THE GREEN METAMORPHOSIS OF A SMALL OPEN ECONOMY*

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Abstract

We design a small open economy model where production combines energy and traditional factors with low short-run substitutability and efficient technology adoption. We study green transitional dynamics. Permanent increases in brown energy prices induce a green transition with short-run inflation and persistent output losses. Fiscal policy significantly impacts the transition: Brown energy taxes are inflationary and crowd out brown energy use in favor of green energy. Green public investment or green subsidies have moderate macroeconomic effects but do not crowd out brown energy use. We discuss fiscal costs and evaluate welfare along the green transition using different metrics.

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1 Introduction

Climate change is a fact, and its consequences, such as the increase in sea levels or the frequency of natural disasters, are palpable. As these phenomena have large economic costs, all economies are aware of the need to evaluate options for growth and development that reconsider the use of non-renewable resources and fossil-based energy. This paper studies the macroeconomic impact of the green transition in small open economies, which, even though individually may not have a sizeable contribution to the global emissions of CO2, certainly affect them as a whole.

We develop a new model of a small open economy with energy use to understand both short and long-run movements in macroeconomic aggregates along the green transition. Our model builds on the standard New Keynesian model for a small open economy. We incorporate an endogenous supply of green energy and allow green and brown energy to be substitutes in energy production. Departing from the existing models and following Hassler et al. (2021) and Hassler et al. (2022), we assume that intermediate goods production is characterized by low substitutability between energy and traditional inputs in the short run that firms can alter over longer periods through directed input-saving technical change. Differently from the previous authors, we consider nominal frictions to study the direct impact of the green transition on inflation as well as its indirect impact through the response of fiscal and monetary policies. Our model captures the main features of Emerging Economies: these economies take international prices and risk-free rates as given; they are typically subject to financial constraints, which are represented by a positive premium on external debt, and have a higher average inflation rate than developed economies. Moreover, we assume a domestic exogenous supply of brown energy, a type of energy that many emerging markets may also produce and export.

The green transition impacts the dynamics of prices and inflation since it induces changes in relative prices of energy and traditional inputs and in the aggregate price level. The transition is induced by energy price increases that impact firms' marginal costs. First, this increase in marginal costs shapes the adoption of technology and energy efficiency along the transition affecting pricing and production decisions. A second aspect of the relative price change is that the increase in marginal costs impacts the prices of consumption goods, triggering substitution and wealth effects on the side of the consumer and a response from monetary and fiscal policies that feedback on the firms' production and technology adoption decisions. This second channel that has been overlooked by the literature lies at the core of our analysis.

Our focus on inflation is policy-driven as inflationary dynamics due to the green transition raise concerns in policy circles. The inflationary cost of the transition has worried policymakers for a long time as Isabel Schnabel, the ECB executive responsible for market operations, said in a press release to the Financial Times: the planned transition away from fossil fuels to a greener low-carbon economy "poses measurable upside risks to our baseline projection of inflation over the medium term." She added that policies to tackle climate change, such as carbon taxes, increase inflationary pressures in the Euro Area. We focus the analysis on emerging economies where these effects may be more substantial and which have traditionally operated in environments with pro-cyclical government spending, debt intolerance, and financing based on the inflation tax. Also, the transition might imply costs that alter the competitiveness of emerging economies, typically small open economies that are more frequently exposed to increases in input costs for energy and other resources.

We calibrate the model to the Chilean economy. We compute transitional dynamics for different cases. In the baseline scenario, we start from the initial steady state and assume a 60 years transition that ends with a 30% increase in brown energy prices. The positive trend in the price of brown energy is compatible with a resource constraint of fossil resources in the rest of the world that the small open economy takes as given. Hassler et al.

