THE GREEN METAMORPHOSIS OF A SMALL OPEN ECONOMY*

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Abstract: We study the macroeconomic effects of a green transition in a small open economy under alternative fiscal instruments: carbon taxes, green subsidies, and public green investment. To do so, we develop a dynamic general equilibrium model incorporating nominal rigidities, financial frictions, and endogenous energy efficiency. Production relies on traditional inputs and energy, with limited short-run substitutability, allowing firms to gradually enhance efficiency. Carbon taxes reduce brown energy use and boost long-run efficiency but cause short-term inflation and output losses. Green public investment and subsidies can achieve similar environmental goals but require large fiscal outlays, increasing debt and sovereign spreads, and depressing consumption. A welfare-based constrained Ramsey benchmark shows that, under a common environmental target, carbon taxes dominate supply-side instruments, with public green investment playing a small complementary role.

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1 Introduction

Environmental disasters are an important source of macroeconomic risk, and the transition from polluting energy sources to clean energy is a central policy challenge to mitigate such risks in the long term. In this paper, we examine the costs and benefits of alternative macroeconomic policies aimed at fostering this transition in a small open economy. Although the benefits of reducing the reliance on polluting energy—often captured in the literature as lower output losses from environmental degradation—are well documented, this study contributes to the literature by focusing on the macroeconomic costs associated with fiscal and monetary policy interventions during the green transition.

Because the green transition entails a permanent change in the economy's productive structure, we adopt a framework with endogenous growth and endogenous steady-state adjustment. Policy evaluation in this context also requires a general-equilibrium approach, since climate policies affect relative prices, investment, innovation, factor allocation, and aggregate demand simultaneously. Given our focus on fiscal and monetary policy, we embed these mechanisms in a New Keynesian model. Unlike standard models, we assume that intermediate-good production requires an energy input, in addition to traditional factors, produced with a mix of polluting and clean energy. We allow for a low substitutability between energy and traditional factors in the short run that firms can alter over longer periods through directed input-saving technical change. In addition to endogenous energy efficiency, 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.

We calibrate the model to Chile, an illustrative emerging market economy that has sustained macroeconomic stability over the past three decades and has articulated clear commitments to decarbonization. Chile's Climate Action Plan 2017–2022 outlines a series of measures to promote non-conventional renewable energy, including the introduction of an energy efficiency law and a planned increase in carbon taxes. The country has set an ambitious target to reduce emissions by up to 45% relative to 2016 levels (4.6 tons of CO_2 per capita), aiming to reach 2.5 tons of CO_2 per capita by 2030. With this information, we define the green transition as a permanent reduction in the use of brown energy of approximately 45% over a 15-year horizon—broadly aligning with the government's climate objectives.

We set our base scenario as a gradual transition driven exclusively by incremental increases in an excise tax on brown energy inputs. Within this base scenario, we find that, while carbon taxes can induce 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, because green energy capacity expands only gradually, the transition leads to higher prices for 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.

Next, we analyze transitions under two alternative instruments: producer subsidies for clean energy ("green subsidies") and public investment in green-energy capacity. Relying exclusively on green subsidies can reduce brown energy consumption to levels comparable to those achieved through carbon taxation over a 15-year horizon—but only if subsidies are increased from 0 to 400%. However, because subsidies do not put pressure on firms' marginal costs, they may result in inefficient energy use. Similarly, a substantial increase in public green investment, equivalent to 16% of GDP, can yield comparable reductions in brown energy consumption, though at the cost of significant fiscal pressure sustained over several years. Public investment boosts productivity in the green sector and lowers green energy prices in the long run. Likewise, subsidies reduce the relative price of green energy, albeit through a more direct channel.

In the medium term, expectations of higher future productivity stimulate firms to increase investment in traditional production factors, raising capital demand and output. This dynamic generates a transition that is both expansionary and deflationary. However, both green subsidies and public investment policies entail notable short-term consumption costs. While these measures enhance the long-term growth trajectory of the economy, they also impose significant fiscal burdens, leading to a rising debt-to-GDP ratio. In a small open economy setting, these fiscal pressures are further amplified by the interplay between real exchange rate depreciation, increasing country risk premiums, and constrained access to external financing. The resulting fiscal strain contributes to higher sovereign spreads, which in turn suppress consumption.

To provide a disciplined benchmark against the simple policy rules, we turn to a welfare-based benchmark for policy evaluation. Specifically, we compute constrained Ramsey allocations in which each policy instrument is chosen optimally subject to achieving the same environmental objective that anchors our quantitative analysis: a 45% reduction in brown energy use within fifteen years. This exercise allows us to quantify how far these rules lie from the welfare frontier implied by the model and to assess the relative efficiency of alternative policy instruments in delivering the green transition.

Carbon pricing emerges as the optimal adjustment mechanism in the model. Whenever carbon taxation is available, the optimal policy systematically drives green production subsidies to zero and relies primarily on carbon pricing to achieve the environmental target. Among the feasible policy combinations, the welfare-maximizing allocation combines carbon taxation with front-loaded public green investment.

In light of the well-documented political resistance to carbon tax increases—often driven by limited trust in government and skepticism toward the Pigouvian rationale for taxation (see Ewald et al. (2022))—our results suggest that carbon taxes remain indispensable for an efficient green transition. At the same time, complementing carbon taxation with public green investment can achieve comparable reductions in brown energy use while lowering the overall welfare costs of the 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.

The framework we propose enhances the existing literature in several dimensions. First, we provide an endogenous growth model that incorporates key features to understand transitional dynamics and macroeconomic trade-offs of climate policy in small open economies. It complements and extends recent studies examining monetary policy and inflation dynamics in the context of the green transition (e.g., Nakov and Thomas (2023), Olovsson and Vestin (2026), Coenen et al. (2023), Del Negro et al. (2023), Sahuc et al. (2024), Ferrari and Nispi Landi (2024)). Second, we provide a welfare-based ranking of three standard policy instruments—carbon taxes, green subsidies, and public green investment—under a binding environmental constraint (a 45% reduction in brown energy use by year 15). We show that this ranking is shaped by general equilibrium forces— notably, the feedback between fiscal policy, spread, and consumption intrinsic to small open economies—that partial equilibrium analyses cannot capture, and that carbon taxes dominate supply-side instruments on welfare grounds, with a small complementary role for public investment. Third, we introduce endogenous energy efficiency as an adjustment margin along the transition. This margin allows firms to reallocate researchers between traditional-input productivity and energy efficiency R&D, and generates non-monotonic medium-run dynamics that are absent from existing models. We show that shutting it down reintroduces the permanent output losses that the recent E-DSGE literature associates with the green transition (e.g., Annicchiarico and Di Dio (2015), Annicchiarico and Di Dio (2017), Carattini et al. (2021), Economides and Xepapadeas (2019)). Finally, we clarify the central role of green–brown energy substitution in open-economy transitions: because brown energy prices and supply are exogenous while green energy is produced domestically, policy-induced changes in relative prices operate primarily through the composition of the energy aggregate rather than through an energy/non-energy trade-off.

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 under a carbon-tax-driven transition, the role of endogenous energy efficiency and monetary policy, and a robustness analysis. Section 5 discusses alternative policy tools and different policy experiments. Section 6 computes constrained Ramsey benchmarks for the green transition and assesses their robustness. 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 home-produced intermediate 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 consumes c_t and supplies labor inelastically, $\bar{h}$.[1] Households can save in a government bond, B_{t+1}, yielding a nominal return R_t after one period, and can save or borrow with a foreign bond, B^*_{t+1}, which offers a return in foreign currency of $R^*_t\Phi^A(\tilde{A}^f_{t+1})$, where $\Phi^A(\tilde{A}^f_{t+1})$ 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:

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

where P_t is the price level, w_t is the real wage, FX_t is the nominal exchange rate, and the

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

terms R_t^k and R_t^G denote the rental returns on traditional and green capital, respectively.

The evolution of the green capital stock follows:

$$s_{t+1}^G = (1-\delta)\, s_t^G - \Phi_s(s_{t+1}^G, s_t^G) s_t^G + i_t^G, \tag{3}$$

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]

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

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

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

We present the household's optimality conditions in the appendix.

[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.

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:

$$y_{H,i,t} = y_{H,t} \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{-\varepsilon_P}. \tag{5}$$

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 (5). 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:

$$y_{H,i,t} = \left[\left(A_{i,t} k_{i,t}^{\alpha} \bar{h}_{i,t}^{(1-\alpha)} \right)^{\frac{\epsilon - 1}{\epsilon}} + \left(A_{e,i,t} e_{i,t} \right)^{\frac{\epsilon - 1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon - 1}}. \tag{6}$$

$A_{i,t}$ 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

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

sector determines the growth rates of the corresponding productivity factors, $A_{e,t}$ and A_t, as follows:

$$g^{A}_{i,t} = \frac{A_{i,t}}{A_{i,t-1}} = 1 + Bn^{\phi}_{i,t}, \tag{7}$$

$$g^{Ae}_{i,t} = \frac{A_{e,i,t}}{A_{e,i,t-1}} = 1 + B_e(1 - n_{i,t})^{\phi}. \tag{8}$$

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 trade-off 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 trade-off. A key parameter influencing their decision is the elasticity of substitution between traditional inputs and energy, denoted by ϵ. We assume this elasticity is close to zero in the short run (i.e., nearly Leontief). Nevertheless, the firm can alter energy efficiency over the medium to long term. By choosing n, firms can reallocate resources from capital and labor to energy 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 com-

[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.

posed 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:

$$e_{i,t} = \bar{E}\left[(1-\zeta)\left(e^G_{i,t}\right)^{\xi} + \zeta\left(e^B_{i,t}\right)^{\xi}\right]^{\frac{1}{\xi}}, \tag{9}$$

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

$$\mathbb{E}_0\left\{\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}\left[P_{H,t}\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon_P} y_{H,t} - P^G_t e^G_{i,t} - \left(P^B_t + P_t\tau^e_t\right)e^B_{i,t} - W_t h_{i,t} - R^k_t k_t - \right.\right.$$
$$\left.\left.\frac{\iota_{PH}}{2}\left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H\right)^2 y_{H,t}P_{H,t}\right]\right\}. \tag{10}$$

Here 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^G_t is the price of green energy, P^B_t is the price of brown energy, τ^e_t is the excise tax, W_t is the nominal wage, R^k_t is the rental rate of capital, $\iota_{PH} \geq 0$ quantifies price adjustment costs, as in Rotemberg (1982).

In our framework, the carbon tax is modeled as an excise tax in domestic currency levied on the use of brown energy by intermediate goods producers, $P_t\tau^e_t$, with τ^e_t being the policy variable. We do not explicitly model emissions or carbon intensity. Instead, we assume a proportional relationship between brown energy use and CO_2 emissions. While this differs from actual carbon pricing—typically defined in monetary units per ton of CO_2—it allows us to isolate the macroeconomic effects of carbon taxation without adding an emissions layer to the production function.

The optimization problem of the firm i involves choosing the allocation of researchers $n_{i,t}$, price $P_{H,i,t}$, and inputs of production $e^B_{i,t}$, $e^G_{i,t}$, $k_{i,t}$, $h_{i,t}$, to maximize the present value of expected profits given by equation (10), subject to equations (5), (7)-(9), while taking as given input prices P^G_t, P^B_t, W_t, and the entire path of fiscal policy instruments, 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

$$\mu_{A,t} g^{\alpha}_{t-1} B n^{\phi-1}_t A_{t-1} = \mu_{A_e,t} B_e (1-n_t)^{\phi-1} g^{\eta}_{t-1} A_{e,t-1}, \tag{11}$$

and the optimal pricing decision results in

$$\pi_{H,t}\left(\pi_{H,t}-\bar{\pi}_H\right) = \beta \mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi^2_{H,t+1}\left(\pi_{H,t+1}-\bar{\pi}_H\right)\frac{y_{H,t+1}}{y_{H,t}}\right] + \frac{\varepsilon_P}{\iota_{PH}}\left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_P - 1}{\varepsilon_P}\right), \tag{12}$$

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^G_t and public green capital $s^{G,P}_t$, which is chosen by the government and firms treat as given. The production function is

$$e_t^G = \Omega L^{1-\eta}[(1-\gamma)(s_t^G)^\omega + \gamma(s_t^{G,P})^\omega]^{(\eta/\omega)}, \tag{13}$$

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 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,

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

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 Imports of foreign goods

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 Exports of domestic goods

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 The production of final goods

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

$$c_t = \left[(1-\chi)^{\frac{1}{\theta}} c_{H,t}^{\frac{\theta-1}{\theta}} + \chi^{\frac{1}{\theta}} c_{F,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{14}$$

where parameter θ determines the elasticity of substitution between domestic and foreign goods, and χ determines the shares of foreign goods in domestic consumption. As is usually the case, we assume investment and government spending follows the same aggregation technology.

The domestic price level is accordingly defined by

$$P_t = \left[(1-\chi) P_{H,t}^{1-\theta} + \chi P_{F,t}^{1-\theta} \right]^{\frac{1}{1-\theta}}, \tag{15}$$

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

2.8 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:

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

2.9 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]

2.10 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:

$$y_{H,t} = (1-\chi) p_{h,t}^{-\theta} \left(c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P} \right) + c_{H,t}^*,$$

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

$$nx_t = \frac{FX_t}{P_t} P^* \frac{B_{t+1}^*}{P^*} - \frac{FX_t}{P_t} P^* \frac{B_t^*}{P^*} R_{t-1}^* \Phi^A \left(\tilde{A}_t^f \right).$$

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

where

$$gdp_t = p_{H,t} y_{H,t} - p_t^B e_t^{B,*}.$$

Then, net exports are defined by

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

It is important at this stage to state that the output growth rate of the economy follows

$$g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^\alpha}{X_{t-1}^{1-\alpha} X_{t-1}^\alpha} = \tilde{A}_t \tilde{k}_t^\alpha. \tag{18}$$

Defining the stock of capital's trend as X_{t-1}, the trend of its productivity factor A_t grows at $X_{t-1}^{1-\alpha}$. In turn, $\tilde{A}_t$ and $\tilde{k}_t$ are the stationarized counterparts of A_t and k_t.

In the appendix, we derive the equilibrium conditions for this balanced growth path, similarly to Hassler et al. (2021).

