}{P_t} k_t + \frac{R^G_t}{P_t} s^G_t + \Gamma_t - \tau_t, \tag{2}$$

where P_t is the price level, w_t is the real wage, FX_t is the nominal exchange rate, and the terms R^k_t and R^G_t denote the rental returns on traditional and green capital, respectively.

The evolution of the green capital stock follows:

$$s^G_{t+1} = (1-\delta)\, s^G_t + \Phi_s(s^G_{t+1}, s^G_t) s^G_t + i^G_t, \tag{3}$$

[1]We do not model a labor supply choice, as it offers limited additional insights for our analysis and complicates numerical solutions.

and for traditional capital,

$$k_{t+1} = (1-\delta)\, k_t + \Phi_k(k_{t+1}, k_t) k_t + i_t, \tag{4}$$

where δ is the depreciation rate, assumed to be the same for both green and traditional capital. The functions Φ_s and Φ_k capture the adjustment costs associated with changes in green and traditional capital, respectively.[2]

Household consumption is a composite bundle of domestic goods, $c_{H,t}$, and foreign goods, $c_{F,t}$, defined by

$$c_t = \left[(1-\chi)^{\frac{1}{\theta}} c_{H,t}^{\frac{\theta-1}{\theta}} + \chi^{\frac{1}{\theta}} c_{F,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{5}$$

where parameter θ determines the elasticity of substitution between domestic and foreign goods, and χ determines the shares of foreign goods in domestic consumption.

The domestic price level is accordingly defined by

$$P_t = \left[(1-\chi) P_{H,t}^{1-\theta} + \chi P_{F,t}^{1-\theta} \right]^{\frac{1}{1-\theta}}, \tag{6}$$

where $P_{H,t}$ and $P_{F,t}$ represent the prices of domestic and foreign goods, respectively.

The function $\Phi_t^A(\tilde{A}_t^f)$ reflects the risk premium associated with the household's foreign debt (not internalized by the household):

$$\Phi_t^A(\tilde{A}_t^f) = \exp\left\{ -\varphi^A \tilde{A}_t^f \right\},$$

where $\tilde{A}_t^f$ is the real foreign debt-to-output ratio (see also Schmitt-Grohé and Uribe (2003)

[2] We also explored a specification with time-to-build investment for both capital types. The results are qualitatively similar, so we use the standard capital adjustment costs as our baseline.

and Justiniano and Preston (2010)):

$$\tilde{A}_t^f = \frac{FX_t}{P_t \bar{Y}} \tilde{B}_t^*.$$

Here, $\bar{Y}$ denotes the steady-state output level, and $\tilde{B}^*$ denotes the aggregate foreign debt. We present the household's optimality conditions in the appendix.

2.2 Domestic final good producer

A representative firm produces the domestic final good, $y_{H,t}$, from varieties, $y_{H,i,t}$, for i $\in$ $[0, 1]$ using the following technology:

$$y_{H,t} = \left[\int_0^1 y_{H,i,t}^{\frac{\varepsilon_P - 1}{\varepsilon_P}} di \right]^{\frac{\varepsilon_P}{\varepsilon_P - 1}}.$$

Here, ε_P is the elasticity of substitution between varieties. The optimization problem of the representative firm is the following:

$$\max_{\{y_{H,i,t}\}_{i \in [0,1]}} P_{H,t} y_{H,t} - \int_0^1 P_{H,i,t} y_{H,i,t} di,$$
$$\text{subject to } y_{H,t} = \left[\int_0^1 y_{H,i,t}^{\frac{\varepsilon_P - 1}{\varepsilon_P}} di \right]^{\frac{\varepsilon_P}{\varepsilon_P - 1}}.$$

The expression below gives the optimal demand function for variety i:

$$y_{H,i,t} = y_{H,t} \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{-\varepsilon_P}. \tag{7}$$

2.3 Intermediate goods producers

Each firm in the intermediate goods sector produces a differentiated variety $y_{H,i,t}$, facing a downward-sloping demand curve, as described in equation (7). The production technology for each variety uses labor $\bar{h}_{i,t}$, physical capital $k_{i,t}$, and energy $e_{i,t}$ as inputs. Following the approach of Hassler et al. (2021, 2022), we assume the production function takes the following form:

$$y_{H,i,t} = \left[\left(A_{i,t} k_{i,t}^{\alpha} \bar{h}_{i,t}^{(1-\alpha)} \right)^{\frac{\epsilon-1}{\epsilon}} + \left(A_{e,i,t} e_{i,t} \right)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}. \tag{8}$$

$A_{i,t}$ and $A_{e,i,t}$ are input-augmenting productivity factors for traditional inputs and energy, respectively, both of which are non-stationary over time. To model the evolution of these productivity factors, we assume that each firm employs a fixed stock of researchers (equal to one) who are tasked with improving these productivities. A fraction $n \in [0,1]$ of the researchers focus on enhancing the productivity of capital and labor, while the remaining fraction $(1-n)$ works on improving energy efficiency, as in Hassler et al. (2022).

An alternative interpretation of n is the fraction of researchers allocated to adapting foreign R&D innovations to the domestic economy. Unlike previous studies, we allow n to be endogenous and determined by firms each period. This flexibility in research allocation is supported by empirical evidence. Studies like Alam et al. (2019) document that corporate R&D investments significantly improve firms' environmental performance through two key channels in line with the natural resource-based view theory. First, R&D facilitates technological advancements that increase production efficiency without requiring additional energy input, thereby reducing energy intensity (the energy-to-output ratio). Second, these investments promote the development of clean energy technologies crucial for transitioning to more sustainable energy systems.

Building on this evidence, we model firms' endogenous decisions to invest in energy efficiency R&D. When firms allocate more researchers to energy efficiency (lower n), they can achieve both objectives documented in the empirical literature: reducing energy intensity in equilibrium and influencing the trajectory of their energy consumption. This creates an important margin of adjustment, as firms can respond to changes in relative energy prices and environmental policies by redirecting their research efforts.

We further assume that fixing the total stock of researchers dedicated to improving capital/labor productivity versus energy efficiency essentially constrains the relative growth paths of these two sectors.[3] Specifically, the proportion of researchers allocated to each sector determines the growth rates of the corresponding productivity factors, $A_{e,t}$ and A_t, as follows:

$$g_{i,t}^{A} = \frac{A_{i,t}}{A_{i,t-1}} = 1 + Bn_{i,t}^{\phi}, \tag{9}$$

$$g_{i,t}^{Ae} = \frac{A_{e,i,t}}{A_{e,i,t-1}} = 1 + B_e(1 - n_{i,t})^{\phi}. \tag{10}$$

The parameter ϕ governs the returns to scale for researchers in both sectors, and B and B_e determine the efficiency of research efforts in increasing the productivity of traditional inputs and energy efficiency, respectively.

As these growth rate equations make clear, firms face a tradeoff when allocating researchers between traditional inputs and energy efficiency. Increasing R&D efforts in one area boosts productivity growth in that sector but reduces it in the other sector. Firms choose the optimal allocation of n to balance this tradeoff. A key parameter influencing their decision is the elasticity of substitution between traditional inputs and energy, denoted by ϵ. While we can assume this elasticity is close to zero in the short run (i.e., nearly Leontief), directed input-saving technical change can alter it over the medium to long term. By choosing n, firms can reallocate resources from capital and labor to energy

[3] A single firm cannot influence macroeconomic trends, but given that all firms behave symmetrically in equilibrium, this assumption is innocuous.

efficiency, improving the energy-to-output ratio and allowing for more flexible resource use in the medium run.

Lastly, it is important to emphasize that firms incur no costs for maintaining their fixed stock of researchers, nor do they face costs when reallocating researchers between sectors, represented by n.[4]

Concerning the energy used in the intermediate production sector, we assume it is composed of both polluting (brown) energy, $e^B_{i,t}$, and clean (green) energy, $e^G_{i,t}$, combined into an aggregate energy input. The following function defines this aggregate:

$$e_{i,t} = \bar{E}\left[(1-\zeta)\left(e^G_{i,t}\right)^{\xi} + \zeta\left(e^B_{i,t}\right)^{\xi}\right]^{\frac{1}{\xi}}, \tag{11}$$

where the parameter ζ captures the weight of brown energy in production, while ξ governs how easily firms can substitute between brown and green energy sources, and $\bar{E}$ serves as a scaling parameter. Finally, brown energy consumption is taxed with an excise tax τ^e.

Firms are monopolistically competitive and set the nominal price of their product, $P_{H,i,t}$, subject to quadratic price adjustment costs. They maximize the objective function

$$\begin{aligned}\mathbb{E}_0\Bigg\{\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}\Bigg[&P_{H,t}\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon_P}y_{H,t} - P^G_t e^G_{i,t} - \left(P^B_t+\tau^e_t\right)e^B_{i,t} - W_t h_{i,t} - R^k_t k_t - \\ &\frac{\iota_{PH}}{2}\left(\frac{P_{H,i,t}}{P_{H,i,t-1}}-\bar{\pi}_H\right)^2 y_{H,t}P_{H,t} + MC_t\left(y_{H,i,t}-\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon_P}y_{H,t}\right)\Bigg]\Bigg\},\end{aligned} \tag{12}$$

[4] Each firm is endowed with a fixed number of researchers, and introducing a cost for maintaining this stock has no impact on the model's results, as both the number of researchers and the associated cost remain constant over time. While introducing an explicit cost for reallocating researchers could potentially slow down the transitional dynamics, it would not alter the fundamental results regarding the effects of various fiscal policies during the transition. This assumption simplifies the model without sacrificing its general insights.

where λ_t is the discount factor of the firm, which coincides with the Lagrange multiplier from the consumer's problem, $P_{H,t}$ is the aggregate price level, P_t^G is the price of green energy, P_t^B is the price of brown energy, τ_t^e is the excise tax, W_t is the nominal wage, $R_{t,K}$ is the rental rate of capital, $\iota_{PH} \geq 0$ quantifies price adjustment costs, as in Rotemberg (1982), MC_t is the marginal cost in nominal terms, and $y_{H,i,t}$ is production.

The optimization problem of firm i involves choosing the allocation of researchers $n_{i,t}$, price $P_{H,i,t}$, and inputs of production $e_{i,t}^B$, $e_{i,t}^G$, $k_{i,t}$, $h_{i,t}$, to maximize the present value of expected profits given by equation (12), subject to equations (7)-(11), while taking as given input prices P_t^G, P_t^B, W_t, and fiscal policy τ^e.

We solve for a symmetric equilibrium where all intermediate firms make the same decisions. Therefore, in what follows, we present the aggregated variables for all i. Using $\mu_{A,t}$ and $\mu_{A_e,t}$ for the Lagrange multipliers of the law of motions of efficiency, the optimal decision for $n_{i,t}$ is given by

$$\mu_{A,t} g_{t-1}^{\alpha} B n_t^{\phi-1} A_{t-1} = \mu_{A_e,t} B_e (1-n_t)^{\phi-1} g_{t-1}^{\mu} A_{e,t-1}, \tag{13}$$

and the optimal pricing decision results in

$$\pi_{H,t}\left(\pi_{H,t}-\bar{\pi}_H\right) = \beta \mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{H,t+1}^2\left(\pi_{H,t+1}-\bar{\pi}_H\right)\frac{y_{H,t+1}}{y_{H,t}}\right] + \frac{\varepsilon_P}{\iota_{PH}}\left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_P - 1}{\varepsilon_P}\right), \tag{14}$$

which is the New Keynesian Phillips curve, where $p_{H,t} = \frac{P_{H,t}}{P_t}$ is the relative price of domestically produced goods to the price level in the economy, $\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}}$ is the domestic inflation rate, and real marginal cost and the deflated domestic production are $mc_t = \frac{MC_t}{P_t}$ and $y_{H,t} = \frac{Y_{H,t}}{P_t}$, respectively. We present the rest of the optimality conditions in the Appendix.

2.4 Energy sectors

2.4.1 Green energy production

Green energy is produced domestically using private green capital s_t^G and public green capital $s_t^{G,P}$, which firms treat as given. The production function is

$$e_t^G = \Omega L^{1-\eta}[(1-\gamma)(s_t^G)^\omega + \gamma(s_t^{G,P})^\omega]^{(\eta/\omega)}, \tag{15}$$

where L is a fixed land factor (assumed to be 1), and Ω represents clean energy productivity. Parameters ω and γ determine the elasticity of substitution and the relative importance between private and public green capital. Parameter η represents the green capital share in production.

Firms solve a static optimization problem, renting private green capital s_t^G to maximize profits, given prices P_t^G, R_t^G, technology, public green capital, and a government subsidy $s_t^{P_e}$.[5] Profits in period t are expressed as follows:

$$\Gamma_t^G = (1 + s_t^{P_e})P_t^G e_t^G - R_t^G s_t^G.$$

In the benchmark calibration, we assume that public and private green capital are substitutes and investigate the sensitivity of our results to this assumption later in the analysis.

2.4.2 Brown energy endowment

To simplify the model, we assume there is no production of brown energy in the economy. The economy receives an endowment of brown energy, $e^{B,d}$, that we assume is traded internationally and can be exported or imported at the international price $P^{B,*}$. Since e_t^B is the domestic demand for brown energy, the imports of brown energy, $e_t^{B,*}$, are given

[5] We also consider the case of subsidizing purchases of green energy from the intermediate good producer, and the transitional dynamics are similar.

by:

$$e_t^{B,*} = e_t^B - e^{B,d}.$$

Under the law of one price, the domestic price of imports equals the foreign price adjusted by the nominal exchange rate. We assume it holds for the brown energy market and, thus, the domestic price of brown energy is the following

$$P_t^B = FX_t P^{B,*}.$$

From the previous expression, note that

$$\frac{P_t^B}{P_t} = \frac{FX_t P^{B,*} P^*}{P_t P^*}$$

and

$$P_t^B = rer_t P^{B,*}$$

holds, where rer_t is the real exchange rate. The international price $P^{B,*}$ and price level P^* are assumed to be exogenous and invariant over time.