(2022) assume that brown energy resources are scarce in the world economy. The positive trend in the price of brown energy captures this resource constraint. The persistent price increase eventually drives the economy to a new steady state with a higher share of green energy use. In the short run, the persistent increases in brown energy prices push marginal costs upwards. Given that agents foresee the increases in brown energy prices, firms accumulate more green capital and smoothly decrease the usage of brown energy, leading to a smooth increase in the ratio of green over brown energy. However, in the short and medium run, the green transition induced by increases in energy prices implies surges in both brown and green energy prices. The change in relative prices results in an inflation boost that smooths out gradually as the firms allocate more researchers to efficient energy usage increasing its productivity and lowering the initial rise of green energy prices. The short-run dynamics of the economy resemble those of a sudden stop. Quantitatively the permanent brown energy price rise increases the ratio of green to brown energy in production by 60 percent in the new steady state and implies a surge in inflation in the first two years and a substantial and persistent output fall. Hence, our analysis suggests that a green transition triggered by permanent increases in brown energy prices induces greenflation in the first few years, which is quantitatively contained, but the output costs are persistent and considerable. We show that monetary policy can reduce the inflationary pressures in the short-run of the transition reacting strongly to inflationary pressures but at the cost of higher output losses.

Given the inability of monetary policy to moderate output losses, we turn to study the role of fiscal policy. We investigate how fiscal policy changes can induce transitional dynamics toward a greener economy. We study three scenarios a) increases in carbon taxes; b) increases in green subsidies, and c) investment in green capital infrastructure. For the sake of comparability, we implement policy changes that induce a similar increase (of 60 percent) in the ratio of green to brown energy use in the new steady state. We find that carbon taxes can accelerate the green transition but come at the cost of inflationary pressures and output losses in the short and medium run. Subsidies and public investment in green capital instead have the potential to accelerate the green transition without generating inflationary pressures and output costs. The transition pace is slower in the case of subsidies and implies elevated green energy prices. Instead, green public investment expands output and reduces green energy prices in the long run since it increases the productivity of the green sector. Hence, the different fiscal options imply very different transitional dynamics.

It is difficult to assess which policy option is preferable without a metric. We first show that the adoption of different fiscal policy instruments entails different fiscal costs in terms of debt-to-GDP deviations and the evolution of spreads along the transition. Carbon taxes increase the economy's debt burden and widen sovereign spreads, while subsidies imply small debt-to-GDP deviations and also smaller spread increases. Nevertheless, the dynamics of spreads and debt or inflation might be misleading in guiding us toward the best policy option.

A natural measure to rank the different policy choices is to look at welfare. We compute welfare metrics using consumption equivalence measures and different assumptions regarding utility. We consider three cases: i) welfare depends on consumption only (no externality case); ii) welfare depends on consumption only, but there is a pollution externality generated by the utilization of brown energy that results in detrimental effects on households' health modeled as consumption losses and iii) a preference for sustainable consumption goods that rewards positively products with a reduced environmental impact in utility. Our conclusions depend on the welfare metric adopted. If one believes that the negative externality from brown energy use is relevant, then carbon taxation is the best policy option along the transition. If one believes that the negative externality from brown energy usage should not concern small emerging economies, or believes in a global preference change towards more sustainable goods, then the best policy option is the investment in green public infrastructure.

Starting from Kilian (2008), many existing studies evaluate the macroeconomic effects of energy price shocks. However, most of the analysis is typically limited to evidence gathered from short-run national or cross-sectional studies and concerns shocks that relate to the price of oil that originates from demand or supply forces and not to economic transformation. Instead, one might be interested in assessing if an economy's vulnerability and resilience to shocks improve with economic development, as analyzed in van de Ven and Fouquet (2017), or actually how the macroeconomy is affected by economic transformation. We aim to understand the transitional dynamics of green transformation and how these interact with monetary and fiscal policy in emerging markets. To the best of our knowledge, this is the first study that combines possibly non-monotone medium-run transitional dynamics with nominal rigidities to study inflation dynamics and the role of fiscal and monetary policy along the green transition.