3 Numerical implementation and functional 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.

3.1 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 significantly affecting 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 normalize the steady-state values of the rest of the 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 1.5.[7]

We set the price adjustment cost parameter, ι_{HP}, 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

[7] Given that we solve our model using perfect foresight, we cannot use the volatility of investment to output ratio to pin down the value of this parameter. Additional exercises (available on request) show that higher adjustment costs slow green capital accumulation, raising green energy prices and medium-run inflation.

relative to real marginal costs is $\frac{\varepsilon_P}{\iota_{HP}}$ 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 ι_{HP} 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^* target the average public debt-to-GDP ratio of 20% and average primary deficit of 5% in the Chilean data. We standardize one unit of brown energy usage as producing $5{,}000$ kWh of electricity, which corresponds to 1 ton of CO_2 emissions, based on estimates from the U.S. Environmental Protection Agency (EPA). Accordingly, we calibrate the carbon tax in our model so that the implied specific levy in the initial steady state equals 5 pesos per ton of CO_2, in line with Chile's baseline carbon tax level (denominated in U.S. dollars per ton of emissions, but expressed here in pesos for simplicity).

Accordingly, the increase in the carbon tax is represented in real terms, rising from 5 to 60 final consumption units—approximately a twelvefold increase in effective carbon pricing—to reflect Chile's stated policy trajectory. In the baseline calibration, both subsidies and public green investment are set to zero.

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

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 transition	1.5
ι_{HP}	Adj. cost of prices	Av. price duration of 1 year	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 subst. between varieties	Avg. markup 11%	10
β	Discount factor	Avg. inflation Chile	0.987
R^*	Gross risk free rate	3 months Tbill U.S.	1.03
φ^A	Sovereign spread parameter	Country spread Chile	0.009
ξ	Elasticity subst. energy inputs	Papageorgiou et al. (2017)	0.67
$e^{B,d}$	e^B Domestic endowment	Imported/total energy	0.5
B_e	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

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 50%.[8] The coefficient B_e in the evolution of energy efficiency, A_e, 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, 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.

[8] 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.

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	0.25
$\bar{E}$	CES energy	Jointly calibrated	2.52
Ω	TFP in e^G	Jointly calibrated	0.04
B	Prod. coef researchers	Jointly calibrated	0.02

The implied elasticity of substitution between traditional inputs and energy, ϵ, is consistent with the value assumed by Hassler et al. (2021). The implied productivity level in green energy production—captured by the parameter Ω in the model—is calibrated to a relatively low value, reflecting the modest scale of observed investment in green capital. As we show later, this calibration plays an important role in shaping the effectiveness of transitional policies based on public investment in green energy.

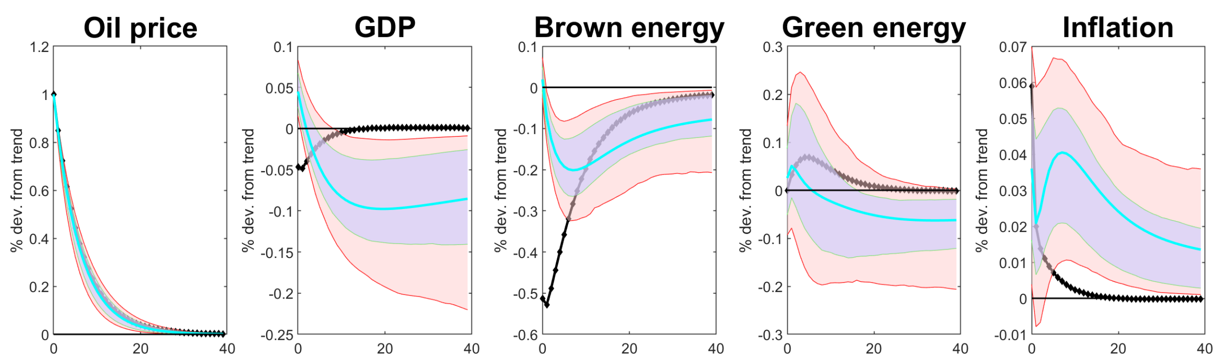
3.2 Empirical Validation: Short-Run Dynamics

Data and computational limitations prevent a direct quantitative assessment of the model along its medium- and long-run dimensions. To provide external validation for our quantitative exercise, we instead focus on short-run dynamics. Specifically, we examine whether the model can replicate the responses to an exogenous oil price shock, which we interpret in our framework as a shock to the cost of brown energy.

To this end, we estimate an SVAR using annual data for Chile over the period 1980–2024. The VAR includes real oil prices, GDP, brown and green energy use, and inflation.[9]

To identify exogenous oil price shocks, we impose an exogeneity restriction by ordering oil prices first in the VAR, following Schmitt-Grohé and Uribe (2018); the remaining variables are left unrestricted. Figure 1 reports the results. The impulse responses to a 1% increase in oil prices, together with their 68% and 95% confidence bands, indicate that such a shock leads to a decline in output and brown energy use (with some delay), a modest increase in green energy use, and an initial rise in inflation.

Figure 1: International brown energy price shock



Note: Model and empirical impulse responses to a world brown energy price shock. The figure presents the point estimate of the empirical IRFs (light blue), 68% and 95% confidence bands, and the model-implied dynamics (black with diamonds).

On the model side, we simulate a temporary increase in the world price of brown energy, $P^{B,*}$, under perfect foresight, with persistence calibrated to match that of the oil shock in the data. The model generates dynamics that broadly match the empirical IRFs, despite some quantitative discrepancies: output contracts, brown energy use declines, firms substitute toward green energy, and inflation rises in the short run. Having established that

[9]Real oil prices are measured in constant 2024 USD per cubic meter. GDP is from the World Bank; inflation is from INE Chile; data on brown and green energy use are from the Energy Institute – Statistical Review of World Energy. Green energy use is proxied by renewable energy consumption (sum of solar, hydro, wind, and other renewable sources); brown energy use is the sum of oil, coal, and gas consumption. Although data are available from 1966 onward, we exclude earlier observations due to the presence of hyperinflation, which would distort the estimation.

the model captures these short-run responses, we now turn to its transitional dynamics.

4 Transitional dynamics

This section presents the quantitative implications of the green transition. We calibrate the initial steady state to Chile, and then, introduce policy changes that initiate a green transition under perfect foresight. This assumption allows us to isolate the pure economic effects of the transition from uncertainty about policy implementation. Our discussion focuses 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 carbon tax rate has remained relatively low. Chile's Climate Action Plan 2017–2022 envisions a gradual increase in the tax over time. To capture this transition, we simulate an increase in the excise tax τ_t^e levied on the quantity of brown energy used by firms. This excise tax has a natural interpretation in the context of climate policy, as it represents a constant cost per unit of emissions. Because the model does not explicitly track emissions or carbon content, we assume a proportional relationship between brown energy use and CO_2 emissions. Accordingly, τ_t^e can be interpreted as a per-unit charge on brown energy inputs, expressed in units of final consumption. The policy experiment therefore consists of increasing this per-unit tax from 5 to 60 units of the final good over the transition.[10] This tax path is calibrated to induce a 45% reduction in brown energy usage in approximately 15 years, broadly consistent with Chile's stated climate goals. Figure 2 illustrates this transition.

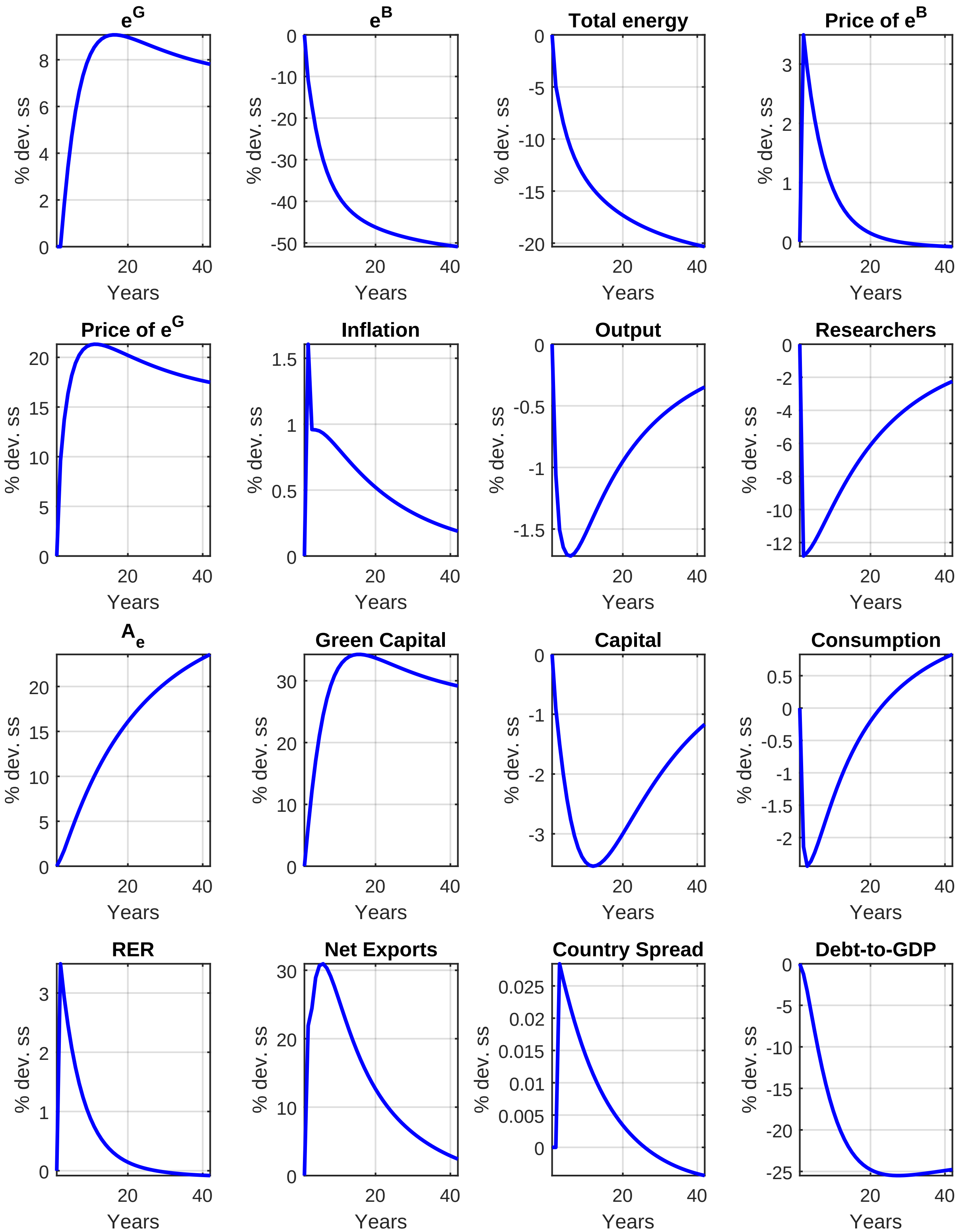
Higher taxes on brown energy increase marginal costs for intermediate firms, fueling inflation in the short and medium term. The rise in carbon taxes increases the after-tax domestic prices of brown energy, and shifts demand toward green energy, gradually pushing up its prices as well, amplifying inflationary pressures. Over time, however, inflation moderates as firms allocate more researchers to improving energy efficiency, enhancing overall energy productivity. In the new equilibrium, the use of brown energy declines by approximately 50%, total energy consumption drops by 20%, and energy efficiency improves by 23%, due to the strategic reallocation of researchers within firms to enhance energy-saving measures in the short term.

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, renders 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, reducing 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.

The model predicts persistent "greenflation" with transitory output costs. Inflationary

[10] Importantly, this increase does not correspond to a proportional tax rate (e.g., from 5% to 60%). Instead, the tax is modeled as a change in the absolute cost per unit of brown energy. In results not reported for brevity, we show that alternative specifications — such as proportional taxation — yield quantitatively similar outcomes. We simulate a 200-period transition; nevertheless, most of the adjustment happens in the first 15 years, in line with the Chilean goals.

Figure 2: 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 60 final consumption units. Variables are in percentage deviations from the initial steady state.

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.

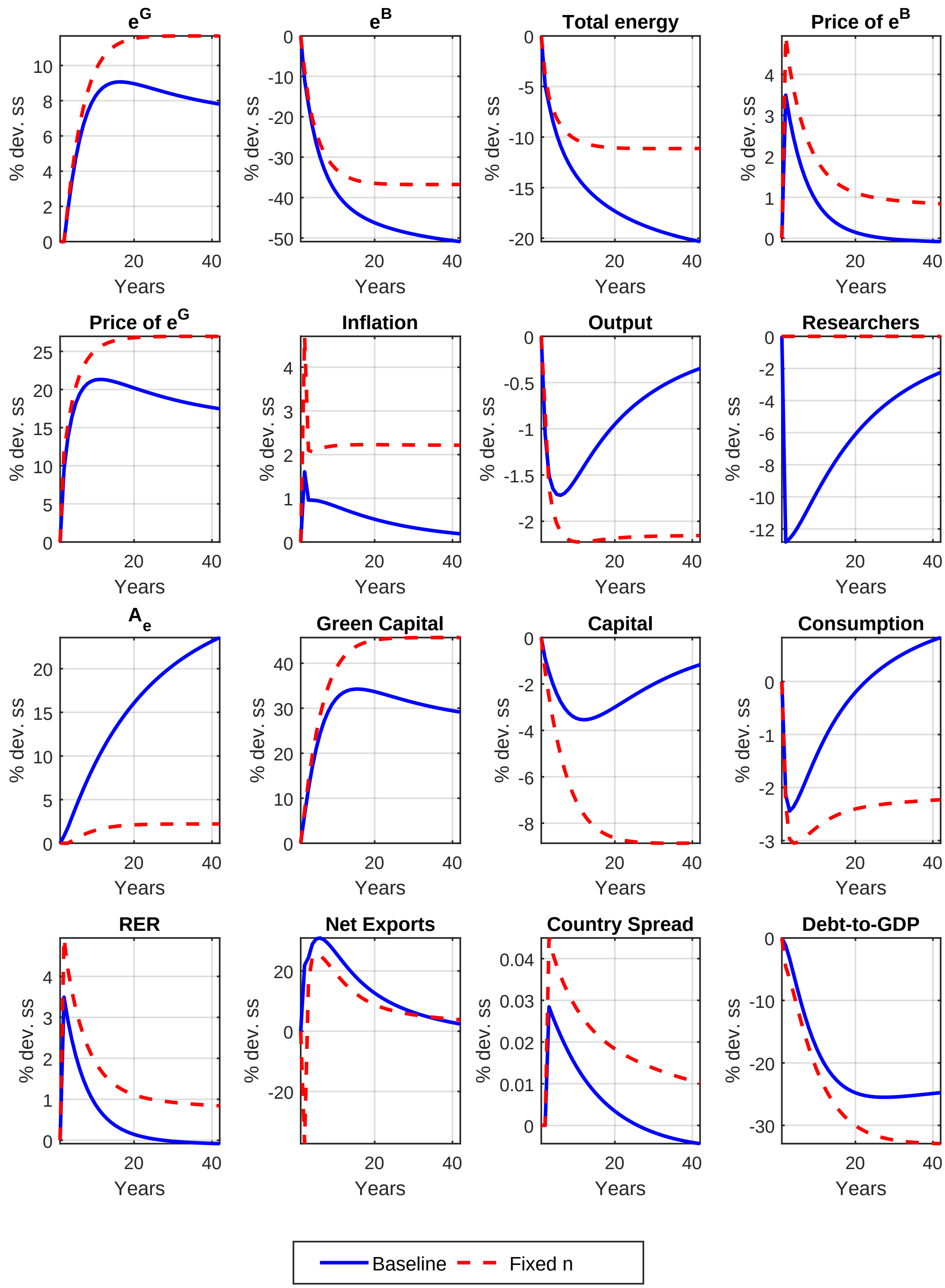
The small open economy structure amplifies transitional dynamics through several key channels. Since the domestic economy takes world prices as given, any real depreciation—driven by weaker investment or fiscal imbalances—directly raises the domestic price of imported brown energy. Rising fiscal deficits also elevate the country risk premium, increasing the cost of foreign borrowing and further suppressing consumption and investment. These openness-related effects intensify the trade-offs of the green transition, making macroeconomic adjustment more costly than in a closed economy.