2.5 Final goods imports

The economy imports foreign differentiated goods $y_{F,i,t}$, for which the law of one price holds. This means $P_{F,i,t} = FX_t P_{F,i,t}^*$. In addition, assuming a small open economy implies $P_{F,t}^* = P^*$. Integrating over all varieties, we obtain $P_{F,t} = FX_t P^*$, which is the price level of imported goods. Dividing by the domestic price level, we get the real exchange rate:

$$p_{F,t} = rer_t = FX_t \frac{P^*}{P_t}.$$

2.6 Final goods exports

The following expression gives the foreign demand for domestically produced goods:

$$c_{H,t}^{*} = \left(\frac{P_{H,t}^{*}}{P^{*}}\right)^{-\theta^{*}} y^{*},$$

where θ^{*} is the elasticity of substitution of foreign and domestic goods in the foreign economy. As for the case of the foreign price level P^{*}, the foreign output y^{*} is exogenous from the point of view of the small open economy.

2.7 Monetary authority

The central bank sets the domestic interest rate R_t following a Taylor rule that depends on inflation (π_t) and output (y_t) deviations from their steady-state value:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R}. \tag{16}$$

2.8 Fiscal authority

The fiscal authority's budget constraint is given by

$$\tau_t + \tau_t^{e} e_t^{B} + b_{t+1} = p_t^{G} e_t^{G} s_t^{P_e} + \frac{b_t}{\pi_t} R_{t-1} + i_t^{G,P} + g_{H,t}, \tag{17}$$

where b_{t+1} is real debt with one-period maturity purchased by domestic households, $g_{H,t}$ is wasteful government consumption, and τ_t represents lump-sum taxes to households, which follow the fiscal rule (see also Chen et al. (2022)):

$$\tau_t - \tau^{*} = \phi_\tau b_{t-1}.$$

Here, τ^* is the steady-state tax level, and ϕ_τ determines the fiscal regime. A sufficiently high ϕ_τ ensures fiscal sustainability by adjusting taxes as needed. $i_t^{G,P}$ represents public investment in green capital, contributing to the accumulation of public green capital $s_t^{G,P}$.[6]

2.9 Aggregation

Aggregating all domestic and foreign agents, we derive the market clearing condition for home-produced goods, the NIPA equation, and the definition of net exports. These expressions are as follows:

$$
\begin{aligned}
y_{H,t} &= (1-\chi)p_{h,t}^{-\theta}\left(c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P}\right) + c_{H,t}^*, \\
p_{H,t}y_{H,t} &= c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P} + \frac{\iota_{PH}}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t}y_{H,t} + nx_t + p_t^B e_t^{B,*}, \\
nx_t &= \frac{FX_t}{P_t}P^*\frac{B_{t+1}^*}{P^*} - \frac{FX_t}{P_t}P^*\frac{B_t^*}{P^*}R_{t-1}^*\Psi^A\left(\tilde{A}_t^f\right).
\end{aligned}
$$

Then, net exports are defined by

$$
nx_t = rer_t b_{t+1}^* - rer_t\frac{b_t^*}{\pi^*}R_{t-1}^*\Psi^A\left(\tilde{A}_t^f\right).
$$

2.10 Balance growth path assumptions

As mentioned earlier, the directed technical change affects the long-run energy share and economic growth (see also Hassler et al. (2021)). Specifically, let X_{t-1} represent the output trend during period t, which is the growth rate of $y_{H,t}$. We define

$$
X_t = A_t k_t^\alpha \tag{18}
$$

[6]We assume that public green capital evolves according to a law of motion similar to equation 4, using the same parameter values.

such that

$$g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^{\alpha}}{X_{t-1}^{1-\alpha} X_{t-1}^{\alpha}} = \tilde{A}_t \tilde{k}_t^{\alpha} \tag{19}$$

is the growth rate of the economy. Since the stock of capital's trend is X_{t-1}, its productivity factor A_t grows at $X_{t-1}^{1-\alpha}$. $\tilde{A}_t$ and $\tilde{k}_t$ are the stationarized counterparts of A_t and k_t, respectively.

To have a balanced growth path, the two additive components of the production function must grow at the same rate, given its functional form. This requirement implies that

$$X_{t-1} = X_{t-1}^{Ae} X_{t-1}^{e},$$

and, from equation (11),

$$X_t^e = X_t^{eG} = X_t^{eB}.$$

Thus, all energy sources grow at the same rate for every period t. Then, from the production function of green energy, we get the following condition:

$$X_{t-1}^{eG} = X_{t-1}^{\eta}.$$

Hence,

$$X_{t-1}^{eB} = X_{t-1}^{e} = X_{t-1}^{\eta}$$

and

$$X_{t-1}^{Ae} = X_{t-1}^{1-\eta}.$$

Finally, from the first-order condition of intermediate producers to energy inputs, prices P_t^G and P_t^B grow at $X_{t-1}^{1-\eta}$. In the Appendix, we present the complete set of stationarized equations.

3 Calibration and solution

This section describes our calibration strategy and solution method. We first discuss the functional forms used in our numerical implementation, then detail our calibration approach targeting Chilean data, and finally explain how we solve for transitional dynamics between steady states.

3.1 Numerical implementation and function forms

The main exercise is to study the transition between an initial steady state with large use of polluting energy to one with low use of polluting energy. For this purpose, we solve for the nonlinear perfect foresight transition between steady states, where we calibrate the initial steady state to match Chilean first-order national account and energy related moments.

We assume the utility function is constant relative risk aversion:

$$U = \frac{c_t^{1-\sigma}}{1-\sigma}.$$

Additionally, we assume quadratic adjustment costs for both traditional and green capital, specified as

$$\Phi\left(\frac{k_{t+1}}{k_t}\right) = \frac{\kappa}{2}\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)^2$$

and

$$\Phi\left(\frac{s^G_{t+1}}{s^G_t}\right) = \frac{\kappa}{2}\left(\frac{s^G_{t+1}}{s^G_t} - \bar{g}\right)^2,$$

where $\bar{g}$ is the average growth rate of the economy g_t at the steady state.

3.2 Calibration

The baseline calibration targets annual data from Chile after the 1990s, a period marked by the adoption of inflation targeting and greater macroeconomic stability. We list the parameter values and targets in Tables 1-3.

We fix some parameters following the existing literature and to standard values when uncontroversial. The intertemporal elasticity of substitution is $\sigma = 1$, and the annual capital depreciation rate is $\delta = 0.1$. Without affecting significantly our qualitative results, we assume that green capital depreciates at the same rate as traditional capital. The capital shares in intermediate goods and green energy production, α and η, are set at 0.26 and 0.33, respectively.

We normalized the steady-state values of the rest of world inflation rate (π^*), the real exchange rate (rer), the international price of brown energy ($p^{B,*}$), and labor ($\bar{h}$) to 1, and set the adjustment cost of traditional and green capitals, κ, to 0.01.

We set the price adjustment cost parameter, $\iota_{H,P}$, to 19. This value is tied to the average price contract length by comparing the log-linearized New Keynesian Phillips curve in the Rotemberg model to the Calvo model. Specifically, the slope of the Phillips curve relative to real marginal costs is $\frac{\varepsilon_P}{\iota_{H,P}}$ in the Rotemberg model and $[(1-\Psi)(1-\Psi\beta)/\Psi]$ in the Calvo model, where $1/(1-\Psi)$ represents the average contract length. The chosen $\iota_{H,P}$ corresponds to an average price contract duration of approximately one year.

We set the Taylor rule coefficient for the interest rate response to inflation deviations, ϕ_π, and the coefficient for interest rate persistence to 1.25 and $\rho_R = 0.75$, respectively, consistent with the quarterly estimates of Martínez et al. (2020), who conducted a Bayesian estimation of a New Keynesian model for Chile. The reaction to output deviations is $\phi_y = 0.25$, a standard value in the literature.

For the fiscal rule, we fix the coefficient ϕ_τ to 0.15, consistent with studies on fiscal and monetary policy interactions, such as Bianchi and Melosi (2017), Chen et al. (2022), and Bianchi (2021). The steady-state values of real debt $\bar{b}$ and taxes τ^* targets the average public debt-to-GDP ratio of 20% and average primary deficit of 5% in the Chilean data. We set the excise tax on carbon to 5, according to the data for Chile, and the subsidies are zero in the baseline calibration.

Table 1: Calibrated parameter values I

Parameter		Target/source	Value
σ	CES elasticity in utility	Standard	1
δ	Depreciation capital	Standard	0.10
α	Capital share in production	Standard	0.26
η	Green capital share in e^G	Standard	0.33
κ	Capital Adjustment costs	Investment volatility	0.01
ι_{HP}	Adj. cost of prices	Standard	19
ρ_R	Interest rate smoothing parameter	Martínez et al. (2020)	0.75
ϕ_π	Interest rate response to inflation	Martínez et al. (2020)	1.25
ϕ_y	Interest rate response to output	Martínez et al. (2020)	0.25
ϕ_τ	Tax response to debt	Standard	0.15
$\bar{b}$	Public debt-to-GDP initial steady state	Average debt-to-GDP Chile	0.21
τ^*	Lump sum taxes at initial SS	Net deficit-to-GDP Chile 5%	0.18
τ^e	excise tax at initial SS	Excise tax Chile	0.05
θ=θ^*	Subst. H & F in consumption	Justiniano and Preston (2010)	0.85
χ	Share F goods in consumption	Justiniano and Preston (2010)	0.24
ε_P	Elasticity between varieties	Avg. markup 11%	10
β	Discount factor	Avg. inflation Chile	0.987
R^*	Gross risk free rate	3 months Tbill U.S.A	1.03
φ^A	Sovereign spread parameter	Country spread Chile	0.009
ξ	Subst. energy inputs	Papageorgiou et al. (2017)	0.67
$e^{B,d}$	e^B Domestic endowment	Imported/total energy	0.5
Be	Productive efficiency researchers	Avg. growth 2.5%	0.18
ϕ	Returns to scale researchers	Hassler et al. (2021)	0.92
γ	Green public and private K	An et al. (2019)	0.44
ω	Public inv. share in e^G	An et al. (2019)	0.66
ζ	Share brown energy	Data Chile	0.3

Following Justiniano and Preston (2010), we set the elasticity of substitution between domestic and foreign goods, in the domestic and foreign countries, θ and θ^*, equal to 0.85 and the share of foreign goods in consumption, χ, to 0.24. The elasticity between domestic varieties, ε_P, is set so that the steady-state markup is 11%.

We calibrate the discount factor, β, to 0.987 to get the average inflation rate of 4%, given the average nominal risk-free rate of 3%. The parameter that characterizes the sovereign spread, ϕ_A, takes the value 0.009 to generate a consistent sovereign spread for Chile that equals 1.0082.

Regarding parameters related to the energy sector, we set the substitution of energy inputs in energy production to 0.67, following the low estimates of Papageorgiou et al. (2017) and the higher estimates of Benmir et al. (2025), assuming that the two energy inputs are substitutes. The domestic endowment of brown energy, $e^{B,d}$, is set to 0.5 to match the imported to total energy ratio in Chile, which is a 50%.[7] The coefficient Be in the evolution of energy efficiency, Ae, is calibrated to reproduce the average real per capita GDP growth rate of 1.025, according to the data, and ϕ is set to 0.92 as in estimation results from Hassler et al. (2021). Parameters in the CES aggregator of public and private green capital, γ and ω, take the values of 0.44 and 0.66, respectively, as in An et al. (2019). Thus, we assume that public and private capital are substitutes in production. An et al. (2019) estimate a nested-CES production function, whereas the two types of capital are considered separately along with labor as inputs. Due to a lack of data availability, we assume that the substitution between public and private capital in production also holds for green energy production.

To finalize the parametrization of the model, we set the share of brown energy, ζ, to 0.3 and jointly calibrate the elasticity of substitution between physical capital and energy, ϵ,

[7] In additional exercises (available upon request), we compare the benchmark calibration with a counterfactual where the small open economy is a net importer of brown energy. The results are qualitatively similar, with slightly lower output and inflationary costs when the country is a net exporter.

the energy coefficient in the CES production, $\bar{E}$, the productivity level in green energy production, Ω, and the coefficient B in the traditional factors total factor productivity (TFP), to match first order moments for Chile in the initial steady state. Our targets are the ratio of brown to total energy (e^B/e), the ratios of total investment ($i^G + i^{G,P}$), and green capital investment to GDP, and we ensure that the sum of energy ratios equals one ($e^B/e + e^G/e = 1$). The data values for these objects are presented in Table 2.

Table 2: Data moments

e^B/e	$(i + i^G + i^{G,P})/y$	$(i^G + i^{G,P})/y$	$(e^B/e + e^G/e)$
0.72	0.20	0.01	1.00

Table 3 presents the values of the resulting parameters.

Table 3: Calibrated parameter values II

	Energy parameters	**Target/source**	**Value**
ϵ	Subst. energy and K	Jointly calibrated	0.4
$\bar{E}$	CES energy	Jointly calibrated	2.4
Ω	TFP in e^G	Jointly calibrated	0.04
B	Prod. coef researchers	Jointly calibrated	0.02

4 Transitional dynamics

We analyze how a small open economy transitions from an initial steady state with high dependence on brown energy to a more sustainable equilibrium. Our analysis begins with an economy calibrated to match Chilean data, as detailed in Section 3. We then introduce policy changes that initiate a green transition and study how economic agents, with perfect foresight about the entire path of adjustment, respond to these changes. This perfect foresight assumption allows us to isolate the pure economic effects of the transition from uncertainty about policy implementation. Throughout our analysis, we focus on both the short-run adjustment costs and the long-run benefits of different transition paths.