Relative to the existing models of the environmental literature as in Nordhaus (2008), Heutel (2012), Fischer and Springborn (2011), among others, we combine the environmental component with a standard general equilibrium model, what is by now tagged as a DSGE-E model (See e.g., Carattini et al. (2021) among others). Similar to Annicchiarico and Di Dio (2015) and Annicchiarico and Di Dio (2017), we add nominal frictions as in the New Keynesian literature. However, our model is new and differs from the existing models in several dimensions. We model the production of energy in the green sector and assume that the final good is produced using energy from both sectors and capital and labor inputs. In addition, we incorporate energy efficiency and allow firms to react to relative energy price movements adjusting available resources to improve energy efficiency, resulting in possible non-monotone medium-run transitional dynamics. Finally, we investigate the role of fiscal policy in inducing the green transition and offer welfare metrics to evaluate the best policy options.

The rest of the paper is organized as follows: Section 2 presents some motivating facts. Section 3 presents the model. Section 4 discusses the calibration and solution method employed. Section 5 presents transitional dynamics and discusses different policy experiments. Section 6 quantifies welfare along the green transition, and Section 7 concludes.

2 Clean energy, policies, and inflationary pressures

Most emerging economies are lagging behind in the adoption of clean sources of energy when compared to developed economies. Figure 1 shows the consumption of renewable and non-renewable energy for the world, Latin America and the Caribbean as a whole, Brazil, Chile, and Sweden and Norway, which are leading the adoption of clean energy.

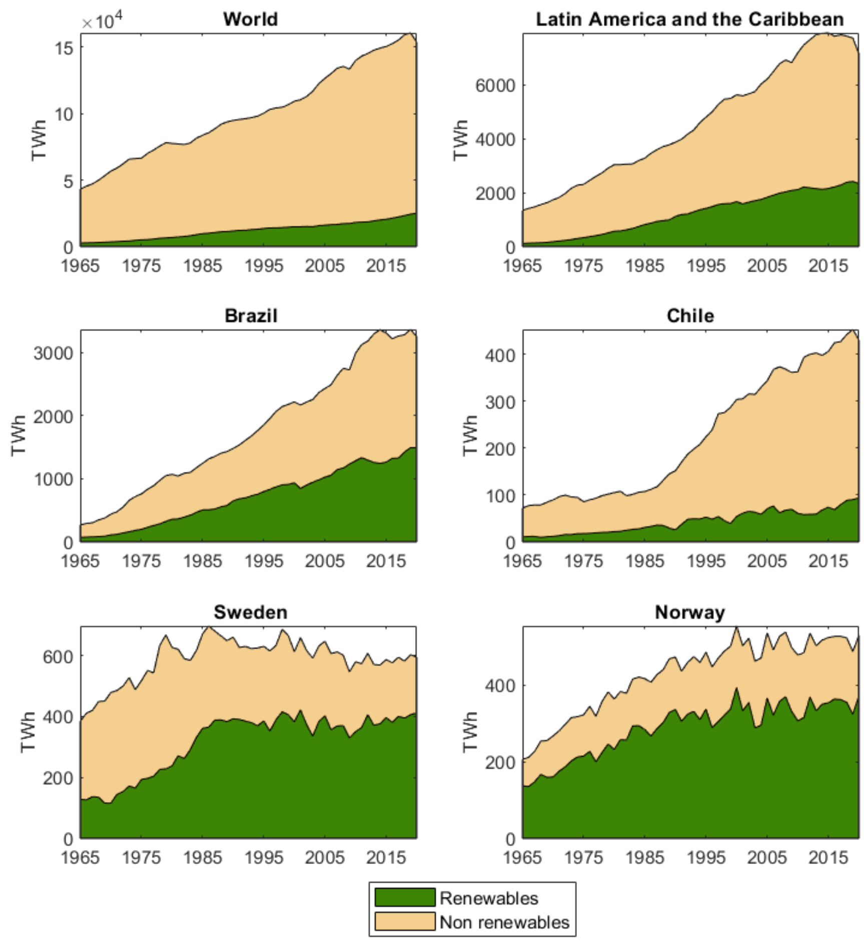

Figure 1: Renewable versus Non-renewable energy consumption

Note: Primary energy consumption in terawatt-hours (TWh). Source: BP Statistical Review of World Energy. 'Renewables' includes Solar, Wind, Hydropower, Nuclear, Biofuels, geothermal, biomass, and waste energy. 'Non-renewables' includes oil, coal, and gas.