4.2 The endogenous energy efficiency channel

A key mechanism in our analysis is the introduction of endogenous energy efficiency, which allows firms to reallocate internal resources in response to changes in relative prices between the energy composite and traditional production inputs. This mechanism shapes the equilibrium dynamics of the model.

To illustrate its importance, we shut down the endogenous energy efficiency channel by assuming a fixed number of researchers within the firm that cannot be reallocated toward improving energy efficiency. In this case, the only remaining margin of adjustment is the composition of energy inputs.

Figure 3: Transitional dynamics: Endogenous energy efficiency vs. fixed researchers



Note: Dynamics for the first 40 years of the transition from the initial to a new steady state in which carbon taxes increase from 5 to 60 units of final consumption. Variables are expressed as percentage deviations from the initial steady state. The blue solid lines correspond to the baseline model, while the red dashed lines correspond to a specification in which the number of researchers is fixed at its steady-state level.

We present the transitional dynamics in this economy, alongside those induced by a carbon tax in the baseline model, in Figure 3. Clearly, the endogenous energy efficiency channel is crucial for the economy's adjustment to the carbon shock in the medium and long run. The increase in the carbon tax induces firms to reduce their use of brown energy and substitute toward green energy, as in the baseline economy. However, since green energy production is endogenous and green capital accumulation is gradual, this adjustment is not immediate, which amplifies the short-run increase in energy costs. As a result, output declines and inflation rises, in line with the baseline model.

However, the absence of endogenous energy efficiency fundamentally alters the medium- and long-run dynamics. Without the ability to improve energy efficiency, the economy cannot fully offset the increase in energy costs, and output does not return to its original steady state. This limited adjustment to changes in relative prices has long-run consequences not only for output but also for inflation, which increases permanently following the contractionary carbon tax shock. By contrast, in the baseline model, the endogenous energy efficiency channel allows the economy to gradually adapt to higher energy prices, mitigating long-run losses.

Finally, the decline in brown energy is smaller in the absence of improvements in energy efficiency, which limits the extent of the transition. Brown energy falls by around 35 percent in the constrained economy, compared with 50 percent in the baseline economy. Despite the larger increase in the use of green energy, the lack of progress in energy efficiency implies that the reduction in total energy use is roughly halved when firms cannot reallocate researchers in response to changes in relative energy prices induced by the tax shock.

This comparison highlights a key contribution of our framework relative to the existing literature, which often predicts persistent output losses from the green transition (see, for example, Coenen et al. (2023), among others). In our model, the presence of endogenous energy efficiency provides an additional adjustment margin that can prevent such permanent losses.

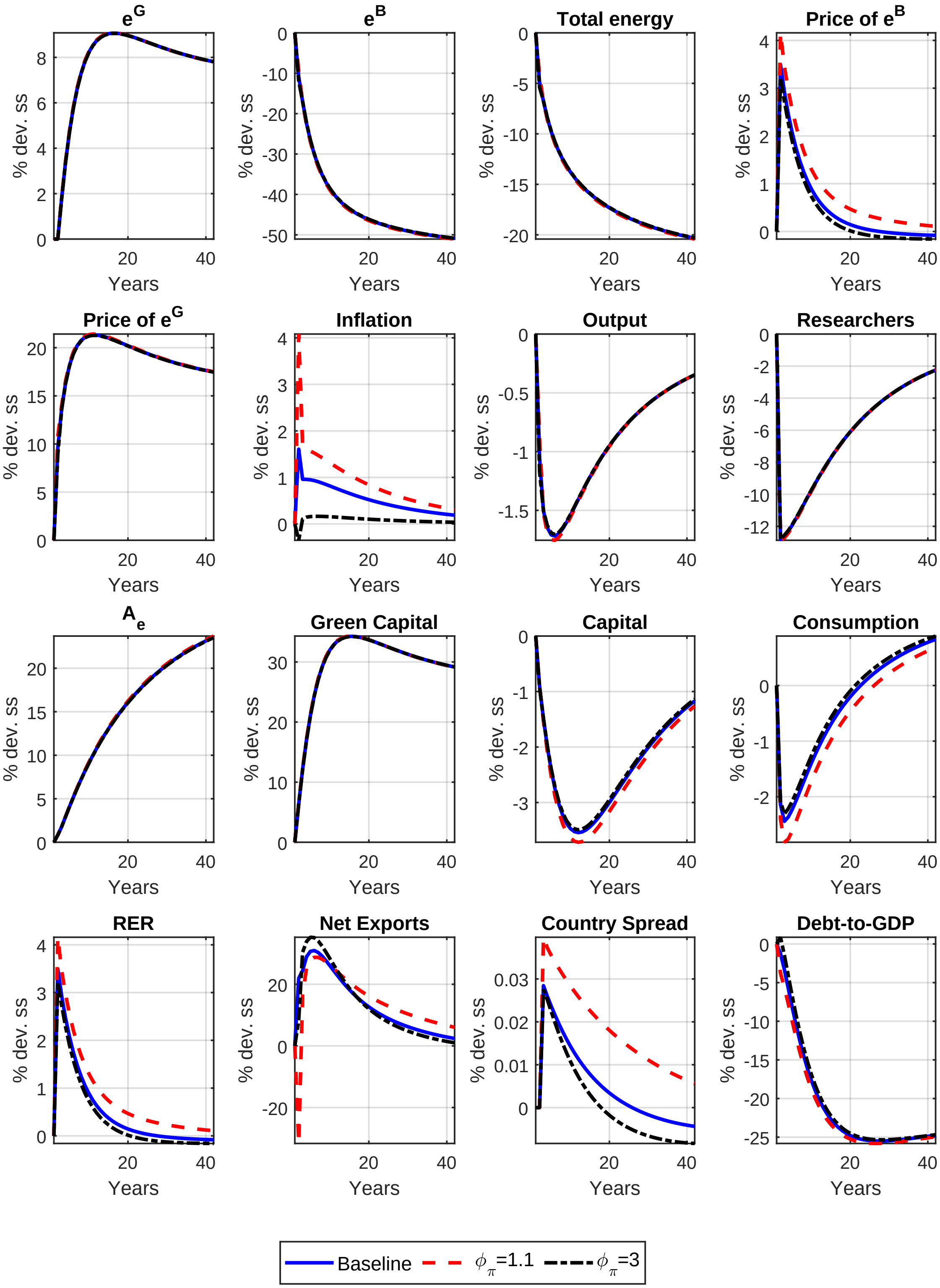
Overall, this exercise clarifies that substitution between green and brown energy is a central margin driving our results. In our small open economy setting, brown energy prices and supply are exogenously determined, while green energy is produced domestically. As a result, policy-induced changes in relative prices operate through substitution toward green energy, which is the key mechanism shaping the transition dynamics. While endogenous energy efficiency affects the long-run path of the economy, the short- and medium-run dynamics are primarily driven by substitution between green and brown energy.

4.3 The role of monetary policy

Monetary policy can affect the greenflationary dynamics described in the previous section. In our benchmark calibration, following Martínez et al. (2020), we set the Taylor rule inflation coefficient to 1.25. In Figure 4, we compare this baseline with two alternative scenarios: a more accommodative stance (inflation coefficient of 1.1) and a more aggressive response to inflation (inflation coefficient of 3.0).

In the standard three-equation model, labor supply is elastic but the model abstracts from investment, so monetary policy affects the economy through labor supply. In our economy, labor supply is inelastic, so this channel is shut off, and monetary policy affects the dynamics through capital accumulation, as well as consumption and output. Under a more accommodative policy, production decreases more due to a larger increase 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.

Figure 4: 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 60 final consumption units for different parameters of the monetary policy rule. Blue lines represent the baseline calibration; black dash-dotted lines are the case of $\phi_\pi = 3$; and red dashed lines are the case of $\phi_\pi = 1.1$. Variables are in percentage deviations from the initial steady state.

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.

In our setup, monetary policy can mitigate inflationary pressures without exacerbating output losses, even in the presence of carbon taxes, a result in line with optimal-policy findings by Nakov and Thomas (2023). However, a more accommodative monetary policy can yield fiscal benefits by reducing the debt-to-GDP ratio, albeit at the cost of elevated inflation and higher country spreads that are reflected in a bigger loss in consumption.

4.4 Robustness Analysis

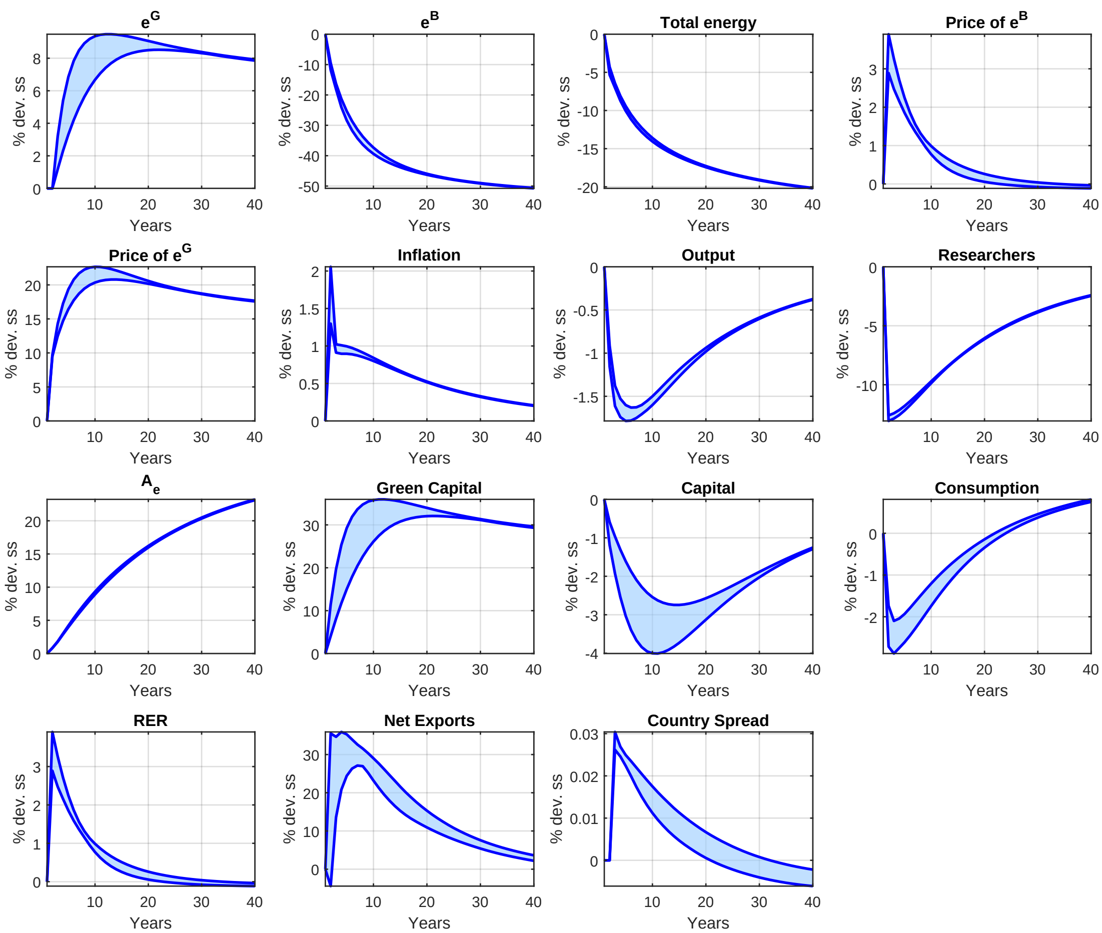
We conduct two exercises that assess the sensitivity of the transitional dynamics to alternative parameter values.

The modeling of the supply side is central to determining how firms respond to changes in relative energy prices in both the short and long run. The transitional dynamics of the green transformation depend fundamentally on firms' ability to substitute across energy sources and to improve energy efficiency. It is therefore important to establish that these dynamics do not hinge on the precise specification of frictions associated with capital adjustment in the green sector, price rigidities, or capital used in the production of intermediate goods.

In the first exercise, we draw from three uniform distributions corresponding to the adjustment costs of physical capital, green capital, and prices. We focus on these parameters because they shape the transition dynamics without affecting the initial or final steady states.

Specifically, we take 25 draws from a uniform distribution over $[0.05, 5]$ for the adjustment cost of capital, 25 draws from the same distribution for the adjustment cost of green capital, and 25 draws from a uniform distribution over $[10, 25]$ for the adjustment cost of prices. This results in $15{,}625$ parameter combinations, for which we evaluate the transitional dynamics. Figure 5 reports the 95% interval of the resulting distribution of transitions.