4.1 A transition induced by increases in brown energy taxes

Following the existing literature, we examine the transitional dynamics driven by increases in brown energy taxes. Our focus on carbon taxation aligns with actual policy, as Chile has made significant climate commitments, including a 2020 update to its Nationally Determined Contribution (NDC) target, aiming for a 45% reduction in CO_2 emissions from 2016 levels by 2030 and carbon neutrality by 2050. In 2014, Chile became the first Latin American country to impose a $5 USD CO_2 tax, targeting emissions and local pollutants. Despite this pioneering move, the tax rate has remained low. The Chilean Climate Action Plan 2017–2022 calls for a gradual, sevenfold increase in the carbon tax.

To facilitate comparison across various fiscal tools, we simulate a moderate scenario in which the excise tax is nearly quadrupled, increasing from 5 in the initial steady state to 18.5 in the new steady state over a 200-year horizon. While this increase is more modest than Chile's proposed policy changes, it allows us to isolate and clearly identify the key economic mechanisms at play during the transition.[8]

Figure 1 illustrates the transitional dynamics for the model economy over the initial 40 years, presented as percentage deviations from the initial steady state.[9] The rise in carbon taxes drives a faster adoption of green energy while curbing the reliance on brown energy. In the new equilibrium, the use of brown energy declines by approximately 18%, total energy consumption drops by 7%, and energy efficiency improves by 6%. This boost

[8] In Appendix A.5, we present an experiment in which taxes gradually rise from 5 in the initial steady state to 35 in the new steady state over a 200-year transition period. The decrease in brown energy use is around 33% of the initial steady state, and the shock induces higher inflation and output losses.

[9] Level-variable dynamics are available upon request. Results for the entire 200-year transition are provided in Appendix Figure A.1.

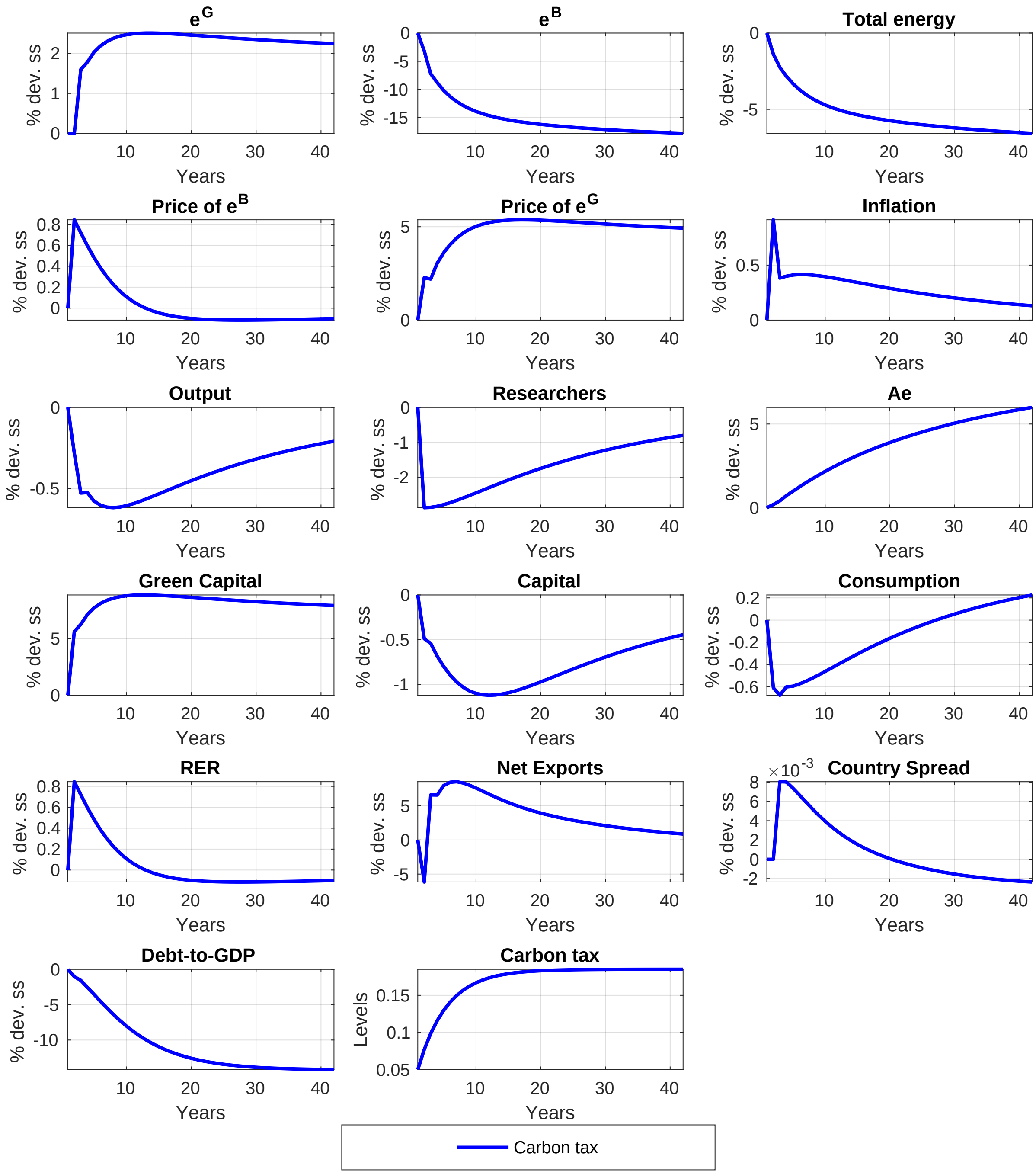
in energy efficiency stems from the strategic reallocation of researchers within firms to enhance energy-saving measures in the short term, which, in turn, influences production dynamics over the long term.

In the short run, higher taxation on brown energy raises the marginal costs for intermediate firms, driving up inflation. The increased after-tax domestic prices of brown energy boost demand for green energy, which, in turn, causes green energy prices to rise as well. This dual price surge leads to heightened inflation in the short and medium term. Over time, inflation gradually moderates as firms reallocate more researchers toward improving energy efficiency, thereby enhancing energy usage efficiency.

The reallocation of researchers during the transition period slows the productivity growth of traditional inputs, damping physical capital accumulation. In the short run, the complementarity between energy and traditional inputs, combined with the inertia in improving energy efficiency and rising costs of brown energy, makes the green transition recessionary. Anticipating long-term increases in brown energy taxation, firms adjust their production by scaling back on traditional inputs, particularly reducing investment demand, which triggers a short-term recession. These recessionary dynamics lead to real currency depreciation and a widening of the country spread. The increase in country spreads and real depreciation damp consumption demand. On the other hand, higher tax revenues from brown energy taxes alleviate the government's real debt burden, offsetting some of the adverse effects.

Compared to existing literature, the model predicts moderate but persistent "greenflation" with transitory output costs. Inflationary effects are tempered because the decline in investment and consumption demand offsets the inflationary pressures arising from higher marginal costs driven by increased carbon taxes. Meanwhile, output losses are short lived, as energy efficiency and growth are endogenously determined. In the short term, output declines due to the reallocation of researchers; however, as energy efficiency

Figure 1: Transitional dynamics: Increases in brown energy taxes



Note: Dynamics for the first 40 years of transition from initial to a new steady state where carbon taxes increase from 5 to 18.5. Variables are in percentage deviations from the initial steady state except for the carbon tax, which is in levels.

improves, output gradually recovers and returns to its original steady state.

4.2 The role of monetary policy

Recent studies explore the role of monetary policy in the green transition, often considering short-term frictions such as sectoral rigidities (e.g., brown vs. green sectors, as in Del Negro et al. (2023)) or price and wage rigidities (as in Olovsson and Vestin (2023)). Our model differs by modeling endogenous energy efficiency and the role of fiscal policy during the transition. Given the central role of monetary policy in the green transition debate, we reexamine the baseline exercise, adjusting the monetary policy stance. In our benchmark calibration, following Martínez et al. (2020), we set the Taylor rule inflation coefficient to 1.25. To understand monetary policy's role, we compare this baseline with two alternative scenarios: a more accommodative stance (inflation coefficient of 1.03) and a more aggressive response to inflation (inflation coefficient of 3.0). Figure 2 illustrates how these different monetary policy stances affect the transition dynamics.

Monetary policy affects capital accumulation through investment as well as consumption and output. Under a more accommodative policy, output declines more due to a larger rise in brown energy prices, which exacerbates inflationary supply-side effects of carbon taxes, fueling "greenflation." In response, firms reallocate researchers toward energy efficiency at the cost of traditional productivity, leading to a reduction in investment demand.

Monetary policy choices impact the external balance during the green transition. A looser policy leads to a higher real depreciation, affecting the country's interest rate spread. More importantly, it influences fiscal space: a looser stance increases brown energy prices through a higher real exchange rate depreciation, boosting revenues from carbon taxes and reducing the debt-to-GDP ratio, albeit with higher inflation. This illustrates the key interaction between monetary and fiscal policies in our model, which is absent in the standard New Keynesian framework.

Consistent with Nakov and Thomas (2023), our model shows that carbon taxes present no tradeoffs for monetary policy: targeting inflation can help mitigate greenflation without additional output losses in our small open economy. However, a more accommodative monetary policy offers fiscal benefits by reducing the debt-to-GDP ratio at the cost of higher inflation.

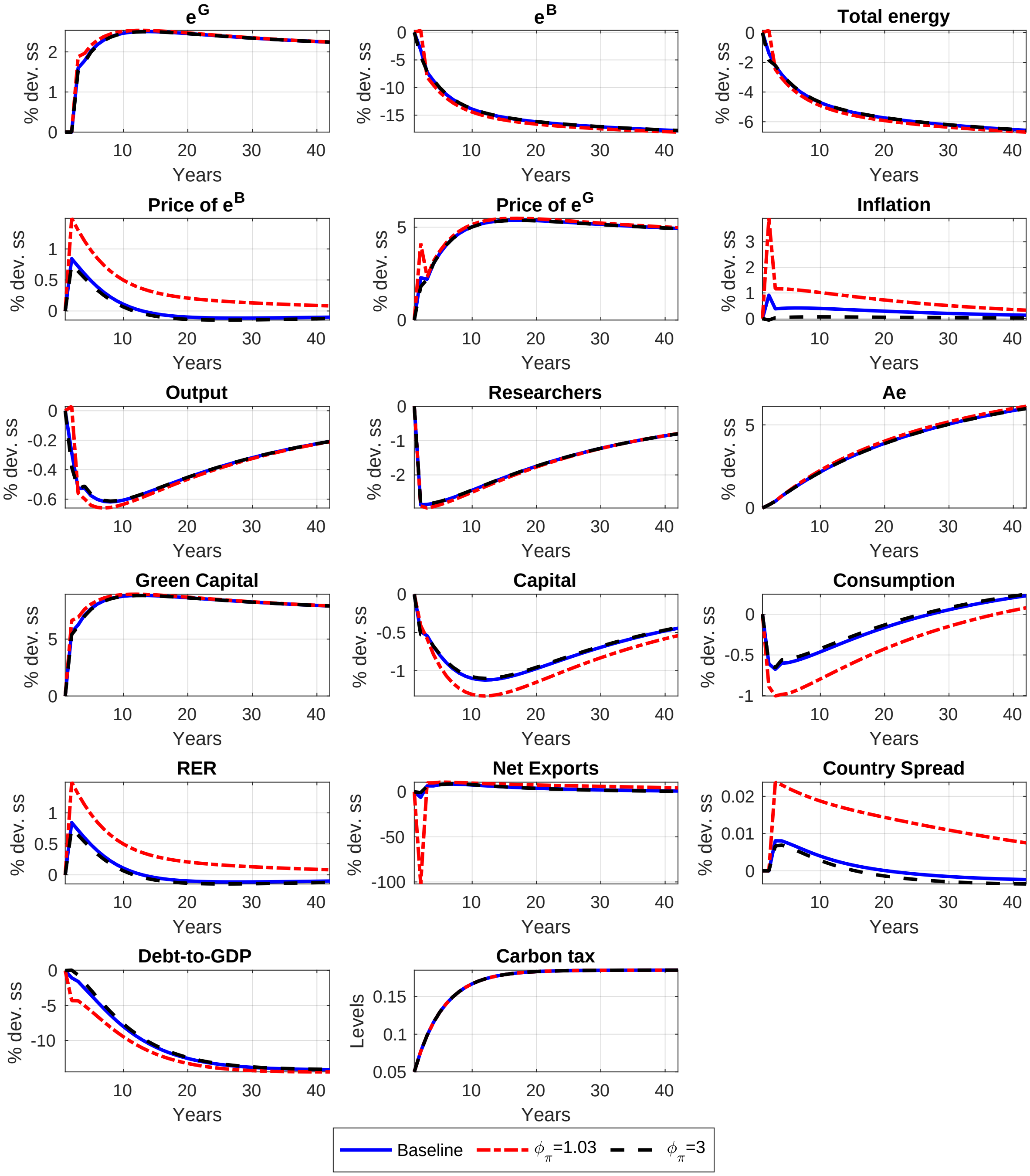
4.3 Sensitivity analysis

The modeling of the supply side is crucial in determining how firms respond to changes in relative energy prices for both the short and long run. The transitional dynamics of the green transformation depend fundamentally on firms' ability to substitute between different energy sources and improve their energy efficiency. Our framework incorporates frictions that can significantly impact the transitional dynamics as well as the initial and final steady states. For this reason, in this subsection we consider various sensitivity exercises.