Although a clear positive trend in the use of green energy is apparent in all countries, there is a large gap between the share of renewable energy used among countries. For example, in Sweden and Norway, which started the transition to clean energy over 60 years ago, renewable energy accounts for 2/3 of total energy consumed, and the consumption of non-renewable energy is clearly trending down. In Latin American economies, this share is much smaller and bears significant heterogeneity: Brazil has clearly already started to move in the green transition, while Chile has not. Moreover, in contrast to Norway and Sweden, the world does not seem to have changed that much in the adoption of renewable energy.

In line with the relatively lower adoption of green energy in emerging economies, Figure 2 shows that these economies have invested little in the development of installed capacity for renewable energy use over the last 20 years.

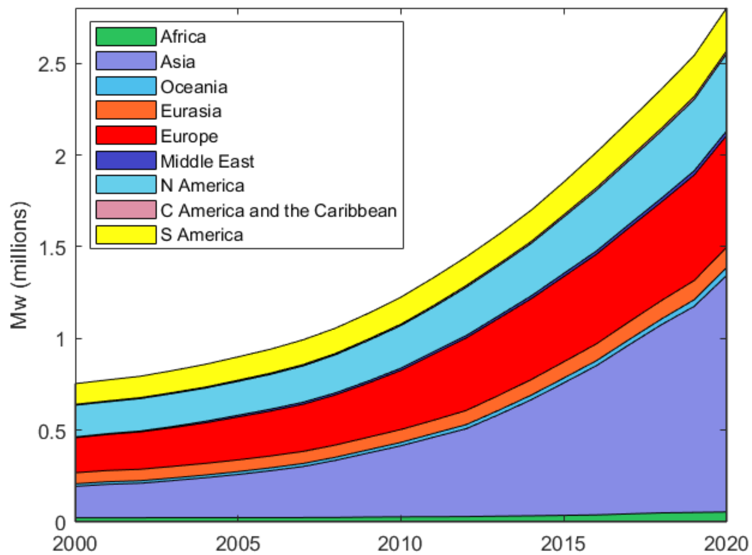

Figure 2: Installed renewable energy capacity.

Source: IRENA (2021), Renewable Capacity Statistics 2021; IRENA (2020), Renewable Energy Statistics 2020, The International Renewable Energy Agency, Abu Dhabi. Data in electricity capacity (MW).

Indeed, Latin America and the Caribbean, Africa, and, naturally, the Middle East have not increased their installed renewable energy capacity since the 2000s, in contrast with countries in the European and Asian continent.[1]

Hence, the evidence suggests that the green transition may imply challenges for some

[1]Even within the European countries, there is significant diversity in the adoption of renewable energy. According to Eurostat, Sweden, Finland, and Latvia are front runners in the green transition, while countries like Poland, Ireland, Hungary, and Belgium are lagging very much behind. The same is true in Asia. Asia's installed renewable energy capacity almost tripled between 2009 and 2018. The growth is primarily led by China, with India being the second largest renewable energy producer in Asia, while South Korea lags behind in clean energy adoption.

middle and low-income economies in the short run. If these economies want to start the green energy transition they may encounter bottlenecks due to a higher demand for green energy in the presence of low renewable energy capacity, which, in turn, may introduce inflationary pressures in the short run. To boost the transition, these economies need to allocate resources to the exploitation of green technology and build the required capacity. This is going to imply higher costs in the short run. Moreover, inducing a change in the use of non-renewable energy towards renewable energy sources will, in the absence of the right level of capacity, imply high costs, which would translate into short-run increases in the price of energy.