Figure 5: Transitional dynamics: Sensitivity analysis

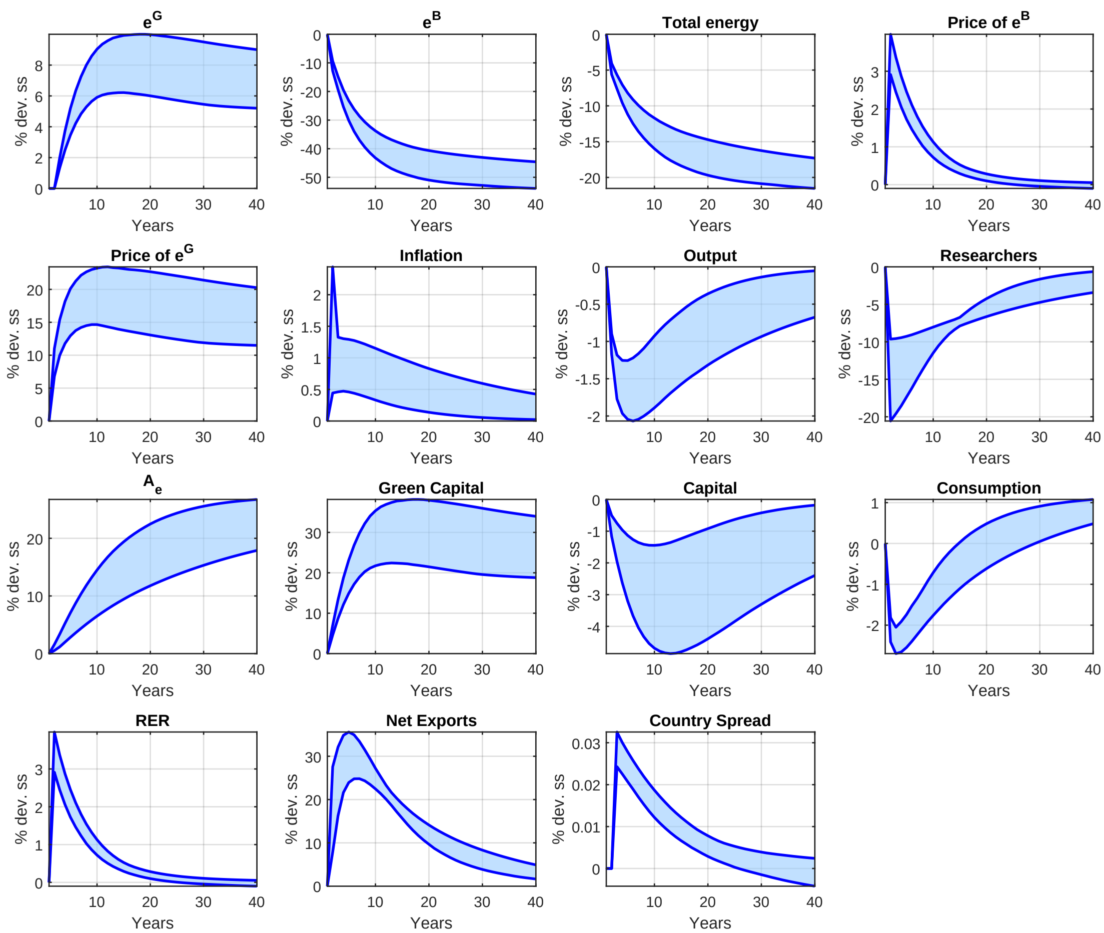


Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units. Shaded areas are the 95% interval. All figures are in % deviations from the initial steady state. Bands reflect joint variation in capital adjustment costs (physical and green capital) and price rigidities.

As shown in the figure, the results are robust to the specific calibration of these parameters. In particular, the qualitative patterns remain unchanged when the adjustment costs of physical and green capital differ and across a wide range of price rigidities.

The second exercise implements the same type of sensitivity analysis for parameters that affect the initial and final steady state. In this case, the parameters that we draw from uniform distributions are ξ from $U[0.55, 0.7]$, ϕ from $U[0.85, 1]$ and ρ_τ that regulates the length of the transition $U[0.75, 0.85]$. For each parameter we draw 10 realizations of the distribution, producing 1000 transitions.

Figure 6: Transitional dynamics: Sensitivity analysis II



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units. Shaded areas are the 95% interval. All figures are in % deviations from the initial steady state. Bands reflect joint variation in the substitution elasticity ξ, research effectiveness ϕ, and the speed of adjustment ρ_τ.

Figure 6 reports the 95% interval of the distribution of transitional dynamics in deviations from the steady state. Although the bands are wider relative to the first exercise, the qualitative dynamics remain close to those of the baseline economy. Hence, our main results do not depend critically on the precise parameterization of researchers' effectiveness in improving energy efficiency, ϕ, or on the elasticity of substitution between green and brown energy in production, ξ, or the assumed speed of adjustment, ρ_τ.

Yet, since multiple parameters vary simultaneously in each exercise, it is difficult to isolate how changes in individual parameters affect the model's dynamics. For completeness, Appendix A.6 presents additional exercises in which parameters are varied one at a time, allowing us to characterize more precisely how the transitional dynamics depend on each coefficient.

5 Alternative fiscal policy tools

Having analyzed carbon taxation—a policy tool heavily emphasized in the existing literature—we now turn to alternative strategies for reducing greenhouse gas emissions. Although studies such as Timilsina (2022) classify climate policies into three broad categories: fiscal / price instruments, regulatory measures, and direct public investment, we focus on two specific alternatives to carbon taxes: green subsidies and public investment in green infrastructure. These instruments present different trade-offs between transition costs and emissions reduction effectiveness.

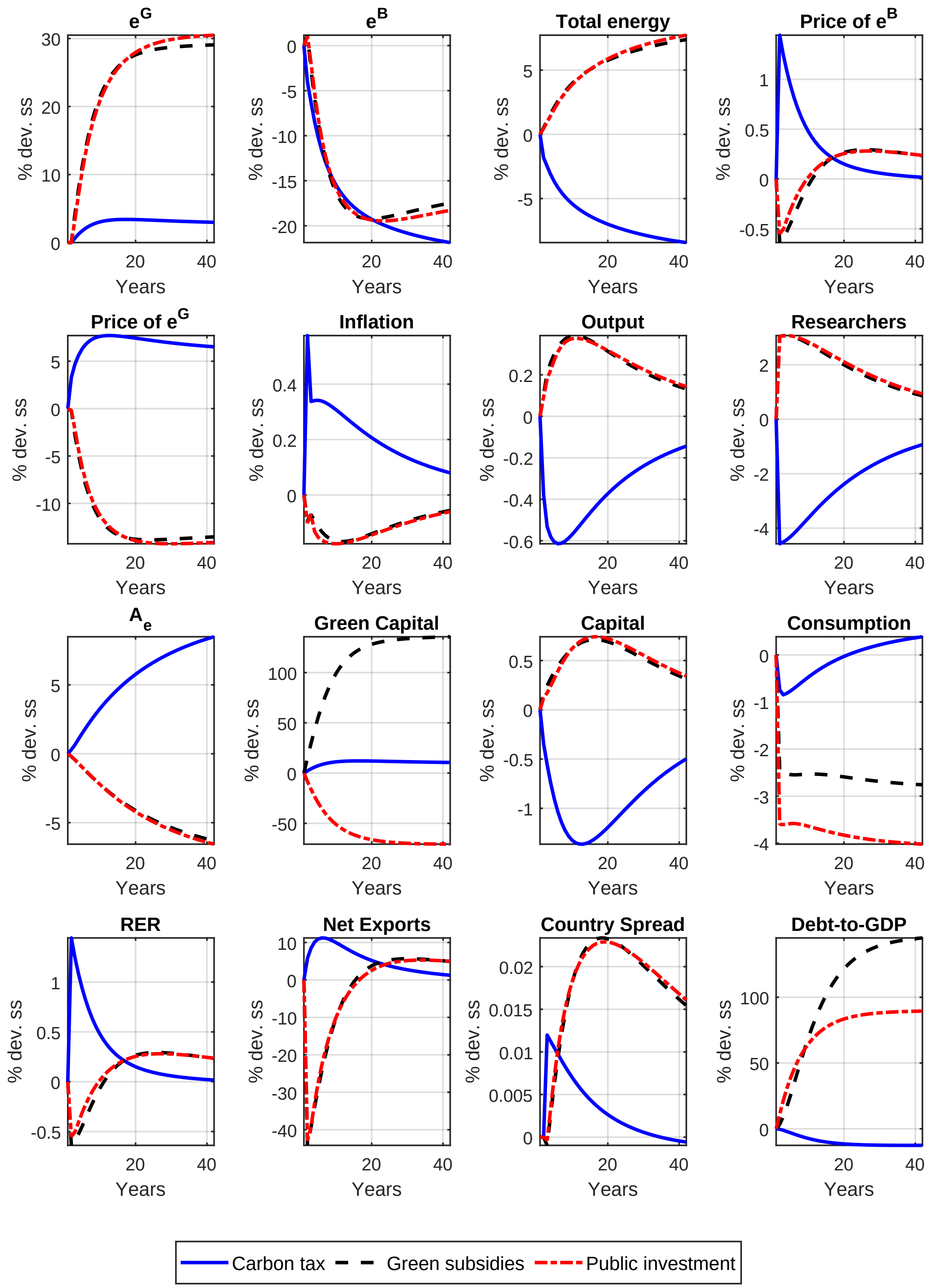
A key finding of our analysis is that, when used in isolation, both instruments require unrealistically large values to achieve the targeted transition. Figure A.4 in the Appendix illustrates the resulting transition when either green subsidies or public investment alone are scaled to achieve a 45% reduction in brown energy use in 15 years. Achieving this goal would require subsidies to increase from 0 to 400%, and public green investment to rise to 16% of GDP. Financing such measures would lead to substantial increases in public debt, rising by 600% and 400%, respectively, in the small open economy. Thus, achieving the green transition targets using either instrument in isolation is clearly unrealistic.

To facilitate comparison across fiscal tools and better understand their mechanisms, we simulate a moderate scenario in which the excise tax nearly quadruples—from 5 in the initial steady state to 22.5 over a 200-period horizon. In another scenario, subsidies rise to 100%, and in a third scenario public green investment increases to 3% of GDP. Each of these measures results in a comparable reduction in brown energy use, approximately 19%, after 20 years.

5.1 Green subsidies

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. Figure 7 depicts a transition where subsidies gradually increase over a 200-period horizon, starting from zero in the initial steady state and reaching 100% in the new steady state with black dashed lines. 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.

Figure 7: Transition using different fiscal instruments



Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 22.5 final consumption units (blue continuous lines); subsidies change from 0 to 100% (black dashed lines); and public investment changes from 0 to 3% of GDP (red dash-dotted lines). Variables are in percentage deviations from the initial steady state.

However, this approach entails substantial costs. The debt-to-GDP ratio rises sharply, increasing by 200% in the new steady state. This fiscal expansion triggers a surge in country risk premiums, and, combined with higher lump-sum taxes under the fiscal rule, leads to a sustained decline in private consumption. While increased green subsidies contribute to a medium-run reduction in brown energy use, over the long term the economy settles into a new steady state with higher brown energy consumption. This occurs because subsidies lower energy prices, weakening incentives to improve energy efficiency. Thus, despite their political appeal, green subsidies are less effective at enhancing long-run energy efficiency and may impose heavier 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% of GDP. We illustrate this transition in Figure 7. 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

[11] In Appendix Figure A.5, 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.

firms to reallocate researchers away from energy efficiency and toward improving the productivity of traditional factors. As energy efficiency deteriorates, overall energy consumption increases. Similar to the case with green subsidies, the economy settles into a new steady state where the reduction in brown energy use is smaller than under a carbon tax-driven transition.

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.

Hence, our analysis suggests that while these policies are not inflationary and entail lower output costs during the transition, they are less effective in reducing brown energy use and impose substantial fiscal burdens. To avoid adverse effects on private consumption, they must be paired with measures that alleviate fiscal pressure in small open economies.

6 The welfare costs of the green transition

Having analyzed the transitional dynamics under alternative simple fiscal rules, we now provide a welfare-based benchmark for policy evaluation. We compute welfare-maximizing *constrained Ramsey benchmarks*, in which each policy instrument is optimally chosen subject to achieving the same environmental goal that anchors the quantitative analysis: a 45% reduction in brown energy use within fifteen years. This exercise provides a disciplined yardstick against which the simpler policy rules considered in the previous sections can be compared, and it allows us to gauge how far those rules fall short of the welfare frontier implied by the model.

Welfare is defined as the discounted sum of period utilities,

$$W = \sum_{t=0}^{T} \beta^t \, \frac{c_t^{1-\sigma}}{1-\sigma}, \tag{19}$$

where c_t denotes the level of households' consumption.

For each instrument or combination of instruments, we solve a constrained welfare maximization problem, subject to the environmental target that brown energy use at year 15 falls by 45% relative to its initial steady-state value,

$$\frac{e_{15}^B}{e_0^B} = 0.55. \tag{20}$$

and subject to the full set of equilibrium conditions of the model described in Section 2.

The environmental target is imposed as an equality, so that all scenarios deliver the same environmental outcome by construction and welfare comparisons isolate differences in macroeconomic adjustment costs. The transition horizon is set to $T = 200$ periods, matching the length of the baseline transition experiment, and period utility is logarithmic ($\sigma = 1$), consistent with the household block of the model.

Because our analysis focuses on large, nonlinear perfect-foresight transitions, an unrestricted period-by-period choice of instruments is computationally demanding and difficult to interpret. We therefore parameterize each policy instrument by two objects with a clear economic interpretation: its terminal level and its speed of adjustment. For the carbon tax, the path is governed by the first-order law of motion

$$\tau_t^e = (1-\rho_\tau)\,\tau_T^e + \rho_\tau\,\tau_{t-1}^e, \tag{21}$$

where τ_T^e denotes the terminal tax level and $\rho_\tau \in [0,1]$ governs the speed at which the tax converges to that level. Analogous laws of motion apply to green subsidies and public green investment, with terminal levels s_T^G and i_T^{ep} and persistence parameters ρ_s and ρ_i, respectively. The resulting paths are smooth, interpretable in terms of levels and rates of change, and directly comparable to the simple policy rules used in the baseline scenario and in Section 5. Details of the numerical implementation are reported in Appendix A.9.[12]

We consider six policy scenarios, corresponding to each instrument in isolation and to their pairwise and joint combinations: (i) carbon tax only; (ii) green subsidy only; (iii) public green investment only; (iv) carbon tax plus green subsidy; (v) carbon tax plus public green investment; and (vi) all three instruments jointly. Table 4 reports the optimal policy parameters and the associated welfare for each scenario. By construction, all six scenarios deliver the same environmental outcome, $e_{15}^B/e_0^B = 0.55$, so welfare differences across policy mixes are directly interpretable as differences in the macroeconomic adjustment costs of achieving a common target.