We start by examining the role of price stickiness, a key friction that affects how changes in carbon taxes translate into price adjustments. As shown in Appendix Figure A.3, stronger price rigidities influence the real exchange rate's response during the transition, given the monetary policy rule, resulting in larger increases in brown energy prices. With more rigid prices, output losses are greater, leading to higher spreads and further reductions in consumption and investment demand.

We next examine how researchers' effectiveness in improving productivity shapes the transition. At the heart of this analysis is the returns to scale parameter in the research sector (ϕ), which governs how researchers' efforts translate into productivity gains. To understand its role, we compare our baseline calibration of ϕ to 0.92 with a lower value of 0.7, representing an environment where researchers face greater difficulties in achieving

Figure 2: Transitional dynamics: The role of monetary policy



Note: Dynamics for the first 40 years of transition from initial to a new steady state where carbon taxes increase from 5 to 18.5 for different parameters of the monetary policy rule. Blue lines represent the baseline calibration; black discontinuous lines are the case of $\phi_\pi = 3$; and red dashed lines are the case of $\phi_\pi = 1.03$. Variables are in percentage deviations from the initial steady state except for the carbon tax.

productivity improvements. The transitional dynamics under this lower effectiveness scenario are shown in red dashed-dotted lines in Figure 3, with all variables expressed as percentage deviations from their respective steady states, except for the carbon tax, which is shown in levels.

The impact of reduced research effectiveness manifests through both steady-state and transitional channels. In the new steady state, the same increase in carbon taxation leads to a slightly smaller reduction in brown and total energy use, reflecting firms' diminished ability to adapt through productivity improvements. More striking are the differences in short-run dynamics: inflation increases more sharply and output declines more severely and persistently during the green transition, when researchers cannot effectively achieve productivity improvements.

These amplified short-run costs emerge from firms' constrained ability to adjust through the productivity channel. When researchers are less effective at improving energy efficiency (evidenced by the flatter slope of Ae in our results), firms must compensate by increasing their investment in green capital. Furthermore, though firms reallocate fewer researchers when ϕ is low, the productivity loss in the traditional sector is more severe due to researchers' reduced effectiveness. This combination of higher required green investment and larger productivity losses in traditional production amplifies the contractionary effects of carbon taxation, resulting in more pronounced output declines during the transition period.

The reduced effectiveness of researchers in improving energy efficiency limits firms' ability to adapt to changes in relative prices. This raises marginal costs in the short run, driving up inflation. The resulting inflationary pressures cause a higher real depreciation and further increases in country spreads, which hurt consumption demand and exacerbate the negative impact on output during the transition.

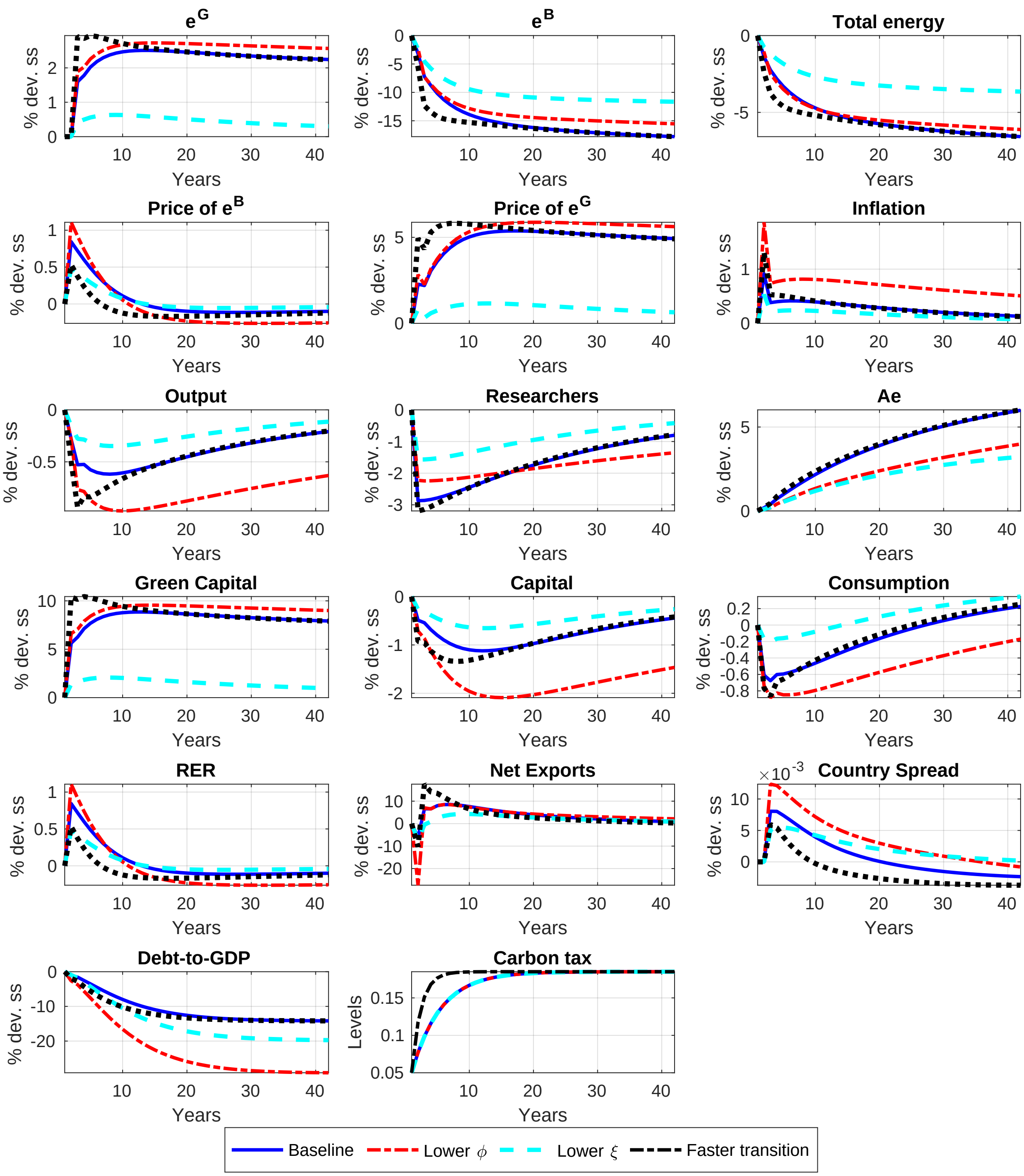
We also examine how changes in the substitutability between green and brown energy in production influences transitional dynamics. Figure 3 depicts these dynamics when the substitutability parameter, ξ, is reduced from 0.67 to 0.4 (cyan dashed lines).

With low substitutability between energy inputs, higher levels of green energy are ineffective at replacing brown energy, resulting in a slower decline in brown energy usage over the long term, despite the carbon tax remaining unchanged relative to the baseline scenario.

Firms, recognizing that green energy cannot effectively substitute for brown energy in production, make smaller adjustments to their energy efficiency during the transition. This reduced adaptation manifests in fewer researchers being allocated to the R&D sector, resulting in a smaller reduction in traditional energy input demand and lower output costs in the short term. These effects contribute to a more moderate real depreciation, which limits the rise in brown energy prices. Moreover, the lower demand for green energy moderates its price increase. As a result, the rise in brown energy taxes exerts less pressure on marginal costs, leading to reduced inflationary pressures throughout the green transition. As a result, the transition costs decrease, but so does the effectiveness of the transition itself. With lower substitutability between energy inputs, larger increases in carbon taxes are required to achieve the desired energy goals.

Finally, given current policy discussions about accelerating the green transition, we examine how the speed of adjustment affects economic outcomes. We compare our baseline scenario, where taxes reach their new steady state in approximately 20 years, to a faster transition completing in 8 years. The results, shown by the black dotted lines in Figure 3, demonstrate that a hastened transition amplifies both inflation and output costs. This occurs because firms must compress their adjustment into a shorter timeframe, leading to more aggressive reallocation of researchers and larger short-term disruptions to production patterns. The model suggests that a more gradual transition would be preferable for moderating greenflation and reducing output costs.

Figure 3: Transitional dynamics: Sensitivity analysis



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 18.5. Blue lines represent the baseline calibration; red dashed lines represent the case of $\phi = 0.7$; cyan dashed lines represent the case of $\xi = 0.4$; and dotted black lines represent the case of a transition in which taxes reach the new steady-state value in eight years. Variables are in percentage deviations from the corresponding initial steady state except for taxes.

Overall, our sensitivity analysis highlights that successful green transition policies must account for each economy's unique characteristics, particularly their supply-side features. These features critically shape both transitional dynamics and the ultimate success of the green transition. Moreover, policymakers must carefully weigh the additional costs of accelerated transitions when planning environmental policies.

5 Alternative fiscal policy tools

Having analyzed carbon taxation, a policy tool emphasized in most of the existing literature, we now explore alternative approaches to reducing greenhouse gas emissions. While studies like Timilsina (2022) identify three broad categories of climate policies– fiscal/pricing policies, regulatory policies, and direct public investment– we focus on two specific alternatives to carbon taxes: green subsidies and public investment in green infrastructure. These tools may offer different tradeoffs between transition costs and effectiveness in reducing emissions.

5.1 Green subsidies

The green transition can be alternatively implemented through subsidies on green energy prices. While subsidies are often politically preferred to taxes as a fiscal tool, their effectiveness in driving the green transition and their associated fiscal costs are not well understood. We quantify these effects by modeling a transition where subsidies gradually increase over a 200-year period, starting from zero in the initial steady state and reaching 100% in the new steady state. The assumed increase in subsidies is intentionally exaggerated to underscore their potential as a fiscal tool for effectively reducing brown energy usage. This transition is illustrated in Figure 4 with black dashed lines.

Our analysis reveals that green subsidies can achieve reductions in brown energy consumption comparable to those achieved by carbon taxes after a 40-year transition, but only at high subsidy rates. More importantly, the transitional dynamics differ markedly from the tax-based transition.

Green subsidies drive green energy adoption and, somewhat counterintuitively, lower the prices of both green and brown energy. This price effect prompts firms to reallocate researchers toward enhancing traditional TFP production. While green capital crowds out traditional capital in the short term, over the long run, the improved efficiency of traditional inputs drives a surge in investment. Consequently, subsidies act as a positive supply shock, leading to lower inflation and output gains and a real exchange rate appreciation.

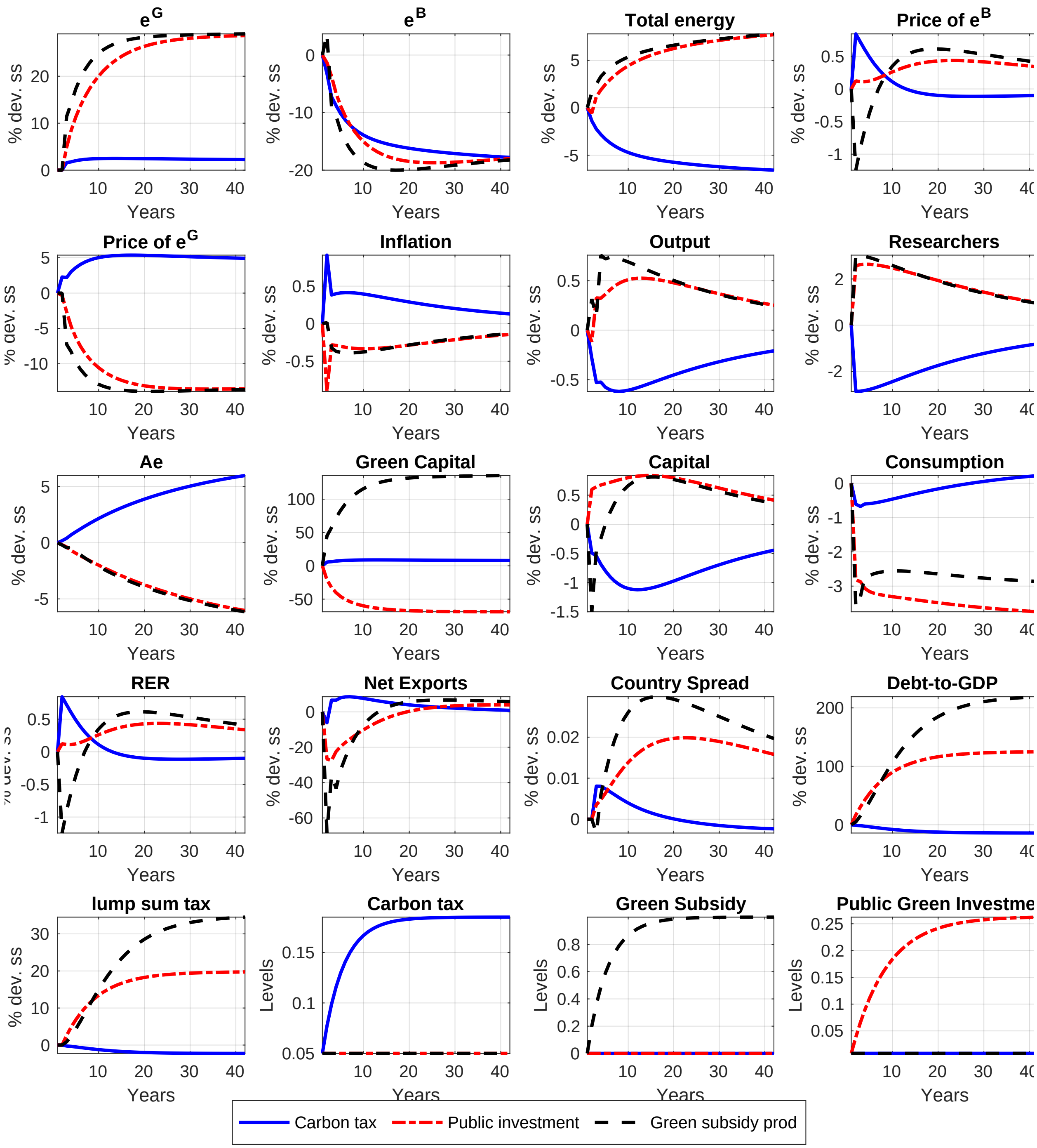
However, this approach comes with substantial costs. The debt-to-GDP ratio increases significantly, rising by 200% in the new steady state. This fiscal expansion leads to a surge in country spreads that, combined with higher lump-sum taxes imposed by the fiscal rule, severely and persistently suppresses private consumption. Thus, our analysis reveals that despite their political appeal, green subsidies may impose greater burdens on consumers in small open economies compared to carbon taxes.