This is not the only potential driver of higher inflation due to the energy transition. A second reason for energy price increases during the transition is that economies will need to tackle the transition using fiscal and monetary measures. Figure 3 plots Carbon Pricing Scores in different countries according to OECD estimates in 2018.[2] Notice that the measure of comparison is 60 euros per metric ton of CO2 equivalent. EUR 60 is a midpoint estimate for carbon costs in 2020 and a low-end estimate for 2030. Pricing all emissions at least EUR 60 in 2018 shows that the country is on a good track to reach the goals of the Paris Agreement to decarbonize by the next mid-century economically. Emerging economies such as Brazil, Chile, India, and Turkey lag very much behind this target, while in 2018, only Switzerland, Luxembourg (not shown in the graph for ease of exposition), and Norway reached a Carbon Pricing Score (CPS_60) of close to 70%. Introducing further carbon taxation to promote the use of green energy will imply increases in the price of polluting energy, another source of inflation in the short run.

[2]This indicator measures how far each economy is to price carbon in order to match the cost of producing it.

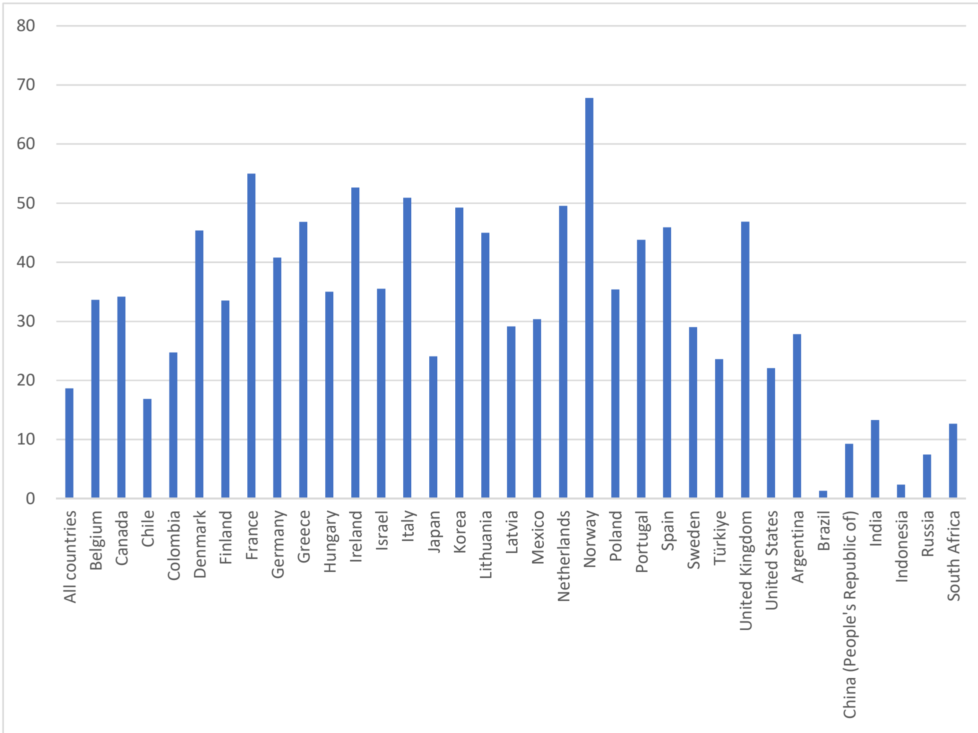

Figure 3: Carbon pricing score

Source: OECD, dataset on effective carbon rates. The indicator in this figure is the Carbon Pricing Score and reflects the distance between the price of carbon and its cost.

The evidence presented in this section suggests that some emerging economies loiter both in investments in renewable energy as well as policies to accelerate the green transition. In the analysis that follows, we try to assess quantitatively the real and nominal costs of transition for such economies and the impact of tax/subsidy and other government policies to promote the green transition in those economies.