Three main findings emerge from Table 4 regarding policy rankings. First, carbon pricing constitutes the dominant adjustment margin in the model. The different policy scenarios display a clear welfare ranking. Policies that rely exclusively on public green investment generate the largest welfare losses (-60.63), while a pure subsidy policy performs somewhat better (-51.61) but remains substantially welfare dominated by tax-based policies. In contrast, the Tax-Only and Tax + Subsidy regimes both achieve markedly smaller welfare losses (-41.93).

Second, combining carbon taxation with public investment delivers the highest welfare among the feasible policy mixes. The Tax + Investment scenario yields welfare losses of only -41.91, marginally improving upon the Tax-Only benchmark. Importantly, the "All Three" scenario converges to exactly the same allocation and welfare level as Tax + Investment, because the optimal subsidy rate is driven to a value numerically indistinguishable from zero. Hence, once carbon taxation and public investment are available,

[12] The constrained optimization is solved in MATLAB using the `fmincon` routine, and the model's equilibrium conditions are evaluated at each candidate policy path using Dynare's perfect-foresight solver.

green production subsidies become redundant from a welfare perspective.

Third, the table shows that whenever a carbon tax instrument is available (Scenarios (i), (iv)–(vi)), the optimizer systematically sets the green subsidy to zero and relies primarily on carbon taxation to achieve the environmental target. Intuitively, the carbon tax directly corrects the environmental externality by increasing the relative cost of brown energy, whereas subsidies operate indirectly by encouraging green production and therefore require larger distortions in investment and resource allocation to achieve the same reduction in brown energy use. As a result, tax-based policies dominate subsidy-based policies from a welfare perspective.

Table 4: Constrained welfare-maximizing policy benchmarks

Policy Scenario	Carbon Tax		Green Subsidy		Public Investment	
	τ_T^e	ρ_τ	s_T^G	ρ_s	i_T^{ep} % of GDP	ρ_i
Tax Only	0.599	0.720	—	—	—	—
Subsidy Only	—	—	3.736	0.002	—	—
Investment Only	—	—	—	—	16%	0.000
Tax + Subsidy	0.599	0.720	0.000[a]	0.000[a]	—	—
Tax + Investment	0.585	0.717	—	—	0.2%	0.000
All Three	0.585	0.716	0.000[a]	0.000[a]	0.2%	0.005

	e_{15}^B/e_0^B	Welfare
Tax Only	0.550	-41.929
Subsidy Only	0.550	-51.605
Investment Only	0.550	-60.630
Tax + Subsidy	0.550	-41.929
Tax + Investment	0.550	-41.907
All Three	0.550	-41.907

Note: τ_T^e is the terminal carbon tax level; s_T^G the terminal green subsidy rate; i_T^{ep} public green investment as a fraction of GDP. Persistence parameters $\rho_j \in [0,1]$ govern adjustment speed, with $\rho_j = 0$ implying immediate implementation and higher ρ_j implying more gradual adjustment. All scenarios achieve the same 45% reduction in brown energy use by year 15 ($e_{15}^B/e_0^B = 0.550$) through a binding equality constraint. Welfare is the discounted sum of period utilities over a long transition horizon.

[a] Whenever a carbon tax is available, the terminal green subsidy optimizes to a value numerically indistinguishable from zero. In those scenarios the terminal subsidy is reported as 0, and the associated persistence parameter ρ_s, which is indeterminate when the terminal level is zero, is set to 0 by convention.

Moreover, the estimated policy persistence parameters reported in the table reveal that when supply-side instruments are the only available policy tools, the welfare-maximizing transition is strongly *front-loaded*. In particular, the optimal persistence parameters are close to zero, implying that subsidies or public investment should be implemented almost immediately rather than phased in gradually. The intuition is straightforward. Because the environmental target must be achieved by year 15, delaying supply-side policies reduces their effectiveness, as green productive capacity must expand sufficiently rapidly to satisfy the target within the required horizon. As a result, optimal supply-side interventions involve an immediate and aggressive adjustment path, in sharp contrast with the gradual implementation that is optimal under carbon taxation.

Also, we find a small but economically meaningful complementarity between carbon taxes and modest public green investment. Adding public investment of around 0.2% of GDP to the carbon tax reduces the optimal terminal tax from 0.599 to 0.585 and raises welfare marginally, from -41.93 to -41.91. The welfare improvement is quantitatively small, but it is consistent with the mechanisms emphasized in Section 5: early public investment accelerates green capital accumulation and relaxes the transition friction in the energy sector, allowing the economy to achieve the same environmental target with a slightly lower carbon tax.

Finally, the benchmarks also speak directly to the simple policy rules analyzed in the previous sections. The welfare-maximizing carbon tax path is quantitatively close, both in its terminal level and persistence, to the baseline transition considered in Section 4.1, and the associated welfare gap is small. Part of this similarity reflects the structure of the optimization problem itself. With only two policy parameters and an equality constraint requiring brown energy use to decline to a given target by year 15, the set of admissible tax paths is already tightly restricted, leaving limited scope for the optimizer to deviate from the baseline specification.[13]

What the policy benchmarks demonstrate unambiguously is that the qualitative ranking of instruments obtained in the previous sections is also the one selected by the welfare

[13]For this reason, the main informational content of Table 4 lies in the *comparison across policy instruments*, rather than in a precise re-calibration of the optimal carbon tax path.

criterion. Carbon taxation dominates supply-side policies, while public investment plays at most a modest complementary role. The transition dynamics associated with these welfare-maximizing allocations are reported in Appendix A.9.

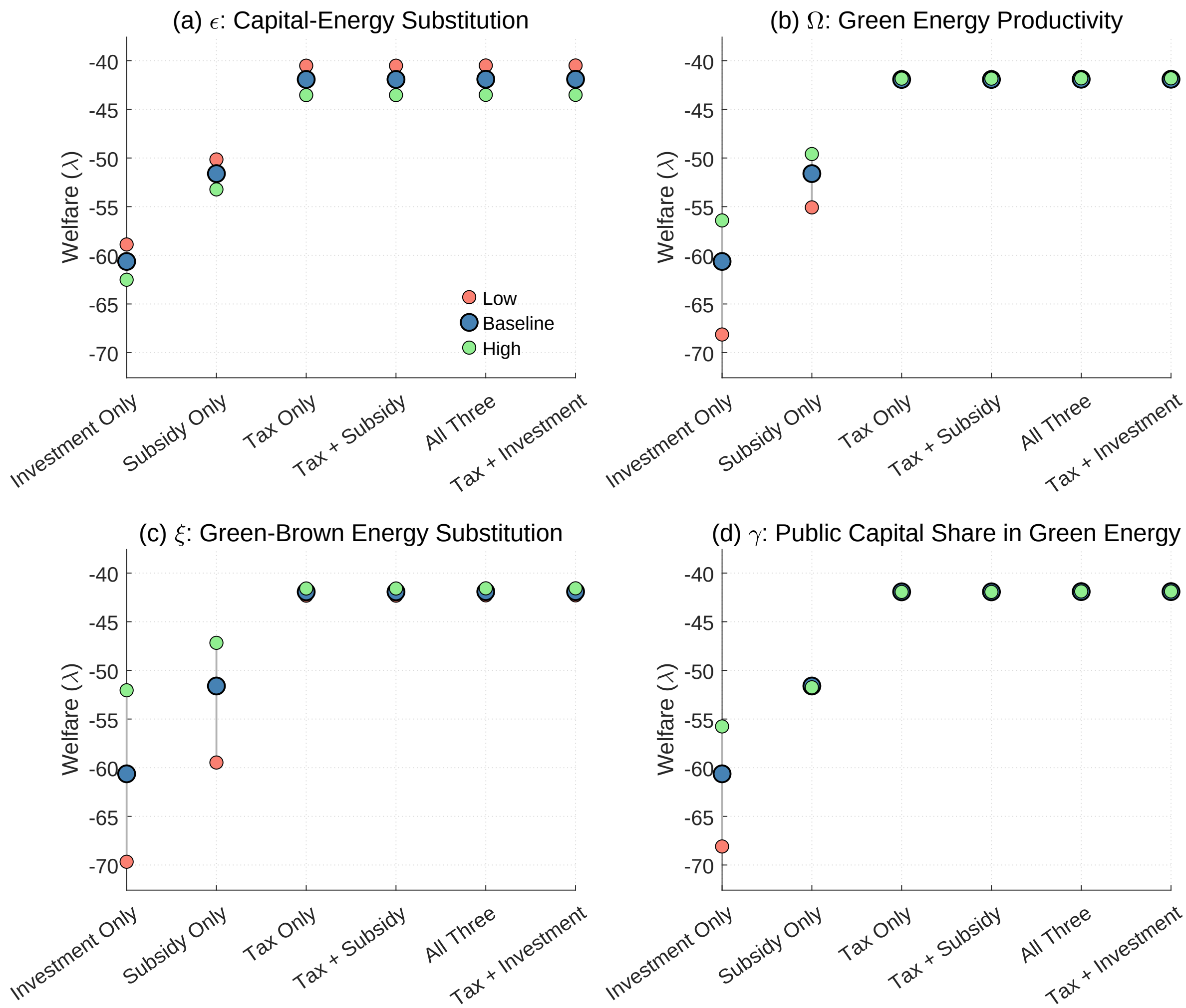
6.1 Robustness of the Ramsey benchmarks

Because welfare comparisons depend critically on key parametric assumptions, we reassess the robustness of the Ramsey benchmarks along four dimensions. To this end, we re-solve the full constrained Ramsey problem for all six policy scenarios under alternative calibrations of i) the elasticity of substitution between capital and energy (ε); (ii) the productivity of green energy production (Ω); (iii) the elasticity of substitution between green and brown energy (ξ); and (iv) the share of public capital in the green energy aggregator (γ).

We vary the first three parameters by $\pm 20\%$ around the baseline; for γ we use a narrower $\pm 10\%$ range, as larger perturbations cause convergence failures in the Investment-Only scenario. In total, this delivers 46 successful optimizations, each imposing the same year-15 environmental target. Because structural parameters shift both the initial and the terminal steady state, welfare levels are not directly comparable across calibrations; what is informative is the *ranking* of policies and the relative welfare gaps across instruments within each calibration.

Figure 8 summarizes the welfare results across alternative parameterizations. In each panel, the red, blue, and green markers correspond respectively to the *low*, *baseline*, and *high* calibrations of the parameter under consideration. For each parameter, the baseline corresponds to the benchmark calibration used throughout the paper, while the low and high cases consider symmetric downward and upward deviations around that benchmark.

Figure 8: Welfare sensitivity of the Ramsey benchmarks



Note: Welfare under each of the six policy scenarios for alternative calibrations of the four structural parameters indicated in each panel. Dots show welfare levels under the low (red), baseline (blue), and high (green) calibration. The welfare ranking is identical across all calibrations, and the gaps between tax-based and supply-side-only policies are large and stable throughout. Alternative calibrations imply different transition paths and different absolute welfare levels; the relevant comparison is within each calibration.

The welfare ranking of policies is preserved across every calibration: tax-based policies consistently dominate supply-side-only policies, and the Tax + Investment mix remains the welfare-maximizing scenario. The welfare gaps between tax-based and supply-side-only policies remain large and stable throughout, confirming that the dominance of carbon pricing is not an artefact of the baseline calibration.

Optimal policy parameters adjust in economically intuitive ways: a higher value of ξ reduces the optimal carbon tax, since the environmental target is easier to reach when energy inputs are more substitutable; a lower Ω raises both the optimal tax and the required supply-side effort since green capital can be produced more efficiently; and a higher γ reduces the optimal terminal investment level for Investment Only, as each unit of public capital becomes more productive. The full set of parameter tables underlying this figure is reported in Appendix A.10.

Hence, despite the well-documented public opposition to carbon taxation—driven by concerns about personal costs, regressivity, economic impacts, inefficiency, and government self-interest (see, e.g., Carattini et al. (2018))—carbon taxes remain the constrained optimal policy instrument for achieving the green transition in our framework.

7 Conclusions

We analyze the transitional dynamics of a green transformation in an emerging small open economy, focusing on the role of fiscal policy and the effectiveness of key instruments: carbon taxes, green subsidies, and public investment. Our findings show that carbon taxes effectively reduce brown energy use and improve energy efficiency but lead to short-term output losses and persistent "greenflation." In contrast, green subsidies and public investment fail to deliver comparable reductions under realistic fiscal constraints. These policies trigger substantial fiscal shocks, raising sovereign risk premiums and borrowing costs, which in turn amplify short-term consumption losses—especially in economies with limited access to external financing.

Monetary policy can help contain inflationary pressures in the short run, but it has limited ability to offset the real costs of the transition. The magnitude and persistence of these trade-offs depend on structural features of the economy, especially those affecting the supply side, such as substitutability between inputs, endogenous energy efficiency, and nominal rigidities.

Our analysis yields two complementary perspectives on policy design. Under a constrained Ramsey benchmark in which all scenarios deliver the same year-15 environmental target, mixed strategies that recycle revenues from carbon taxes into green public investment improve welfare relative to tax-only transitions, by easing the fiscal burden associated with standalone interventions. However, carbon taxation is the dominant adjustment margin: green subsidies add no welfare value when carbon pricing is available, while modest public green investment provides a small complementary role by accelerating green capital accumulation. Taken together, these results point to a central role for carbon taxes, with supply-side instruments most useful either as political substitutes for stronger pricing or as modest complements along the transition.

It is important to note that our analysis assumes perfect foresight and full credibility in fiscal policy implementation. Future research should explore the implications of uncertainty, commitment problems, and heterogeneous household responses for the design and political economy of green transition policies.

In sum, there is no easy optimal path to a sustainable energy future for small open economies. Policymakers must carefully balance environmental goals with macroeconomic stability, fiscal space, and political feasibility.