5.2 Public green investment

An alternative approach to promoting the green transition is through green public investment. For example, the German government plans to accelerate the transition by investing in green infrastructure. Former Finance Minister Christian Lindner recently announced a €200 billion initiative (2022–2026) to fund industrial transformation, including climate protection, hydrogen technology, and electric vehicle charging networks. At the same time, Germany aims to increase investment in renewable energy production.

To evaluate this approach, we simulate a scenario where public investment in green infrastructure rises from near-zero to 3.5% of GDP. While this represents a substantial fiscal expansion, using this magnitude allows direct comparison with our previous policy sce-

Figure 4: Transition using different fiscal instruments



Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 18.5 (blue continuous lines); subsidies change from 0 to 100% (black discontinuous lines); and public investment changes from 0 to 3.5% of GDP (red dashed lines). Carbon taxes, green subsidies, and public green investment are in levels. The rest of the variables are in percentage deviations from the initial steady state.

narios by targeting similar reductions in brown energy usage after 40 years. We illustrate this transition in Figure 4.[10]

The surge in green public investment crowds out green private investment, as we assume the two are substitutes in green energy production.[11] Within the green energy sector's production framework, the rise in green public capital enhances the sector's productivity, leading to a decline in green energy prices and an increase in its usage. As cheaper green energy replaces brown energy, overall energy costs for firms decrease. This shift prompts firms to allocate more resources toward improving the TFP of traditional factors, reallocating researchers to enhance the energy efficiency of traditional inputs. Consequently, energy efficiency deteriorates while energy consumption rises.

The productivity growth of traditional factors fuels higher capital investment and output, while the drop in energy prices lowers inflation. However, the fiscal costs associated with such a policy are significant. Similar to the case of subsidies, though to a lesser extent, the debt-to-GDP ratio increases substantially, leading to a persistent surge in the country spread. The higher debt burden, coupled with implied increases in lump-sum taxes and elevated demand for capital, results in considerable and sustained crowding out of private consumption.

While green subsidies and public green investment lead to a smoother transition with fewer output losses and lower inflation, they impose significant consumption losses on households in a small open economy. In Appendix A.7, we explore an alternative scenario where the economy achieves the same reduction in brown energy use, with green

[10] An increase in green subsidies and public investment results in the same reduction in brown energy at period 42 as observed in the baseline simulation. However, in the final steady state, brown energy consumption is lower in the scenario involving a carbon tax increase, as the rise in subsidies and investment causes an overshooting of brown energy reduction in the short term. We have also simulated a transition that targets the same brown energy reduction in the final steady state under all three fiscal instruments. These simulation results are available upon request.

[11] In Appendix Figure **??**, we explore the scenario where the two inputs are complements. In that case, green public investment becomes a more effective fiscal policy tool, encouraging firms to invest more in green capital and further reducing brown energy usage.

subsidies or public green investment raised by the same amount as in the previous experiment. However, in this case, the debt-to-GDP ratio does not increase in the new steady state. After the transition, the debt-to-GDP ratio returns to its original level, with wasteful government spending adjusting throughout the process to ensure this outcome. We show that, in this scenario, permanently reducing government spending by 10% for public green investment and by 30% for green subsidies effectively limits debt increases and curbs the rise in borrowing costs. This adjustment allows consumers to borrow and benefit from productivity gains without significantly harming private consumption.

Therefore, these policies must be coupled with measures that alleviate fiscal stress to avoid negatively impacting private consumption. Similarly, debt instruments designed to manage the debt burden during the transition could have a comparable effect.

5.3 Fiscal policy mix

Public opposition to carbon taxation is well-documented in the literature. For instance, Carattini et al. (2018) identify key concerns including personal costs, regressivity, negative economic impacts, inefficiency, and the self-interest of the state. Given these political challenges and our previous findings about the costs and benefits of individual policies, we explore whether policy combinations might achieve emissions reductions more effectively. Specifically, we examine scenarios where moderate carbon tax increases help finance either green subsidies or public green investment.

Figure 5 presents two policy experiments targeting the same reduction in brown energy use as our baseline scenario. The first experiment, shown with black dotted lines, combines a moderate carbon tax increase (from 5 to 13.5) with green subsidies (rising from 0% to 25%). The second experiment, represented by dashed magenta lines, pairs the same tax increase with public investment in green capital (rising from 0% to 0.8% of GDP). These combinations demonstrate how mixed approaches can achieve environmental goals while mitigating the drawbacks of individual policies.

Given the dynamics of the pure policies (represented by the continuous lines in the graph), it is unsurprising that both policy mixes are associated with lower short-run output and inflation losses as well as a lighter fiscal burden in terms of debt-to-GDP ratio increases and bond spreads. Specifically, debt-to-GDP increases by 45% under the green subsidy mix and by 18% under the public green investment mix. As a result, consumption falls less in the latter scenario. In general, the use of additional fiscal tools leads to similar reductions in brown energy consumption and moderate consumption losses, as the effects of mixed policies on debt-to-GDP and spreads remain contained.

Alternative fiscal combinations can also achieve larger long-run reductions in brown energy use. For example, in experiments not shown here for brevity, we find that increasing taxation from 5 to 50, combined with a 3.5% of GDP rise in public green investment or a 100% increase in green subsidies, can reduce brown energy usage by 60% in the new steady state. However, this would raise debt-to-GDP by around 100%, leading to higher borrowing costs and reduced private consumption.

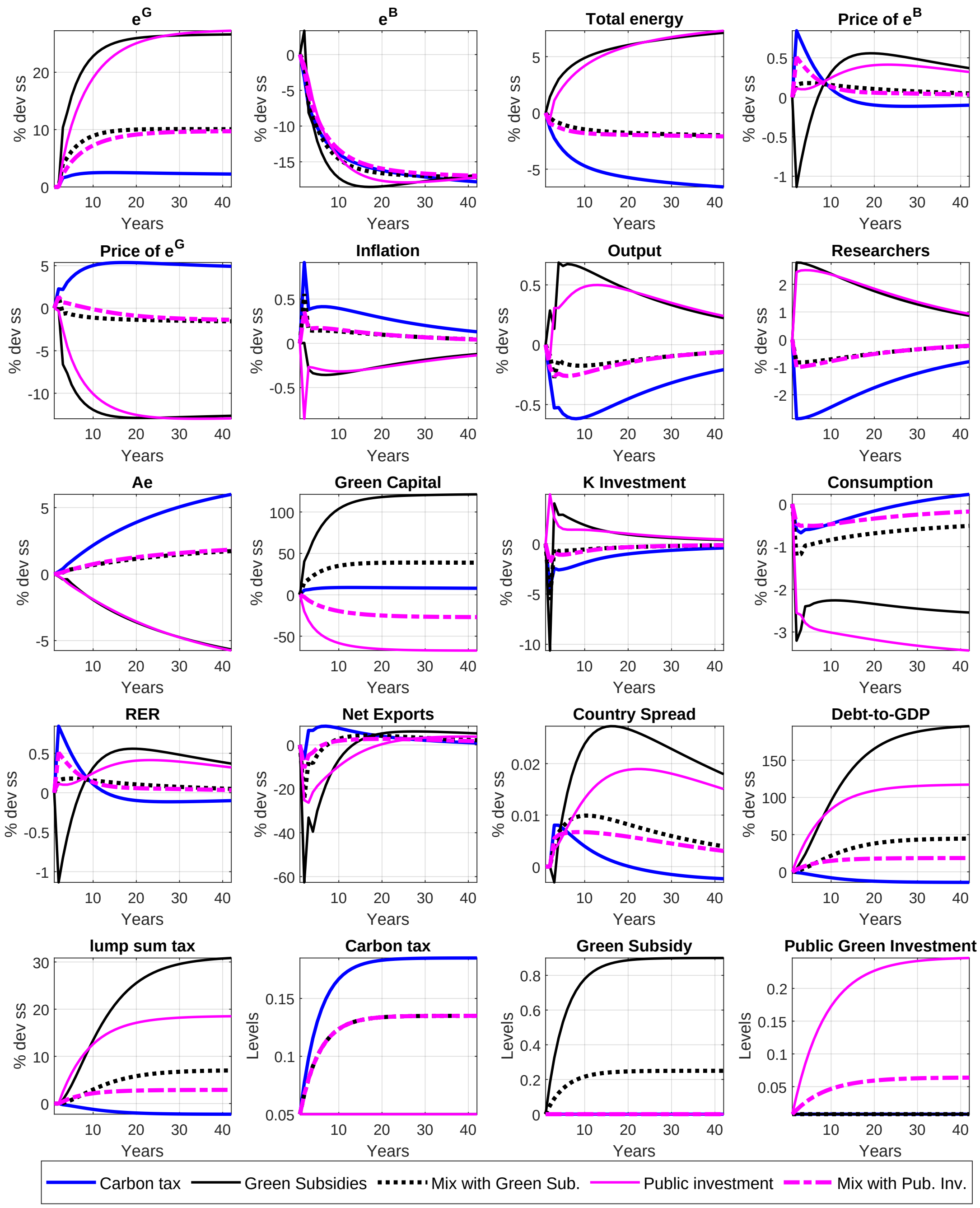
But how do these policy combinations affect welfare? We answer this question in the next section.

6 The welfare costs of the green transition

A natural measure to rank the different policy choices is to look at welfare. However, our model has many policy instruments that can deliver different welfare implications. Hence, a main message we want to highlight in this section is that the welfare implications of the transition are determined by specific assumptions about the combination of instruments and fiscal choices, as we will show below.

In this section, we calculate the welfare costs of the green transition in different transition

Figure 5: Transition with fiscal policy mix



Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 18.5 (blue continuous lines); subsidies change from 0 to 100% (black continuous lines); carbon taxes increase from 5 to 13.5 and green subsidies rise from 0% to 25% (black discontinuous lines); public investment changes from 0 to 3.5% of GDP (magenta continuous lines); carbon taxes increase from 5 to 13.5 and public investment in green capital increases from 0% to 0.8% of GDP (magenta discontinuous lines). Carbon taxes, green subsidies, and public green investment are in levels. The rest of the variables are in percentage deviations from the initial steady state.

scenarios. First, we recover the trend along the transitions using (18) and (19):

$$X_t = \tilde{A}_t \tilde{k}_t^{\alpha} X_{t-1},$$

for a given initial condition X_0, common to all scenarios. Without loss of generality, we normalize $X_0 = 1$. Second, we recover the path of consumption in levels along the transition

$$c_t = \tilde{c}_t X_{t-1},$$

where $\tilde{c}_t$ is the detrended value of consumption.

We calculate welfare using a consumption equivalence measure. We adopt as a benchmark the consumption in the initial steady state and compute how much consumers are willing to give up on the initial steady-state consumption to reach a level of welfare along the transition that is comparable to their initial steady state; that is,

$$W_k = \sum_{t=1}^{T} \beta^t ln\left(c_{t,k} + \Lambda_k\right), \tag{20}$$

with

$$W_k = \sum_{t=1}^{T} \beta^t ln\left(c_{0,k}\right), \tag{21}$$

where T is equal to 200 periods, the length of the transition. k is the correspondent scenario: i) an increase in carbon taxes from 5 to 18.5; ii) an increase in green subsidies from 0 to 100%; iii) an increase in Green Public Infrastructure from 0 to 3.5% of GDP; iv) a policy mix with increases in brown taxes from 5 to 13.5 and of green subsidies from zero to 25%; and iv) a policy mix with increases in brown taxes from 5 to 13.5 and of green public investment from zero to 0.8% of GDP. We also include in this section the case of increases in subsidies and green energy that are financed with cuts in wasteful government spending. Notice $c_{0,k}$ is the consumption level at the initial steady state, and it is the same for all k.

Table 4: Welfare comparisons

Carbon tax rise from 5 to 18.5	0.012
Green subsidy 100%	0.012
Public infrastructure 3.5% GDP	0.017
Carbon tax rise from 5 to 13.5 - subsidy increase by 25%	0.009
Carbon tax rise from 5 to 13.5 - green capital rise by 0.8% of GDP	0.006
Green subsidy 100% govt. spending cut 30%	-0.06
Public infrastructure 3.5% GDP spending cut 10%	-0.03

The value of Λ_k determines the welfare gains or losses compared to the initial steady state. Positive values of Λ_k imply that consumers are worse off along the transition to the new steady state than with the initial steady-state consumption level, and negative values, instead, represent welfare improvements.

Table 4 presents the Λ_k values for the scenarios considered. The green transition proves costly in terms of welfare, as we have not included factors in the utility function—such as health benefits or survival probability—that could make the transition more beneficial for the agents in our model economy. Among the fiscal policy strategies, increasing public investment in green infrastructure is the costliest in welfare terms, since it induces the highest consumption losses during the transition.