3 The Model

We adapt a small open economy New-Keynesian model to incorporate energy efficiency in production, directed technology change, and production of green energy. The domestic economy is populated by households, final domestic good producers, intermediate goods producers, producers of green energy, a government that determines fiscal policy, and an independent monetary authority. In turn, the rest of the world determines demand for home exports and provides imports of final goods and brown energy fully elastically at internationally given prices and buys/sells an asset subject to default risk. In the remainder of this section, we describe each of the sectors in detail.

3.1 Households

The representative household in the domestic economy supplies a fixed share of its available time to work, $\bar{h}$, chooses consumption c_t, assets, and two types of investment: in capital goods i_t and in green technology i_t^G.[3] The investment in green technology adds to the green capital stock, s_{t+1}^G, which evolves according to the following law of motion:

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

Capital k_t follows a standard law of motion:

$$k_{t+1} = (1-\delta)\, k_t + \Phi_k(k_{t+1}, k_t) k_t + i_t, \tag{2}$$

where parameter δ represents a constant depreciation rate that we assume is the same in both specific capital stocks. Similarly, both capital stocks are subject to adjustment costs represented by function Φ_i, for $i = S, K$.[4]

[3] The model with a labor supply choice does not provide the analysis with additional insights and it is harder to solve numerically.

[4] We have also considered a specification with time-to-built in investment for both capital stocks. The results

On top of investing in capital and green technology, the household can save in two different assets: a domestic public bond B_{t+1} that pays a nominal return R_t after one period or a foreign bond B^*_{t+1}, with return $R^*_t \Phi^A_{t+1}(A^f_{t+1})$ in the next period, in foreign currency. The bonds are nominal. In addition, the representative agent pays lump-sum taxes τ_t to the government and receives profits from the firms in the economy, Γ_t.

The household consumption c_t is a bundle composed of domestic, $c_{H,t}$, and foreign goods, $c_{F,t}$, given by:

$$c_t = \left[(1-\chi)^{\frac{1}{\theta}} c_{H,t}^{\frac{\theta-1}{\theta}} + \chi^{\frac{1}{\theta}} c_{F,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{3}$$

and their prices are $P_{H,t}$ and $P_{F,t}$. The optimal demand for domestic and foreign goods is:

$$c_{H,t} = (1-\chi) \left(\frac{P_{H,t}}{P_t} \right)^{-\theta} c_t,$$

and

$$c_{F,t} = \chi \left(\frac{P_{F,t}}{P_t} \right)^{-\theta} c_t.$$

Here P_t denotes the CPI in the domestic country and is given by:

$$P_t = \left[(1-\chi) P_{H,t}^{1-\theta} + \chi P_{F,t}^{1-\theta} \right]^{\frac{1}{1-\theta}}. \tag{4}$$

we present here are qualitatively similar, given that our calibration is annual, we have decided to keep the specification with standard capital adjustment costs as our baseline.

The household chooses, c_t, B_{t+1}, B^*_{t+1}, i^G_t, i_t, s^G_{t+1}, k_{t+1} to maximize:

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

s.t.

$$i^G_t + i_t + c_t + \frac{B_{t+1}}{P_t} + FX_t \frac{B^*_{t+1}}{P_t} = \dots$$

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

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

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

where FX_t is the nominal exchange rate, and $\Phi^A_t(\tilde{A}^f_t)$ is a debt-elastic interest rate premium given by:

$$\Phi^A_t(\tilde{A}^f_t) = \exp\left\{ -\phi^A \left[\tilde{A}^f_t + \mu^f \right] \right\}.$$

Here, μ^f is the country risk premium, and $\tilde{A}^f_t$ is the real outstanding foreign debt in domestic currency to output ratio as in Justiniano and Preston (2010):

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

This implies

$$\tilde{A}^f_t = \frac{FX_t P^*_{t-1} P^*_t}{P^*_t P_t \bar{Y}} \frac{\tilde{B}^*_t}{P^*_{t-1}} = \frac{rer_t}{\pi^*_t \bar{Y}} \tilde{b}^*_t,$$

where $\bar{Y}$ is the domestic output at the steady state and $b^*_{t+1} = \frac{B^*_{t+1}}{P^*_t}$. We present the household's optimality conditions in the appendix.