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A Appendix

A.1 Equilibrium equations

A.1.1 Households

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

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

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

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

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

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

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

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

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

A.1.2 Intermediate goods producers

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$X_t = A_t k_t^\alpha$$

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

A.2 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

$$X_t = A_t k_t^\alpha \tag{A.1}$$

such that

$$g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^{\alpha}}{X_{t-1}^{1-\alpha} X_{t-1}^{\alpha}} = \tilde{A}_t \tilde{k}_t^{\alpha} \tag{A.2}$$

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 (9),

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

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

A.3 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.4 Equilibrium equations

A.4.1 Households

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

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

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

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

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

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

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

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

A.4.2 Intermediate goods producers

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

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

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

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

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

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

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

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

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

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

A.4.3 Green energy producer

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

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

A.4.4 Brown energy sector

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

A.4.5 Government

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

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

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

A.4.6 Definitions

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

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

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

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

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

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

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

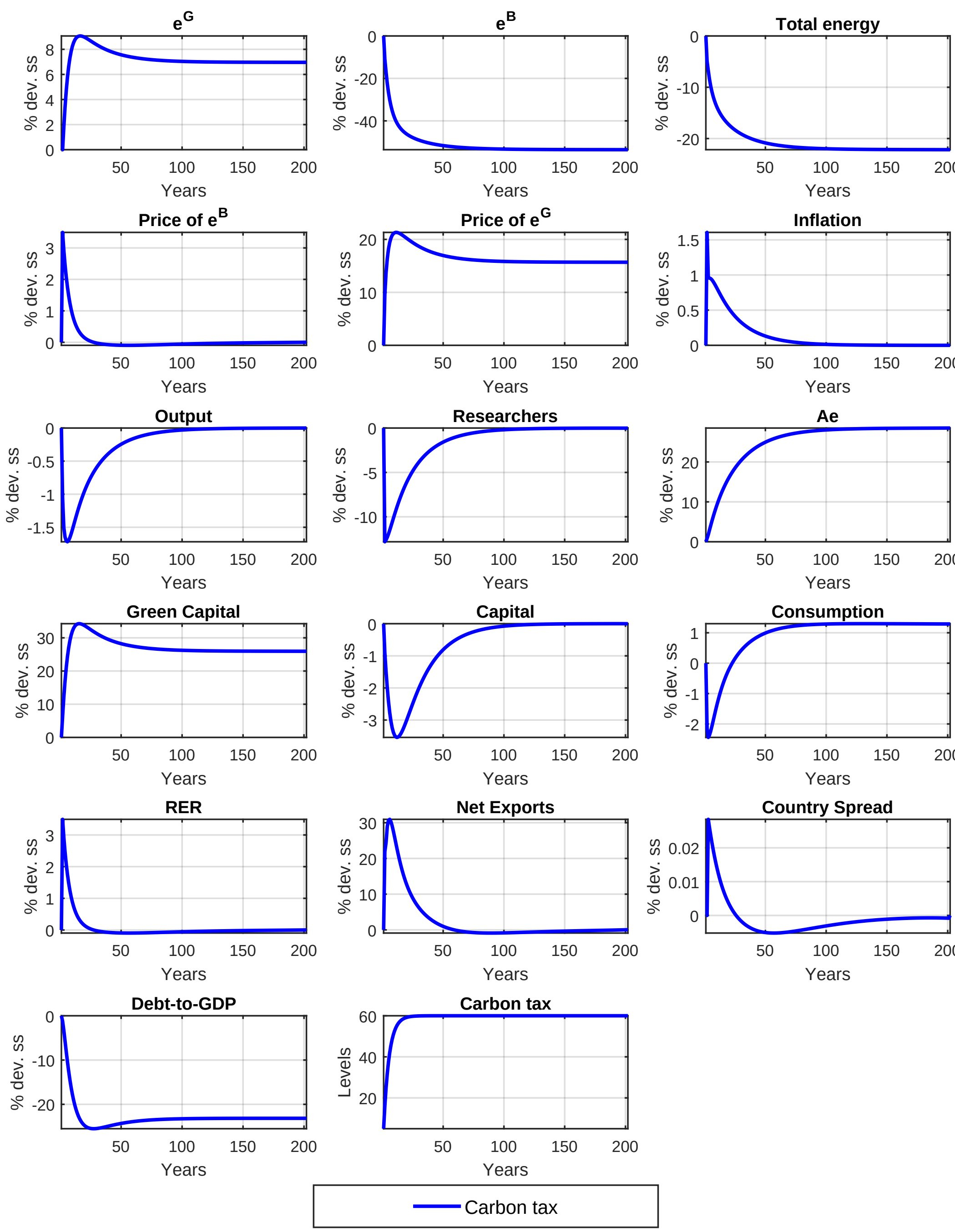
$$g_t = \tilde{A}_t \tilde{k}_t^{\alpha}$$

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

A.5 Transitional dynamics for the whole transition period

Figure A.1 reports the full transition dynamics. We report the first 40 years in the text.

Figure A.1: Transitional dynamics: 200-periods



Note: Dynamics for the entire transition period where carbon taxes increase from 5 to 60 final consumption units. Variables are in percentage deviations from the initial steady state, except for carbon taxes, which are in levels.

A.6 Sensitivity analysis

The transitional dynamics of the green transformation depend critically on firms' ability to substitute across energy sources and improve energy efficiency. Since our framework incorporates frictions that affect both transitional dynamics and steady states, we perform several sensitivity exercises.

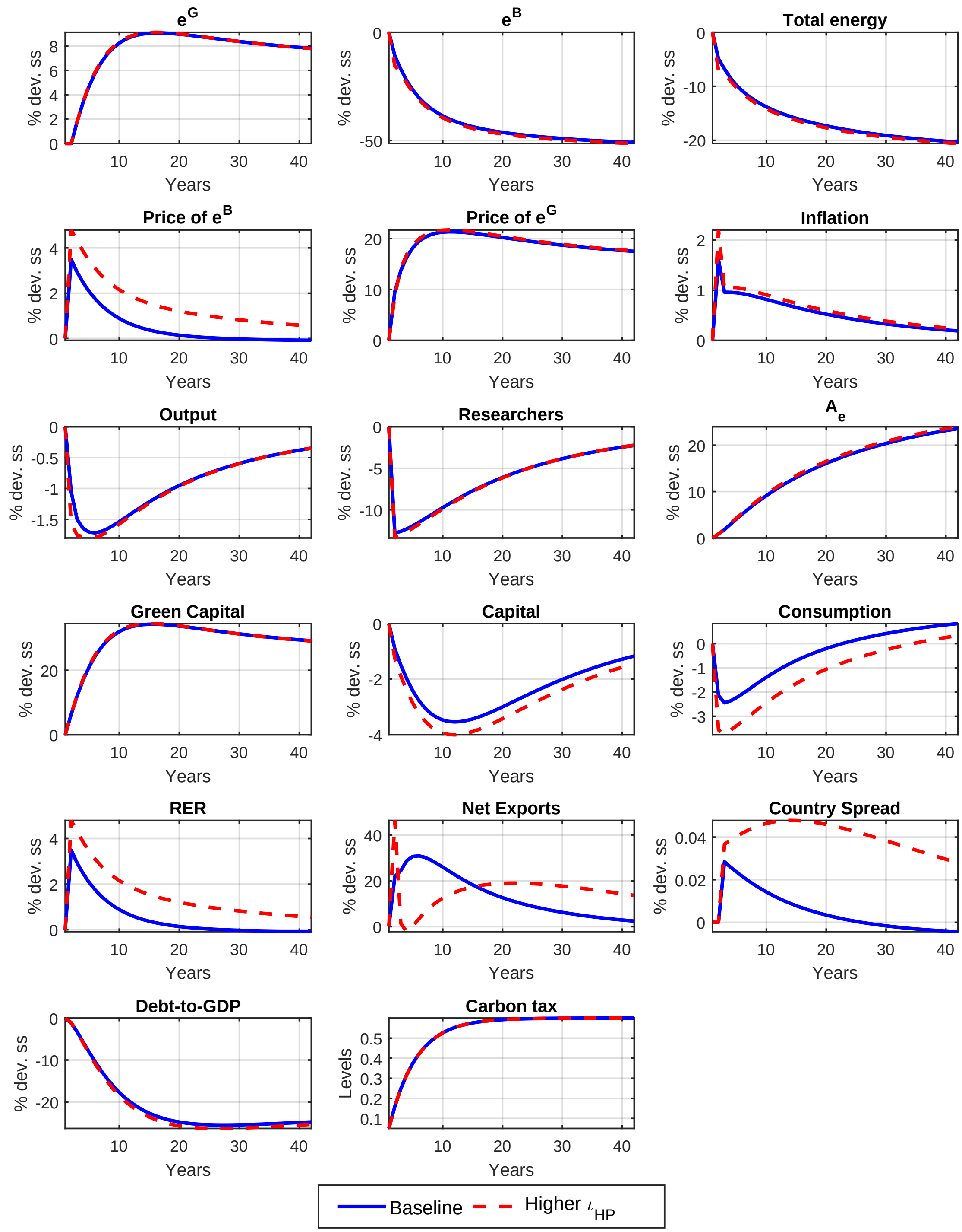
We begin by studying price stickiness. As shown in Figure A.2, stronger price rigidities amplify the increase in brown energy prices and worsen output losses during the transition. Higher inflation also generates larger spreads, further depressing consumption and investment.

We next analyze the role of researchers' effectiveness in improving productivity, governed by the returns-to-scale parameter in the research sector (ϕ). We compare the baseline calibration, $\phi = 0.92$, with a lower value of $\phi = 0.7$, corresponding to an economy in which productivity improvements are harder to achieve. The resulting dynamics are shown by the red dash-dotted lines in Figure A.3.

Lower research effectiveness affects both steady states and transition dynamics. In the long run, the same carbon tax generates a substantially smaller reduction in brown energy use. In the short run, inflation rises more sharply and output declines more severely and persistently. Intuitively, when firms cannot improve energy efficiency sufficiently, they must rely more heavily on green capital accumulation, while suffering larger productivity losses in the traditional sector. This combination amplifies the contractionary effects of carbon taxation.

The weaker productivity channel also raises marginal costs and inflationary pressures, leading to stronger real depreciations and higher country spreads, which further depress consumption and output during the transition.

Figure A.2: Transitional dynamics: The role of price rigidity



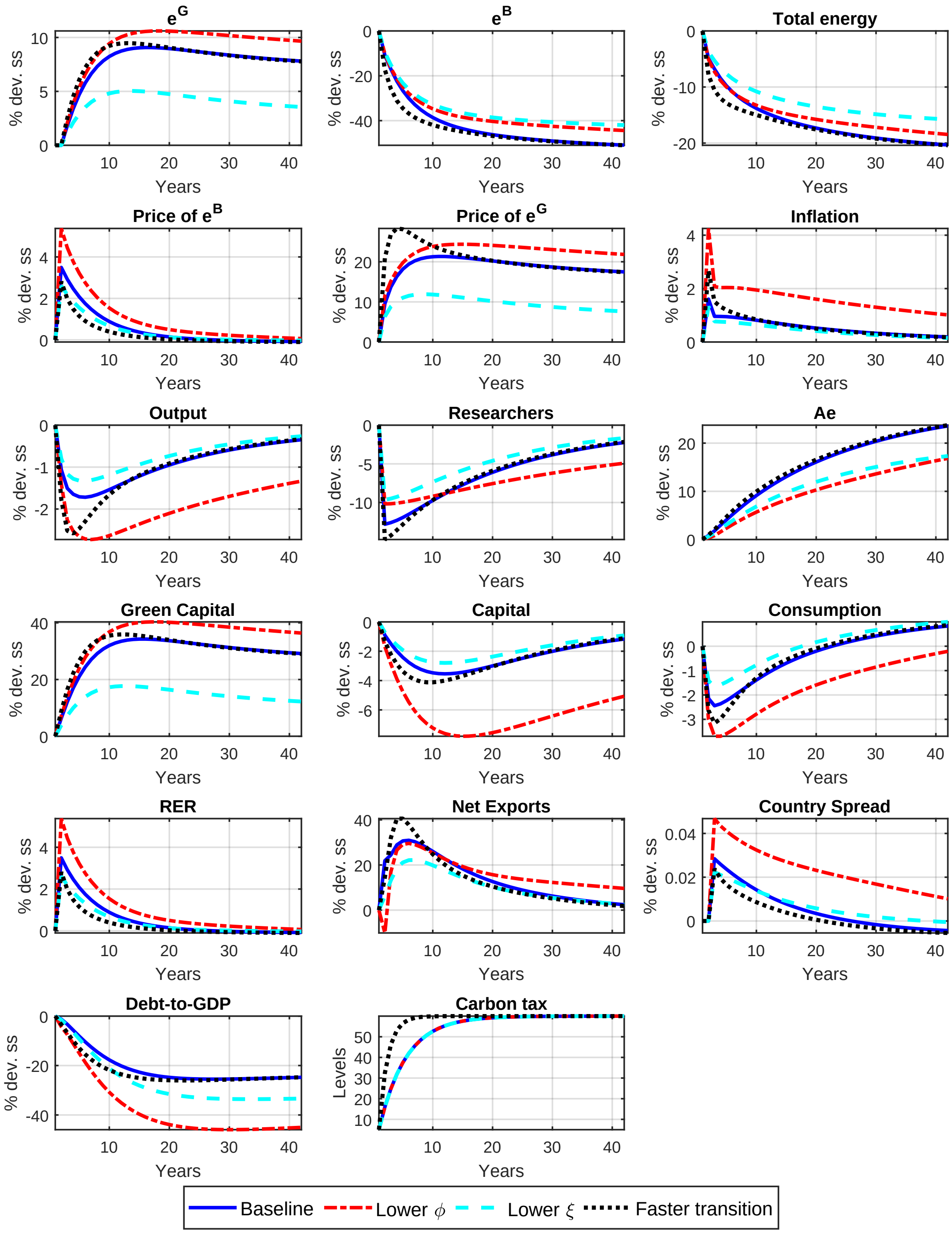
Note: Dynamics for the first 40 years of transition from the initial to the new steady state where carbon taxes increase from 5 to 60 final good consumption units for different values of price rigidity sensitivity. Blue lines represent the baseline calibration; red dashed lines are the case of $\iota_{HP} = 120$. Variables are in percentage deviations from the initial steady state, except for the carbon tax, which is in levels.

We also examine how the substitutability between green and brown energy affects transitional dynamics. Figure A.3 reports the case in which the elasticity of substitution parameter, ξ, falls from 0.67 to 0.4 (cyan dashed lines). Lower substitutability makes green energy a weaker replacement for brown energy, so the same carbon tax generates a smaller long-run reduction in brown energy use.