However, recall that our model incorporates endogenous growth, meaning fiscal policy choices also affect the economy's trend growth. Although green subsidies and public investment significantly crowd out private consumption in the short run, they increase long-term trend growth, benefiting household consumption over time. If the transition is solely achieved through increases in public investment, which take time to materialize and enhance productivity, the short-run consumption losses outweigh the long-term gains.[12]

[12] This result, of course, depends on our assumptions about green energy production, such as the substitutability between private and public green capital as well as the share of public green capital in total green energy production. In additional exercises (not presented here for brevity), we find that if public and private green capital are complements, investing in public infrastructure leads to better welfare outcomes, as it does not crowd out private consumption (see Figure **??** for transitional dynamics in this case). The trend growth results are available upon request.

If the increase in public investment is partly financed through carbon taxes, the short-run transitional costs are reduced by half. Taxes help limit the rise in the debt-to-GDP ratio, which, in turn, reduces borrowing costs and mitigates the short-term burden on agents in a small open economy. In fact, this policy mix proves to be the most effective option if there are no other fiscal maneuvers available. However, if the government can reduce wasteful spending by 10% to partially finance public green investment without raising carbon taxes, welfare improves throughout the transition. In this case, there are no short run costs, and the higher growth rate resulting from increased green capital benefits the economy in the long term.

The intuition behind the welfare costs of transitions driven by increases in green subsidies is similar to that of public green investment. When used in isolation, green subsidies are less costly than public green investment. Although consumption falls more persistently during the transition, the long-term benefits from the increase in economic growth offset these short-run costs, resulting in welfare impacts similar to those of carbon taxes. A policy that combines green subsidies with taxes on brown energy further reduces these short-term costs. Finally, if the government can reduce spending by 30% during the transition to control the rise in public debt, green subsidies can deliver net welfare benefits.

To summarize, Table 4 shows that unless the transition is financed through mechanisms that reduce the cost of public debt (as seen in the last two rows of the table), the short-term costs of spending policies outweigh the long-term benefits, resulting in welfare losses from the green transition. However, these costs are mitigated when the government partially finances public infrastructure or green subsidies with moderate increases in excise taxes on brown energy.

7 Conclusions

We study the transitional dynamics of green transformation through fiscal policies in emerging markets, exploring various policy instruments and combinations to foster a greener economy. Increases in brown energy taxes reduce brown energy usage, but at the cost of short-term output losses and greenflation. Green subsidies can significantly reduce brown energy consumption, but only when set at 100%. Green public investment boosts green energy use and lowers green energy prices in the long run. However, both green subsidies and public investment incur substantial fiscal costs to achieve similar reductions in brown energy usage as carbon taxes, while also leading to short-term consumption losses as the increased fiscal burden raises country spreads. We find, however, that monetary policy can influence greenflation in the short run but does little to alleviate the output costs of the green transition. The specific characteristics of the economy, including supply-side features, are crucial when designing transitional policies, as they determine the macroeconomic dynamics and welfare costs.

Related to this last point, mixed policies that use revenues from carbon taxes to partially finance green subsidies or public investment are welfare-improving. It is important to note that our analysis assumes perfect foresight, with no uncertainty about fiscal policy implementation. Future research should explore how our conclusions might change under uncertainty regarding the execution of green transition policies.

In conclusion, our analysis shows that there is no simple path to the green transformation of a small open economy. Policymakers must carefully consider the tradeoffs and sacrifices necessary to secure a greener future.

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A Appendix

A.1 Equilibrium equations

A.1.1 Household

$$\lambda_t = c_t^{-\sigma}$$

$$k_{t+1} = (1-\delta)k_t + i_t + \frac{\kappa}{2}\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)^2 k_t$$

$$\lambda_t \frac{1}{P_t} = \beta \mathbb{E}_t\left[\frac{\lambda_{t+1} R_t}{P_{t+1}}\right]$$

$$\lambda_t = \beta \mathbb{E}_t\left[\lambda_{t+1}\frac{R_t^*}{\pi_t^*}\frac{rer_{t+1}}{rer_t}\varphi_{t+1}^A(\tilde{A}_{t+1}^f)\right]$$

$$\lambda_t q_t \left(1 - \kappa\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)\right) = \beta \mathbb{E}_t\left[\lambda_{t+1}\frac{R_{t+1}^k}{P_{t+1}} + \lambda_{t+1} q_{t+1}\left(1 - \delta + \left(-\kappa\left(\frac{k_{t+2}}{k_{t+1}} - \bar{g}\right)\frac{k_{t+2}}{k_{t+1}} + \frac{\kappa}{2}\left(\frac{k_{t+2}}{k_{t+1}} - \bar{g}\right)^2\right)\right)\right]$$

$$s_{t+1}^G = (1-\delta)\, s_t^G + \Phi_s(s_{t+1}^G, s_t^G) s_t^G + i_t^G$$

$$\lambda_t q_t^G \left(1 - \kappa\left(\frac{s_{t+1}^G}{s_t^G} - \bar{g}\right)\right) = \beta \mathbb{E}_t\left[\lambda_{t+1}\frac{R_{t+1}^s}{P_{t+1}} + \lambda_{t+1} q_{t+1}^G\left(1 - \delta + \left(-\kappa\left(\frac{s_{t+2}^G}{s_{t+1}^G} - \bar{g}\right)\frac{s_{t+2}^G}{s_{t+1}^G} + \frac{\kappa}{2}\left(\frac{s_{t+2}^G}{s_{t+1}^G} - \bar{g}\right)^2\right)\right)\right]$$

$$\lambda_t q_t^G = \lambda_t$$

$$p_{H,t} y_{H,t} = c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P} + \frac{\iota_{PH}}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t} y_{H,t} + nx_t + p_t^B e_t^{B,*}$$

A.1.2 Intermediate goods producers

$$y_{H,t} = \left[\left(A_t k_t^{\alpha} \bar{h}^{(1-\alpha)}\right)^{\frac{\epsilon-1}{\epsilon}} + \left(A_{e,t} e_t\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

$$e_t = \bar{E}\left[(1-\zeta)\left(e_t^G\right)^{\xi} + \zeta\left(e_t^B\right)^{\xi}\right]^{\frac{1}{\xi}}$$

$$r_t^k = mc_t y_{H,t}^{1/\epsilon}\left(A_t k_t^{\alpha}\bar{h}^{1-\alpha}\right)^{-1/\epsilon} A_t \alpha k_t^{\alpha-1}\bar{h}^{1-\alpha}$$

$$w_t = mc_t y_{H,t}^{1/\epsilon}\left(A_t k_t^{\alpha}\bar{h}^{1-\alpha}\right)^{-1/\epsilon} A_t(1-\alpha)k_t^{\alpha}\bar{h}^{-\alpha}$$

$$p_t^G = mc_t y_{H,t}^{1/\epsilon}\left(A_{e,t}e_t\right)^{-1/\epsilon} A_e(1-\zeta)\left(\frac{e_t}{e_t^G}\right)^{1-\xi}$$

$$p_t^B + \tau_t^e = mc_t y_{H,t}^{1/\epsilon}\left(A_{e,t}e_t\right)^{-1/\epsilon} A_e\zeta\left(\frac{e_t}{e_t^B}\right)^{1-\xi}$$

$$\pi_{H,t}\left(\pi_{H,t}-\bar{\pi}_H\right) = \beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{H,t+1}^2\left(\pi_{H,t+1}-\bar{\pi}_H\right)\frac{y_{H,t+1}}{y_{H,t}}\right] + \frac{\varepsilon_{Pt}}{\iota_{PH}}\left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_{Pt}-1}{\varepsilon_{Pt}}\right)$$

$$\mu_{A,t}Bn_t^{\phi-1}A_{t-1} = \mu_{A_e,t}B_e(1-n_t)^{\phi-1}A_{e,t-1}$$

$$\mu_{A,t} = \beta\frac{\lambda_{t+1}}{\lambda_t}(1+Bn_{t+1}^{\phi})\mu_{A,t+1} + mc_t y_{h,t}^{1/\epsilon}(A_t k_{t-1}^{\alpha}H^{1-\alpha})^{-1/\epsilon}k_{t-1}^{\alpha}H^{1-\alpha}$$

$$\mu_{A_e,t} = \beta\frac{\lambda_{t+1}}{\lambda_t}(1+B_e(1-n_{t+1})^{\phi})\mu_{A_e,t+1} + mc_t y_{h,t}^{1/\epsilon}A_{e,t}^{-1/\epsilon}e_t^{(\epsilon-1)/\epsilon}$$

A.1.3 Green energy producer

$$e_t^G = \Omega L^{1-\eta}[(1-\gamma)(s_t^G)^{\omega} + \gamma(s_t^{G,P})^{\omega}]^{(\eta/\omega)}$$

$$\Omega L^{1-\eta}\eta[(1-\gamma)(s_t^G)^{\omega} + \gamma(s_t^{G,P})^{\omega}]^{(\eta/\omega)-1}(1-\gamma)\eta(s_t^G)^{\omega-1} = \frac{R_t^s}{(1+s_t^{P_e})P_t^G}$$

A.1.4 Brown energy sector

$$p_t^B = rer_t p_t^{B,*}$$

A.1.5 Government

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R}\left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi}\left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R}$$

$$\tau_t + \tau_t^e e_t^b + b_{t+1} = s_t^{P_e}p_t^G e_t^G + \frac{b_t}{\pi_t}R_{t-1} + i_t^{G,P} + g_{H,t}$$

$$\tau_t - \tau^* = \phi_\tau b_{t-1}.$$

A.1.6 Definitions

$$1 = \left[(1-\chi)(p_{H,t})^{1-\theta} + \chi(rer_t)^{1-\theta}\right]^{\frac{1}{1-\theta}}$$

$$nx_t = rer_t b^*_{t+1} - rer_t \frac{b^*_t}{\pi^*_t} R^*_{t-1} \Psi^A \left(\tilde{A}^f_t\right)$$

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}} \pi_t$$

$$y_{H,t} = (1-\chi) p_{h,t}^{-\theta} \left(c_t + g_{H,t} + i_t + s^G_t + i^{G,P}_t\right) + c^*_{H,t}$$

$$c^*_{H,t} = \left(\frac{P^*_{H,t}}{rer_t}\right)^{-\theta^*} y^*_t$$

$$\frac{A_t}{A_{t-1}} = 1 + B n_t^\phi$$

$$\frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e (1-n_t)^\phi$$

$$X_t = A_t k_t^\alpha$$

$$e^{B,*}_t = e^B_t - e^{B,d}_t$$

A.2 Stationarized equilibrium equations

Define X_{t-1} as the GDP trend, and define: $g_t = \frac{X_t}{X_{t-1}}$ as the growth rate. We assume variables at t are stationarized by X_{t-1}. For instance, $\tilde{c}_t = \frac{c_t}{X_{t-1}}$.

Define: $\tilde{\lambda}_t = \frac{\lambda_t}{X_{t-1}^{-\sigma}}$.

In this section, we present the stationarized equilibrium equations.

A.3 Equilibrium equations

A.3.1 Household

$$\tilde{\lambda}_t = \tilde{c}_t^{-\sigma}$$

$$g_t\tilde{k}_{t+1} = (1-\delta)\tilde{k}_t + \tilde{i}_t + \frac{\kappa}{2}\left(\frac{\tilde{k}_{t+1}g_t}{\tilde{k}_t} - \bar{g}\right)^2 \tilde{k}_t$$

$$\tilde{\lambda}_t = \beta g_t^{-\sigma}\mathbb{E}_t\left[\frac{\tilde{\lambda}_{t+1}R_t}{\pi_{t+1}}\right]$$

$$\tilde{\lambda}_t = \beta g_t^{-\sigma}\mathbb{E}_t\left[\tilde{\lambda}_{t+1}\frac{R_t^*}{\pi_t^*}\frac{rer_{t+1}}{rer_t}\varphi_{t+1}^A(\tilde{A}_{t+1}^f)\right]$$

$$\tilde{\lambda}_t q_t\left(1-\kappa\left(\frac{\tilde{k}_{t+1}g_t}{\tilde{k}_t} - \bar{g}\right)\right) = \beta g_t^{-\sigma}\mathbb{E}_t\left[\tilde{\lambda}_{t+1}r_{t+1}^k + \tilde{\lambda}_{t+1}q_{t+1}\left(1-\delta+\left(-\kappa\left(\frac{\tilde{k}_{t+2}g_{t+1}}{\tilde{k}_{t+1}} - \bar{g}\right)\frac{\tilde{k}_{t+2}g_{t+1}}{\tilde{k}_{t+1}} + \frac{\kappa}{2}\left(\frac{\tilde{k}_{t+2}g_{t+1}}{\tilde{k}_{t+1}} - \bar{g}\right)^2\right)\right)\right]$$

$$g_t\tilde{s}_{t+1}^G = (1-\delta)\tilde{s}_t^G + \tilde{i}_t^G + \frac{\kappa}{2}\left(\frac{\tilde{s}_{t+1}^G g_t}{\tilde{s}_t^G} - \bar{g}\right)^2 \tilde{s}_t^G$$

$$\tilde{\lambda}_t q_t^G\left(1-\kappa\left(\frac{\tilde{s}_{t+1}^G g_t}{\tilde{s}_t^G} - \bar{g}\right)\right) = \beta g_t^{-\sigma}\mathbb{E}_t\left[\tilde{\lambda}_{t+1}r_{t+1}^s + \tilde{\lambda}_{t+1}q_{t+1}^G\left(1-\delta+\left(-\kappa\left(\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \bar{g}\right)\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} + \frac{\kappa}{2}\left(\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \bar{g}\right)^2\right)\right)\right]$$

$$p_{H,t}\tilde{y}_{H,t} = \tilde{c}_t + \tilde{g}_{H,t} + \tilde{i}_t + \tilde{i}_t^G + \tilde{i}_t^{G,P} + \frac{\iota_{PH}}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t}\tilde{y}_{H,t} + \tilde{nx}_t + \tilde{p}_t^B e_t^{B,*}$$