Because firms perceive green energy as a poor substitute, they adjust energy efficiency less aggressively during the transition. Fewer researchers are reallocated toward R&D, leading to a smaller decline in traditional energy demand and milder short-run output losses. As a result, real depreciation, brown energy prices, and inflationary pressures all increase less sharply than in the baseline economy. The transition therefore becomes less costly in the short run, but also substantially less effective. Achieving the same environmental targets would require significantly larger carbon tax increases.

Finally, we study the role of transition speed. We compare the baseline economy, in which carbon taxes converge to their steady state over 20 years, with a faster transition completed in 8 years. As shown by the black dotted lines in Figure A.3, a faster transition amplifies both inflation and output losses. Firms must compress their adjustment into a shorter horizon, inducing a more abrupt reallocation of researchers and larger short-run production disruptions. The model therefore suggests that a gradual transition is more effective at containing greenflation and mitigating output costs.

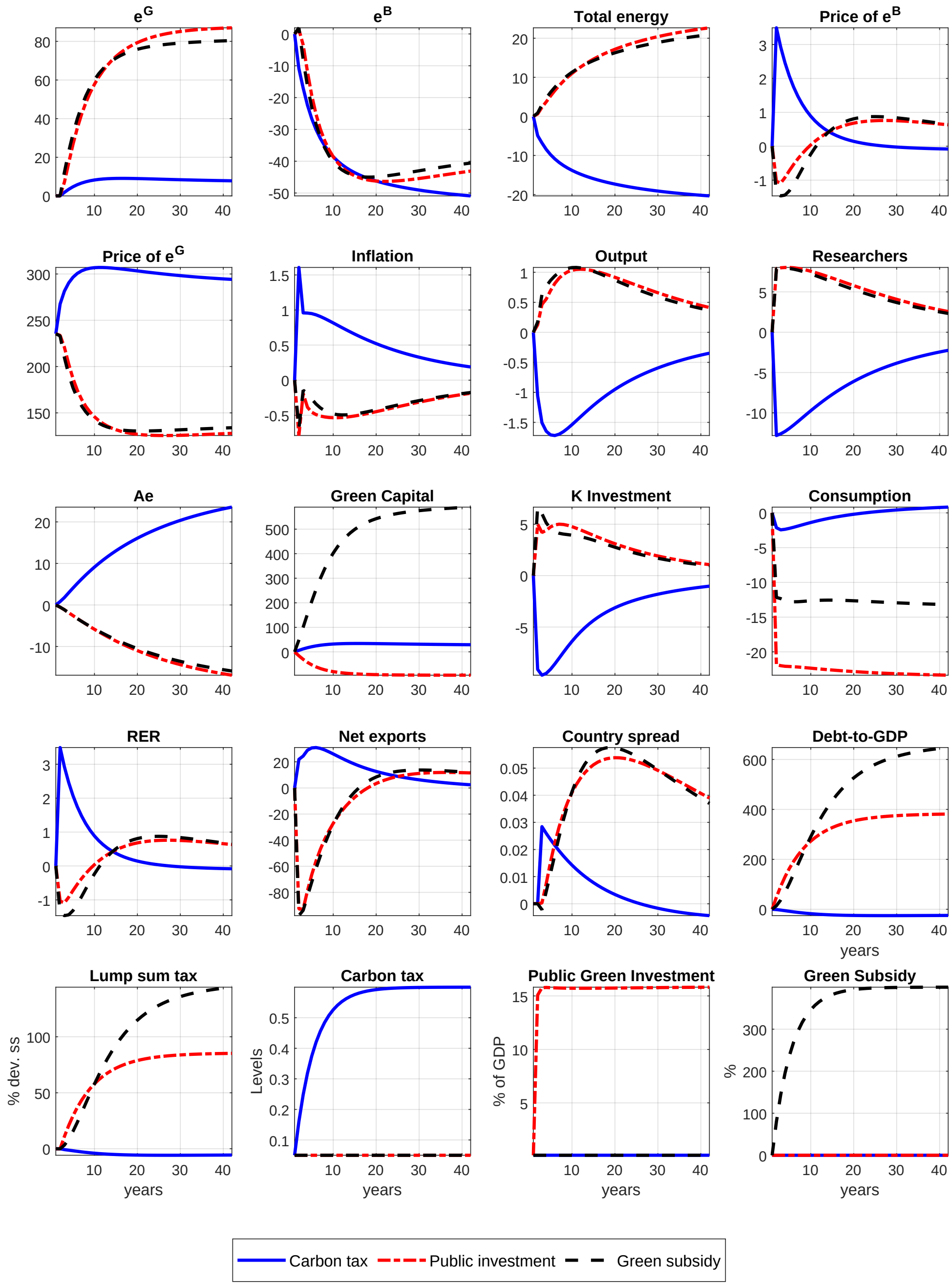
Figure A.3: Transitional dynamics: Sensitivity analysis



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units. Blue solid lines represent the baseline calibration; red dash-dotted lines represent the case of $\phi = 0.7$; cyan dashed lines represent the case of $\xi = 0.4$; and black dotted 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.

A.7 Transition with subsidies and public green investment

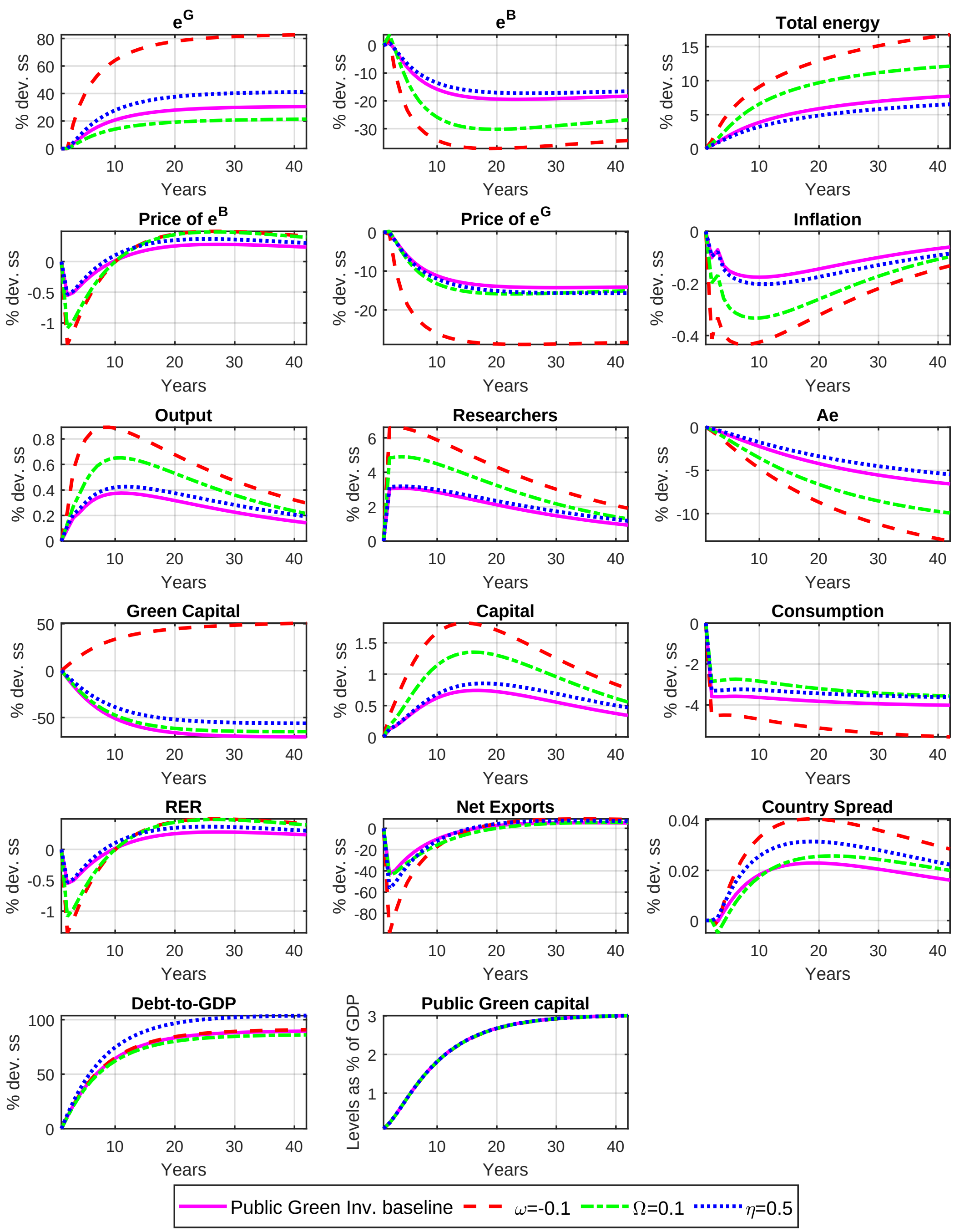
Figure A.4: Transition with subsidies and green investment



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 60 final good consumption units (blue continuous lines); where only subsidies increase from 0 to 400% (black dashed lines); where only green public investment increase from 0 to 16% of GDP (red dashed lines).

A.8 Energy production parameters and public green investment

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 green public investment increases from 0 to 3% of GDP. Purple continuous lines show the transition with the baseline calibration, and red dashed lines show the transition when $\omega = -0.1$; Green dashed lines the case of $\Omega = 0.1$ and blue dotted lines the case of $\eta = 0.5$. Variables are in percentage deviations from the corresponding initial steady state, except for green public investment, which is in levels as a percentage of GDP.

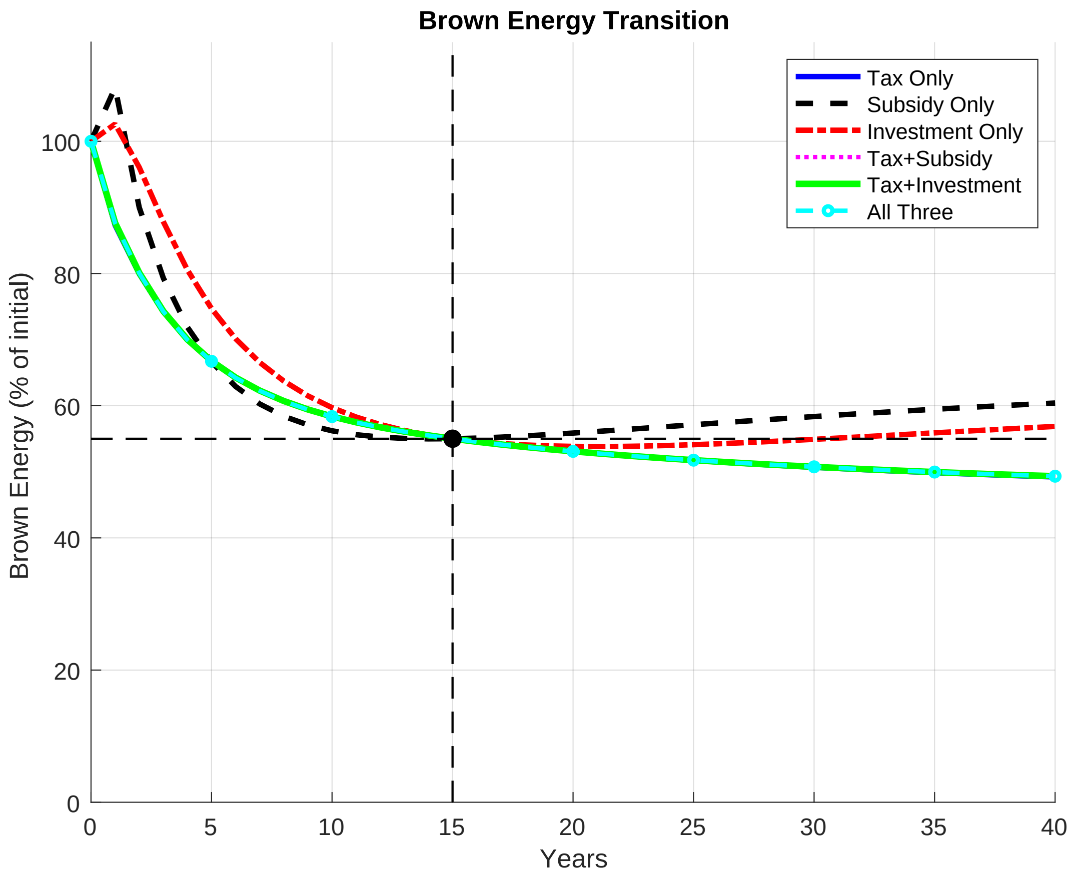
A.9 Constrained Ramsey benchmarks: implementation and transition dynamics

This appendix documents the numerical implementation of the constrained Ramsey benchmarks of Section 6 and reports the transition dynamics that generate the optimal parameters and welfare levels in Table 4.

Implementation. The constrained welfare-maximization problem defined in Section 6 by equations (19) to (21) is solved numerically in MATLAB using the `fmincon` routine. The terminal policy levels are constrained to be non-negative and the persistence parameters are restricted to the unit interval, $\rho_j \in [0, 1]$. At each candidate policy path, the model's equilibrium conditions are evaluated using Dynare's perfect-foresight solver, and the resulting consumption path is used to compute welfare according to equation (19); the environmental target (20) is imposed as a nonlinear equality constraint. The solver is run from multiple starting points that span the feasible region, and all starts converge to the same optimum.

Transition dynamics. Figure A.6 plots the brown energy paths under the six constrained benchmarks. By construction, each policy achieves the 45% reduction by year 15. Tax-based policies (including the mixed scenarios that optimally rely mainly on taxes) generate smooth transition paths, while subsidy-only and investment-only scenarios attain the same target at substantially higher welfare cost.