A.3.2 Intermediate goods producers

$$\tilde{y}_{H,t} = \left[\left(\tilde{A}_t\tilde{k}_t^\alpha\bar{h}^{(1-\alpha)}\right)^{\frac{\epsilon-1}{\epsilon}} + \left(\tilde{A}_{e,t}\tilde{e}_t\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

$$\tilde{e}_t = \bar{E}\left[(1-\zeta)\left(\tilde{e}_t^G\right)^\xi + \zeta\left(\tilde{e}_t^B\right)^\xi\right]^{\frac{1}{\xi}}$$

$$r_t^k = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_t \tilde{k}_t^{\alpha} \bar{h}^{(1-\alpha)} \right)^{-1/\epsilon} \tilde{A}_t \alpha \tilde{k}_t^{\alpha-1} \bar{h}^{(1-\alpha)}$$

$$\tilde{w}_t = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_t \tilde{k}_t^{\alpha} \bar{h}^{(1-\alpha)} \right)^{-1/\epsilon} \tilde{A}_t (1-\alpha) \tilde{k}_t^{\alpha} \bar{h}^{-\alpha}$$

$$\tilde{p}_t^G (1 - s_t^{P_e}) = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_{e,t} \tilde{e}_t \right)^{-1/\epsilon} \tilde{A}_{e,t} (1-\zeta) \left(\frac{\tilde{e}_t}{\tilde{e}_t^G} \right)^{1-\xi}$$

$$\tilde{p}_t^B + \tilde{\tau}_t^e = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_{e,t} \tilde{e}_t \right)^{-1/\epsilon} \tilde{A}_{e,t} \zeta \left(\frac{\tilde{e}_t}{\tilde{e}_t^B} \right)^{1-\xi}$$

$$\pi_{H,t} \left(\pi_{H,t} - \bar{\pi}_H \right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1}^2 \left(\pi_{H,t+1} - \bar{\pi}_H \right) \frac{\tilde{y}_{H,t+1}}{\tilde{y}_{H,t} g_t} \right] + \frac{\varepsilon_{Pt}}{\iota_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_{Pt} - 1}{\varepsilon_{Pt}} \right)$$

$$\mu_{A,t} g_{t-1}^{\alpha} B n_t^{\phi-1} A_{t-1} = \mu_{A_e,t} B_e (1-n_t)^{\phi-1} g_{t-1}^{\mu} A_{e,t-1}$$

$$\mu_{A,t} = \beta \frac{\tilde{\lambda_{t+1}}}{\tilde{\lambda}_t} g_t^{-\sigma} (1 + B n_{t+1}^{\phi}) \mu_{A,t+1} g_t^{\alpha} + mc_t \tilde{y}_{h,t}^{1/\epsilon} (\tilde{A}_t \tilde{k}_{t-1}^{\alpha} \bar{h}^{(1-\alpha)})^{-1/\epsilon} \tilde{k}_{t-1}^{\alpha} \bar{h}^{(1-\alpha)}$$

$$\mu_{A_e,t} = \beta \frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t} g_t^{-\sigma} (1 + B_e (1-n_{t+1})^{\phi}) \mu_{A_e,t+1} g_t^{\mu} + mc_t \tilde{y}_{h,t}^{1/\epsilon} \tilde{A}_{e,t}^{-1/\epsilon} \tilde{e}_t^{(\epsilon-1)/\epsilon}$$

A.3.3 Green energy producer

$${}_t^G = \Omega L^{1-\eta} [(1-\gamma)(\tilde{s}_t^G)^{\omega} + \gamma (\tilde{s}_t^{G,P})^{\omega}]^{(\eta/\omega)}$$

$$\Omega L^{1-\eta} \eta [(1-\gamma)(\tilde{s}_t^G)^{\omega} + \gamma (\tilde{s}_t^{G,P})^{\omega}]^{(\eta/\omega)-1} (1-\gamma) \eta (\tilde{s}_t^G)^{\omega-1} = \frac{r_t^s}{\tilde{p}_t^G}$$

A.3.4 Brown energy sector

$$\tilde{p}_t^B = rer_t \tilde{p}_t^{B,*}$$

A.3.5 Government

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}} \right)^{\phi_\pi} \left(\frac{y_t}{y} \right)^{\phi_y} \right]^{1-\rho_R}$$

$$\tilde{\tau}_t + \tau_t^e \tilde{e}_t^b + \tilde{b}_{t+1} = s_t^{G_e} \tilde{i}_t^G + s_t^{P_e} \tilde{p}_t^G \tilde{e}_t^G + \frac{\tilde{b}_t}{\pi_t} R_{t-1} + \tilde{i}_t^{G,P} + \tilde{g}_{H,t}$$

$$c_{H,t}^* = \left(\frac{P_{H,t}^*}{rer_t} \right)^{-\theta^*} y_t^*$$

A.3.6 Definitions

$$1 = \left[(1-\chi)(p_{H,t})^{1-\theta} + \chi (rer_t)^{1-\theta} \right]^{\frac{1}{1-\theta}}$$

$$\tilde{nx}_t = rer_t \tilde{b}_{t+1}^* g_t - rer_t \frac{\tilde{b}_t^*}{\pi_t^*} R_{t-1}^* \Psi^A \left(\tilde{A}_t^f \right)$$

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}} \pi_t$$

$$\tilde{y}_{H,t} = (1-\chi) p_{h,t}^{-\theta} \left(\tilde{c}_t + \tilde{g}_{H,t} + \tilde{i}_t + \tilde{s}_t^G + \tilde{i}_t^{G,P} \right) + \tilde{c}_{H,t}^*$$

$$\tilde{c}_{H,t}^* = \left(\frac{p_{H,t}^*}{rer_t} \right)^{-\theta^*} \tilde{y}_t^*$$

$$\frac{A_t}{A_{t-1}} = 1 + B n_t^{\phi}$$

$$\frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e (1-n_t)^{\phi}$$

$$g_t = \tilde{A}_t \tilde{k}_t^{\alpha}$$

$$\tilde{e}_t^{B,*} = \tilde{e}_t^{B} - \tilde{e}_t^{B,d}$$

A.4 Transitional dynamics for the whole transition period

In the main text, we simulate a transition of 200 periods and show transitional dynamics for the first 40 years. However, some variables reach the final steady state at T=200. Although all policies are fully implemented within the 40 periods, some variables continue to adjust until they finally converge at T=200. In figure A.1 we show the 200-years transition.

A.5 High increase in the carbon tax

In figure A.2 we present an experiment in which taxes gradually rise from 5 in the initial steady state to 35 in the new steady state.

A.6 The role of price rigidity

In figure A.3 we show the role of price rigidity.

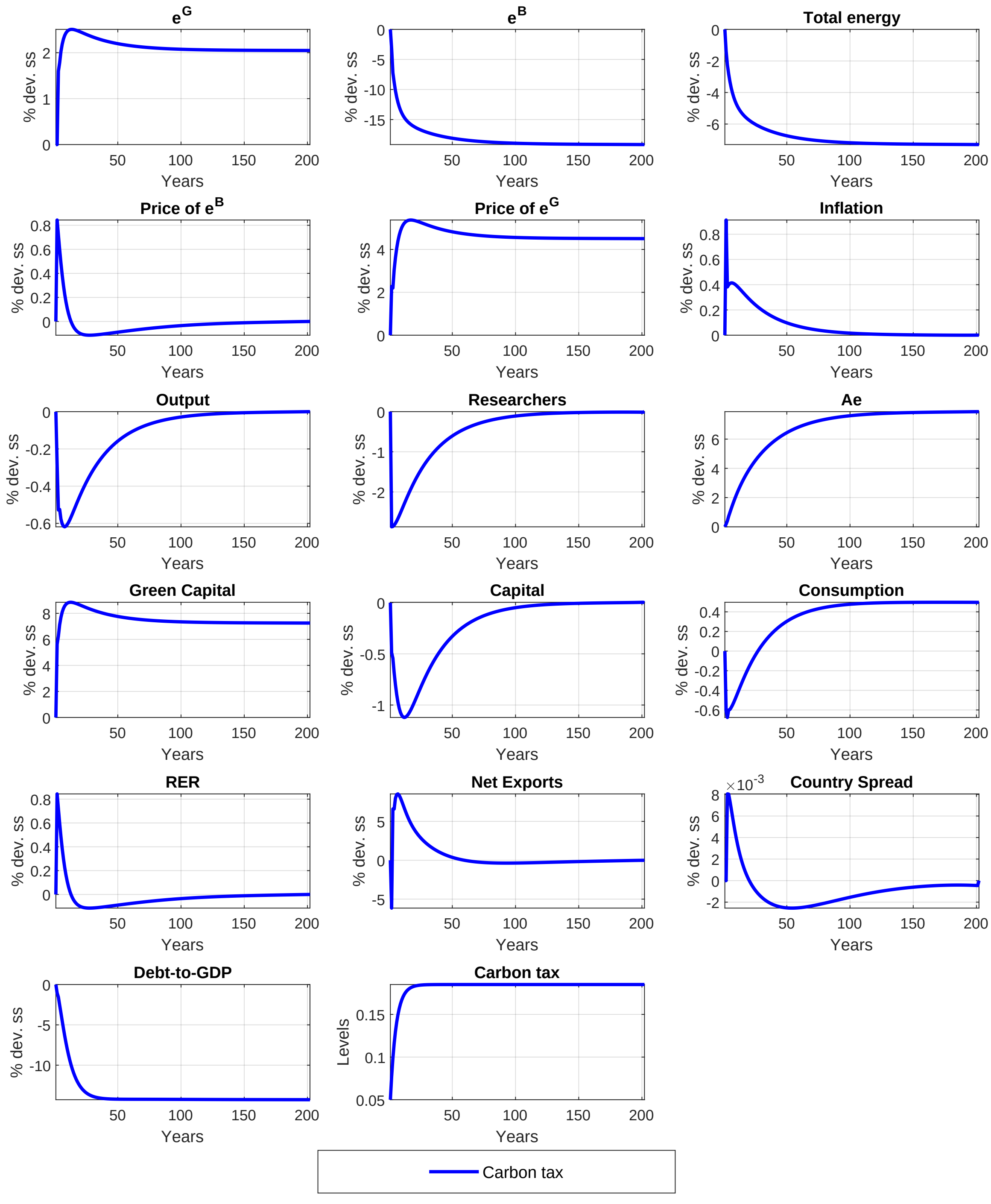
A.7 Alternative fiscal adjustment

In figure A.4 we show the transition with debt consolidation and reduction in government spending in the new steady state.

A.8 The role of energy production parameterization

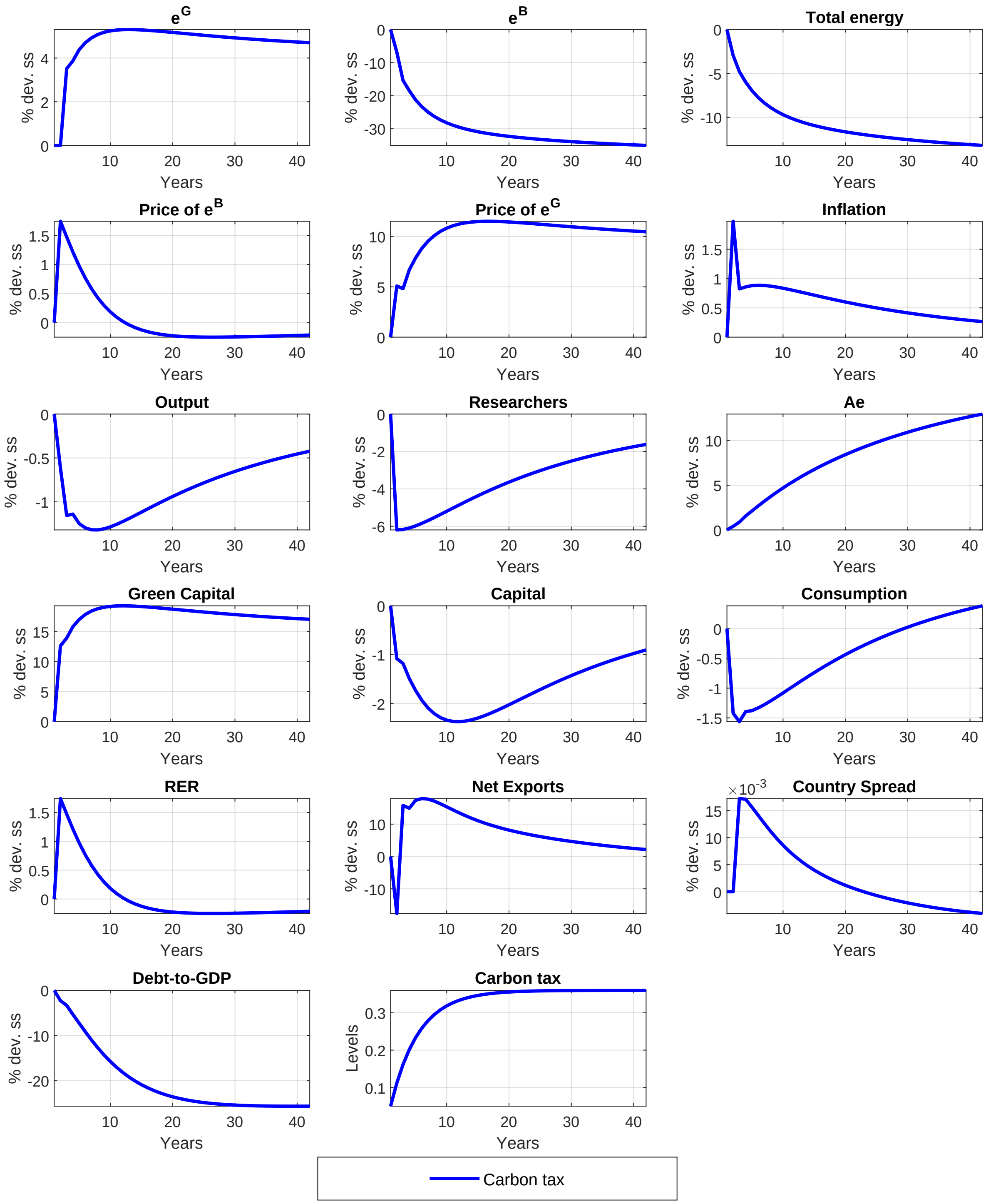
Figure A.5 shows the role of different parameters in energy production.