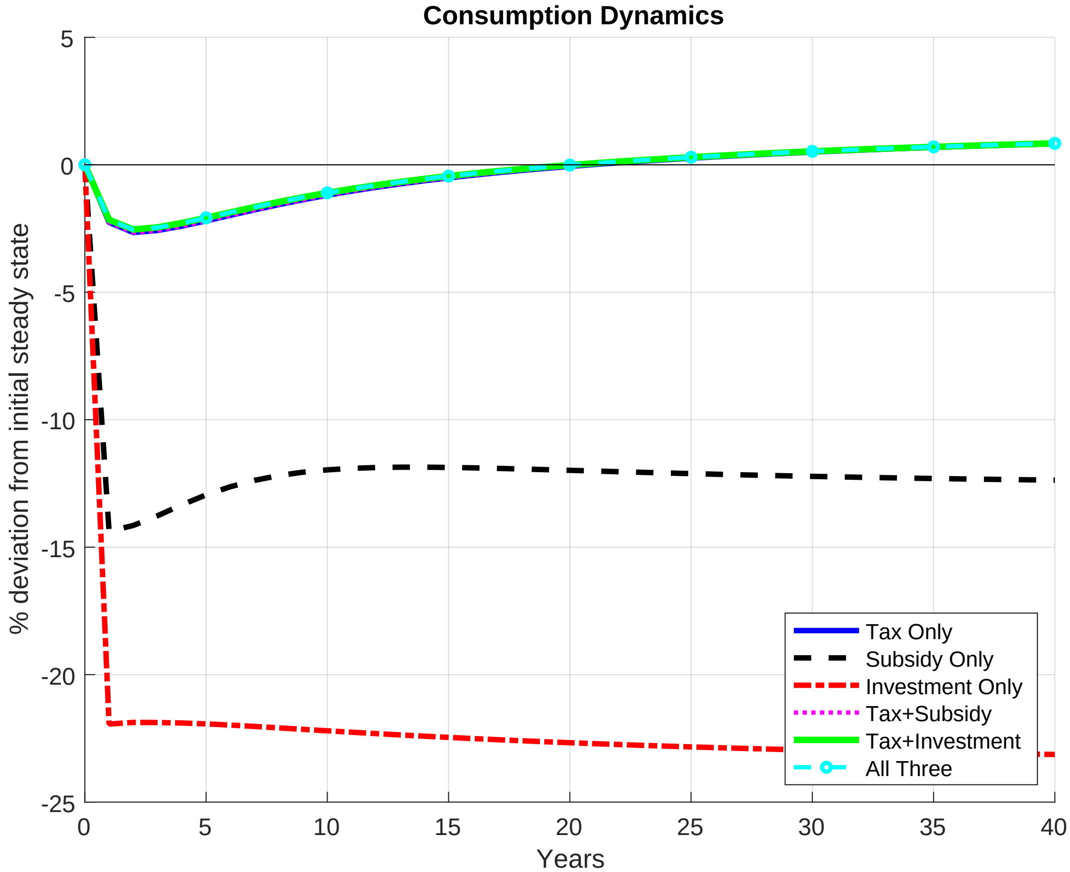
Figure A.6: Ramsey benchmarks: brown energy transition



Note: Brown energy e_t^B along the first years of the transition for each of the six constrained welfare-maximizing policy benchmarks. All scenarios are constrained to deliver $e_{15}^B/e_0^B = 0.55$.

Figure A.7 reports consumption dynamics. Tax-based policies display transitional consumption losses that gradually unwind. In contrast, subsidy-only and investment-only benchmarks feature deeper and more persistent consumption declines, consistent with the larger fiscal burdens and associated sovereign spread responses required to reach the same environmental target.

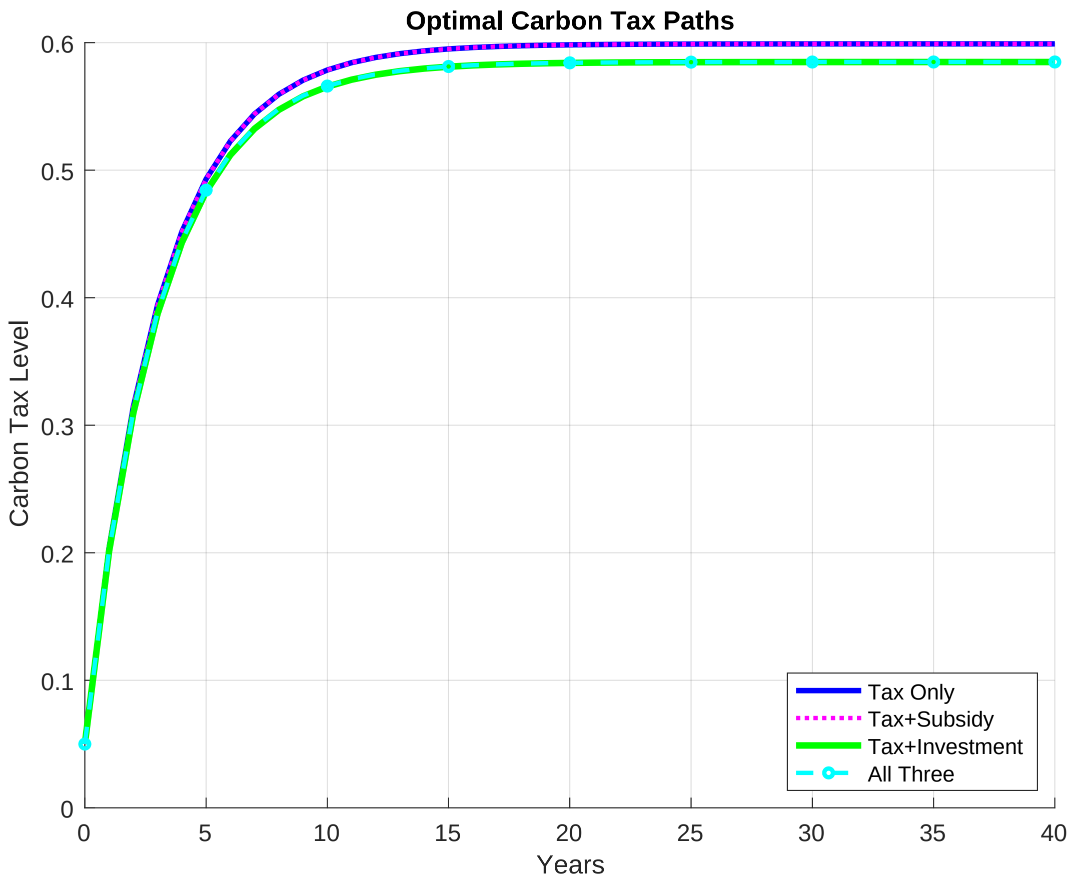
Figure A.7: Ramsey benchmarks: consumption dynamics



Note: Consumption along the transition under each of the six constrained welfare-maximizing policy benchmarks. Variables are in percentage deviations from the initial steady state.

Figure A.8 shows the optimal carbon tax paths in scenarios where carbon taxation is available. The Tax-Only and Tax + Subsidy cases yield essentially identical tax paths because the optimal subsidy is zero. When public investment is also available, the optimal tax path is marginally lower, reflecting the complementarity discussed in Section 6: modest investment helps reach the target with slightly less reliance on carbon pricing.

Figure A.8: Ramsey benchmarks: optimal carbon tax paths



Note: Carbon tax paths τ_t^e along the transition for the Ramsey benchmarks that feature carbon taxation. Tax levels are expressed in model units consistent with the calibration in the main text.

Caveats. The welfare metric used in this paper focuses on macroeconomic adjustment costs and does not incorporate environmental or health benefits beyond the imposed brown energy reduction target. Including such benefits would affect welfare levels but is unlikely to overturn the relative ranking of instruments within the model.

A.10 Sensitivity of the Ramsey benchmarks

This appendix reports the optimal policy parameters underlying the sensitivity analysis summarized by Figure 8 in Section 6.1. Table A.1 lists the baseline and alternative calibrations used for each structural parameter, and Tables A.2–A.5 report the optimal policy parameters obtained when each parameter is perturbed. The optimization problem, solution algorithm, and policy parameterization are identical to those described in Appendix A.9. Because structural parameters determine both the initial and the terminal steady state of the model, alternative calibrations imply different transition paths and different absolute welfare levels. The sensitivity analysis is therefore informative about the *ranking* of policies and the *relative* welfare gaps across instruments within each calibration, rather than about level comparisons across calibrations.

Table A.1: Parameter calibrations used in the sensitivity analysis

	Description	Baseline	Low	High
ε	Elasticity of substitution, capital–energy	0.25	0.20 (-20%)	0.30 ($+20\%$)
Ω	Productivity in green energy production	0.04	0.032 (-20%)	0.048 ($+20\%$)
ξ	Elasticity of substitution, green–brown energy	0.67	0.536 (-20%)	0.804 ($+20\%$)
γ	Public capital share in green energy aggregator	0.44	0.396 (-10%)[a]	0.484 ($+10\%$)[a]

Note: Baseline values as reported in the calibration of Section 2. The environmental constraint (45% reduction in brown energy by year 15) and the welfare criterion are held fixed across all calibrations.
[a] For γ, perturbations of $\pm 20\%$ cause convergence failures in the Investment-Only scenario under the perfect-foresight solver, so a narrower $\pm 10\%$ range is used for this parameter.

Two patterns are worth highlighting. First, the optimizer sets the green subsidy to zero in every calibration where a carbon tax is available, without exception, confirming that the dominance of carbon pricing over supply-side instruments is a robust feature of the model. Second, optimal policy parameters adjust across calibrations in ways that are consistent with the model's mechanisms: a higher value of ξ reduces the optimal carbon tax, since the environmental target is easier to reach when energy substitution is less costly; a lower Ω raises both the optimal tax level and the required supply-side effort; and a higher γ reduces the optimal terminal investment level in the Investment-Only scenario, as each unit of public capital is more productive. These adjustments reflect the internal consistency of the optimization, and in no case do they alter the welfare ranking of policies.

Table A.2: Optimal policy parameters: variations in the capital–energy substitution elasticity (ε)

Policy Scenario	Carbon Tax		Green Subsidy		Public Investment	
	τ_T^e	ρ_τ	s_T^G	ρ_s	i_T^{ep}	ρ_i
Panel A: Low calibration ($\varepsilon = 0.20$, -20%)						
Tax Only	0.607	0.544	—	—	—	—
Subsidy Only	—	—	3.705	0.002	—	—
Investment Only	—	—	—	—	0.150	0.000
Tax + Subsidy	0.607	0.544	0.000[a]	0.000[a]	—	—
Tax + Investment	0.594	0.541	—	—	0.002	0.001
All Three	0.594	0.541	0.000[a]	0.000[a]	0.002	0.001
Panel B: High calibration ($\varepsilon = 0.30$, $+20\%$)						
Tax Only	0.596	0.789	—	—	—	—
Subsidy Only	—	—	3.755	0.002	—	—
Investment Only	—	—	—	—	0.149	0.000
Tax + Subsidy	0.596	0.789	0.000[a]	0.000[a]	—	—
Tax + Investment	0.581	0.789	—	—	0.002	0.000
All Three	0.581	0.789	0.000[a]	0.000[a]	0.002	0.002

Note: τ_T^e terminal carbon tax; s_T^G terminal green subsidy; i_T^{ep} terminal public green investment (fraction of GDP); ρ_j persistence parameters. All policies satisfy $e_{15}^B/e_0^B = 0.55$. [a] When the terminal green subsidy optimizes to zero, the corresponding persistence parameter ρ_s is indeterminate and set to 0 by convention.

Table A.3: Optimal policy parameters: variations in green energy productivity (Ω)

Policy Scenario	Carbon Tax		Green Subsidy		Public Investment	
	τ_T^e	ρ_τ	s_T^G	ρ_s	i_T^{ep}	ρ_i
Panel A: Low calibration ($\Omega = 0.032$, -20%)						
Tax Only	0.669	0.751	—	—	—	—
Subsidy Only	—	—	5.170	0.003	—	—
Investment Only	—	—	—	—	0.191	0.000
Tax + Subsidy	0.669	0.751	0.000[a]	0.000[a]	—	—
Tax + Investment	0.657	0.751	—	—	0.002	0.000
All Three	0.657	0.750	0.000[a]	0.000[a]	0.002	0.005
Panel B: High calibration ($\Omega = 0.048$, $+20\%$)						
Tax Only	0.546	0.689	—	—	—	—
Subsidy Only	—	—	2.917	0.003	—	—
Investment Only	—	—	—	—	0.125	0.000
Tax + Subsidy	0.546	0.689	0.000[a]	0.000[a]	—	—
Tax + Investment	0.531	0.685	—	—	0.002	0.000
All Three	0.531	0.685	0.000[a]	0.000[a]	0.002	0.002

Note: see notes to Table A.2.

Table A.4: Optimal policy parameters: variations in the green–brown energy substitution elasticity (ξ)

Policy Scenario	Carbon Tax		Green Subsidy		Public Investment	
	τ_T^e	ρ_τ	s_T^G	ρ_s	i_T^{ep}	ρ_i
Panel A: Low calibration ($\xi = 0.536$, -20%)						
Tax Only	0.685	0.722	—	—	—	—
Subsidy Only	—	—	5.524	0.001	—	—
Investment Only	—	—	—	—	0.200	0.000
Tax + Subsidy	0.685	0.722	0.000[a]	0.000[a]	—	—
Tax + Investment	0.671	0.720	—	—	0.003	0.000
All Three	0.671	0.720	0.000[a]	0.000[a]	0.003	0.000
Panel B: High calibration ($\xi = 0.804$, $+20\%$)						
Tax Only	0.516	0.709	—	—	—	—
Subsidy Only	—	—	2.545	0.008	—	—
Investment Only	—	—	—	—	0.094	0.000
Tax + Subsidy	0.516	0.709	0.000[a]	0.000[a]	—	—
Tax + Investment	0.503	0.706	—	—	0.001	0.000
All Three	0.503	0.706	0.000[a]	0.000[a]	0.001	0.001

Note: see notes to Table A.2.

Table A.5: Optimal policy parameters: variations in the public capital share in green energy (γ)

Policy Scenario	Carbon Tax		Green Subsidy		Public Investment	
	τ_T^e	ρ_τ	s_T^G	ρ_s	i_T^{ep}	ρ_i
Panel A: Low calibration ($\gamma = 0.396$, -10%)						
Tax Only	0.595	0.718	—	—	—	—
Subsidy Only	—	—	3.699	0.002	—	—
Investment Only	—	—	—	—	0.192	0.000
Tax + Subsidy	0.595	0.718	0.000[a]	0.000[a]	—	—
Tax + Investment	0.586	0.716	—	—	0.002	0.000
All Three	0.586	0.716	0.000[a]	0.000[a]	0.002	0.002
Panel B: High calibration ($\gamma = 0.484$, $+10\%$)						
Tax Only	0.603	0.721	—	—	—	—
Subsidy Only	—	—	3.774	0.002	—	—
Investment Only	—	—	—	—	0.120	0.000
Tax + Subsidy	0.603	0.721	0.000[a]	0.000[a]	—	—
Tax + Investment	0.583	0.719	—	—	0.002	0.000
All Three	0.583	0.719	0.000[a]	0.000[a]	0.002	0.000

Note: see notes to Table A.2. A narrower $\pm 10\%$ range is used for γ because $\pm 20\%$ perturbations cause convergence failures in the Investment-Only scenario.