Figure A.1: Transitional dynamics: 200 years



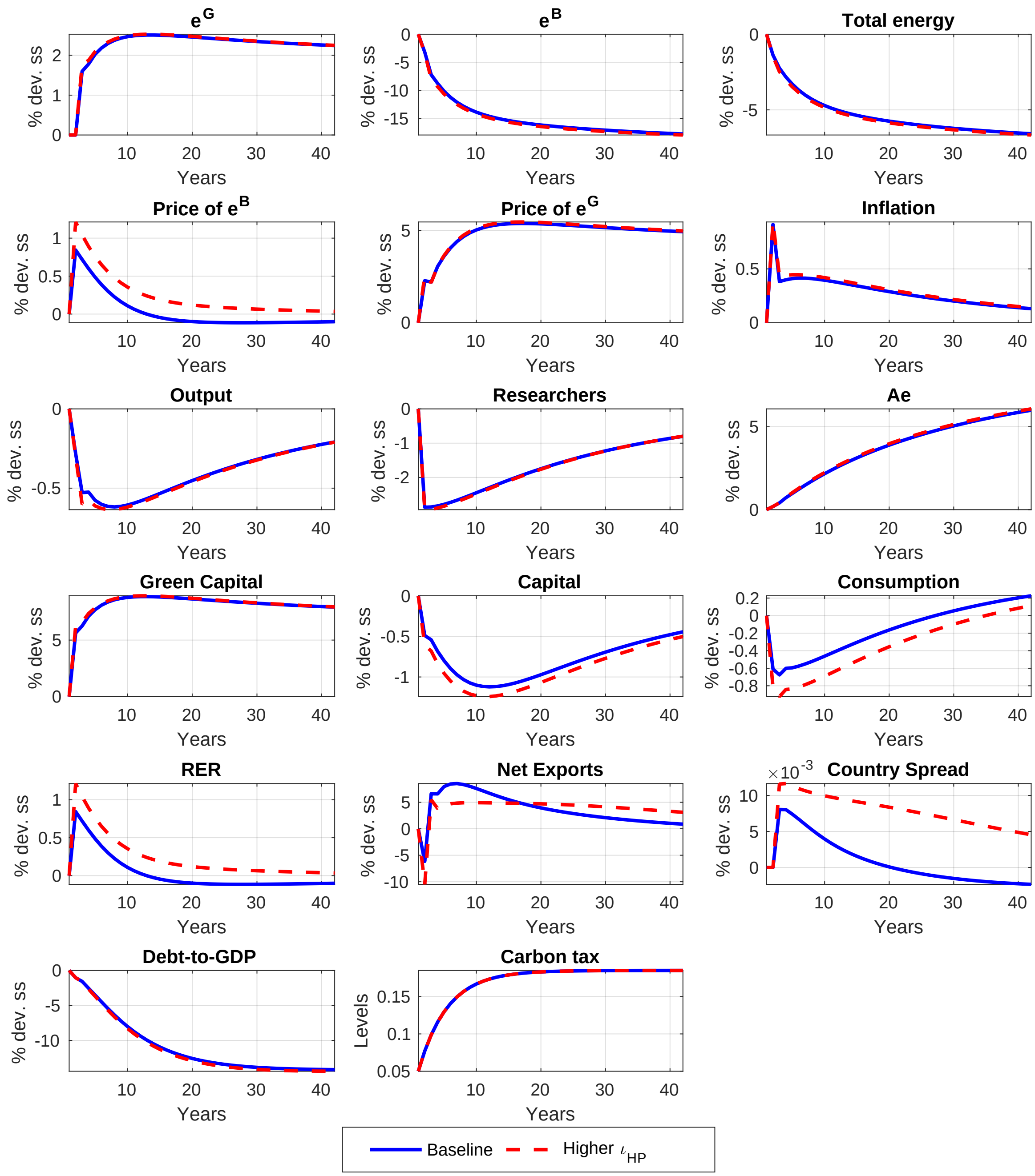
Note: Dynamics for the entire transition period where carbon taxes increase from 5 to 18.5. Variables are in percentage deviations from the initial steady state, except for carbon taxes, which are in levels.

Figure A.2: High increase in the carbon tax



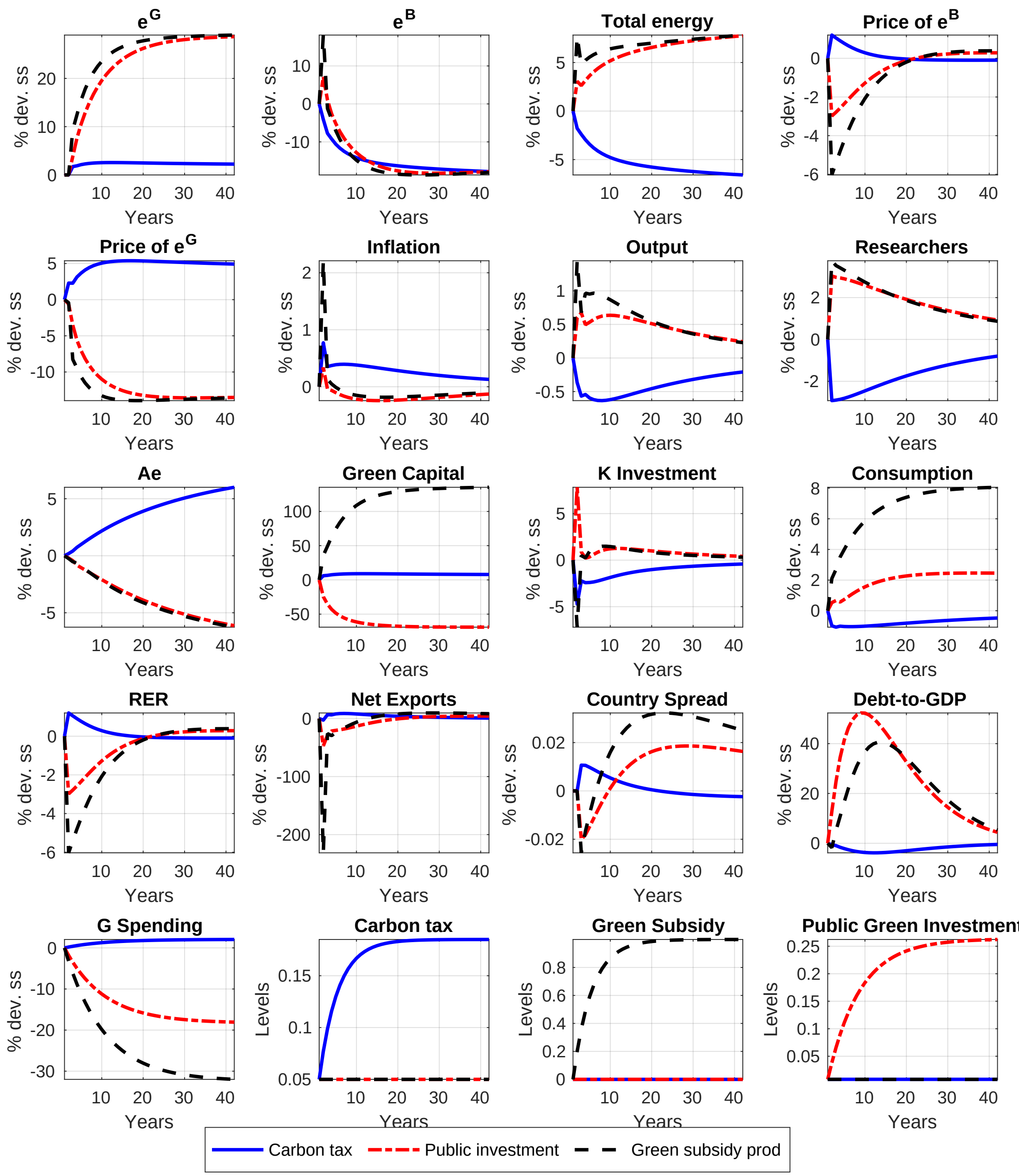
Note: Dynamics for the entire transition period where carbon taxes increase from 5 to 35. Variables are in percentage deviations from the initial steady state, except for carbon taxes, which are in levels.

Figure A.3: Transitional dynamics: The role of price rigidity



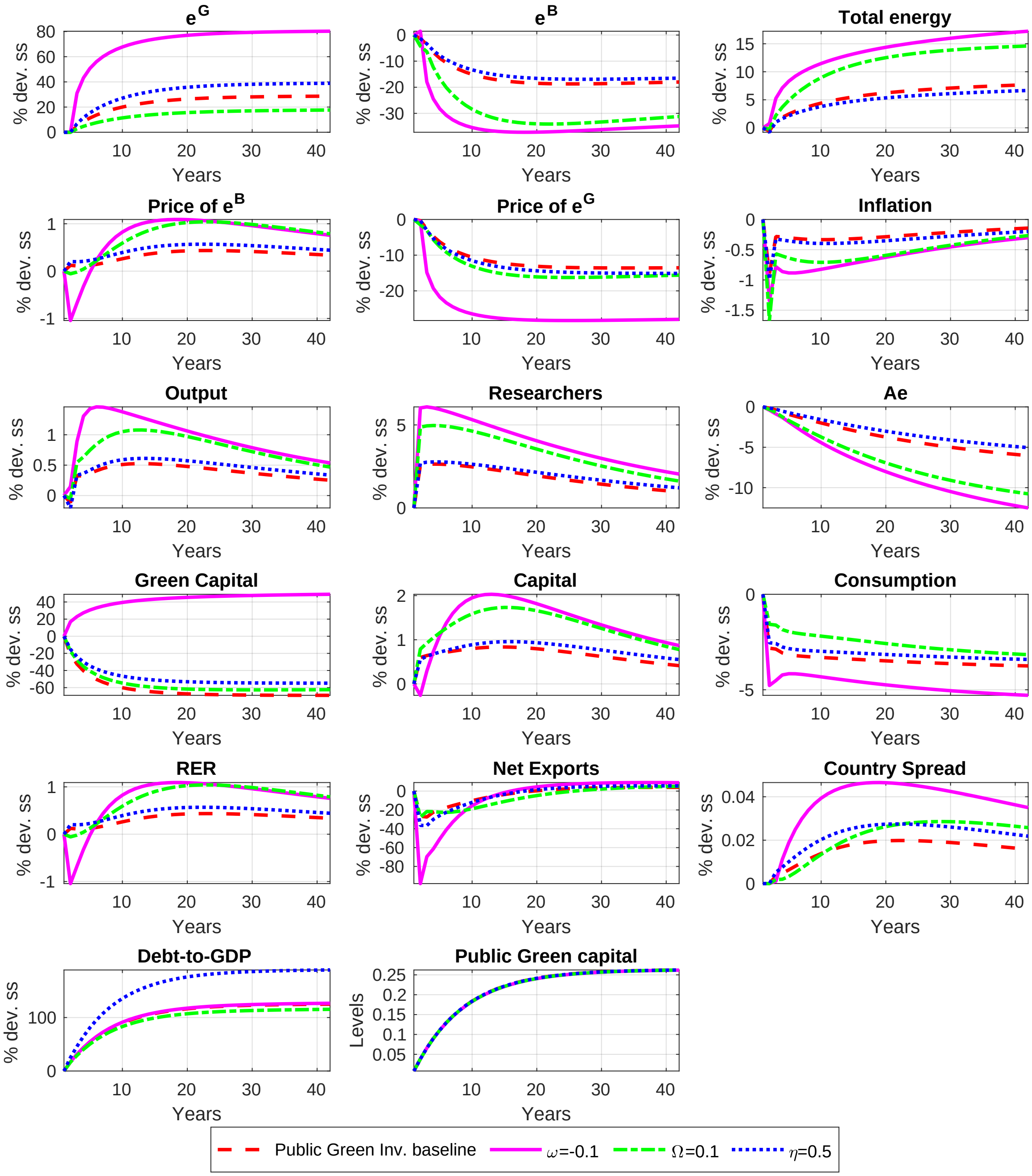
Note: Dynamics for the first 40 years of transition from the initial to the new steady state where carbon taxes increase from 5 to 18.5 for different parameters of the monetary policy rule. Blue lines represent the baseline calibration; red dashed lines are the case of $\iota_{HP} = 120$. Variables are in percentage deviations from the initial steady state, except for the carbon tax, which is in levels.

Figure A.4: Transition with debt consolidation and reduction in government spending



Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 18.5 (blue continuous lines); subsidies change from 0 to 100% (black discontinuous lines); and public investment changes from 0 to 3.5% of GDP (red dashed lines). Carbon taxes, green subsidies, and public green investment are in levels. The rest of the variables are in percentage deviations from the initial steady state.

Figure A.5: Sensitivity of energy production



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 35. Blue continuous lines show the transition with baseline calibration, and red dashed lines show the transition when $\omega = -0.1$. Variables are in percentage deviations from the corresponding initial steady state, except for green public investment, which is in levels.