3.2 Domestic final good producer

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

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

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

$$\max_{y_t, \{y_{H,i,t}\}_{i\in[0,1]}} P_{H,t} y_{H,t} - \int_0^1 P_{H,i,t} y_{H,i,t} di,$$

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

The optimal demand function for variety i is given by the following expression:

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

3.3 Intermediate-good producers

Each firm in the intermediate-goods sector produces a variety $y_{H,i,t}$ in a monopolistic competition environment, facing a downward demand function, $a_{i,H,t}$. The technology for producing variety i uses fixed labor $\bar{h}_i$, physical capital $k_{i,t}$, and energy $e_{i,t}$ as productive inputs. Following Hassler et al. (2021) and Hassler et al. (2022), we assume the following technology:

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

A_t and $A_{e,t}$ are input-augmenting productivity factors, that are non-stationary. To account for changes in A and A_e, we assume that each firm disposes of a fixed stock of researchers equal to one, a fraction n of which can be allocated to improve the productivity of capital/labor, and the remaining fraction $(1-n)$ is used to improve the efficiency of energy services, as in Hassler et al. (2022). Relative to the former authors, we assume that n is endogenous and determined at the firm level and use it as a way for the firms in the domestic economy to adjust to changes in the relative price of energy. Fixing the stock of researchers dedicated to improving the efficiency in the energy versus the capital/labor services is actually fixing the relative movements of the two trends.[5] More precisely, the proportion of researchers in each sector affects the corresponding growth rates of productivity $A_{e,t}$, A_t, in the following fashion:

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

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

As is clearly demonstrated by the determinants of the two growth rates, firms face a trade-off in the allocation of researchers. A rise in R&D in one sector increases its productivity growth rate at the cost of decreasing the one in the other sector. We assume that the firms optimally choose n_t to balance this trade-off. Notice that a key parameter of the production function is the elasticity of substitution between traditional inputs and energy. Although we can assume this elasticity to be near zero in the short run, i.e., almost Leontief, directed input-saving technical change can alter this elasticity at longer horizons. That is, by choosing n, the producer can move resources from A_t to $A_{e,t}$ increasing the efficiency (or intensity) of use of energy compared to labor and capital, allowing for medium-run increasing resource use.

[5]Obviously, a single firm cannot change the economy's trends. Given that all firms behave symmetrically in equilibrium, we find this to be an innocuous assumption.

With regards to the energy used in the intermediate production sector, we assume that it is an aggregate of the polluting ($e^B_{i,t}$) and clean energy ($e^G_{i,t}$), given by

$$e_{i,t} = \left[(1-\zeta)\left(e^G_{i,t}\right)^{\xi} + \zeta\left(e^B_{i,t}\right)^{\xi}\right]^{\frac{1}{\xi}}, \tag{6}$$

where ζ characterizes the relative importance of brown over total energy resources and ξ determines the elasticity of substitution between brown and green energy.

The optimization problem of firm i consists in choosing the allocation of researchers $n_{i,t}$, price $P_{H,i,t}$, and inputs of production $e^B_{i,t}$, $e^G_{i,t}$, $k_{i,t}$, $h_{i,t}$ taking as given the demand function $a_{i,H,t}$, given by (5), and input prices P^G_t, P^B_t, W_t. When the firm changes the variety price, it has to pay an adjustment cost given by:

$$\Phi^{PH}(.) = P_{H,t}\frac{\kappa_{PH}}{2}\left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H\right)^2 a_{H,t}$$

in nominal terms, as in Rotemberg (1982). Additionally, the firm has to pay a government tax τ^e proportional to the purchases of brown energy $P^B_t e^B_t$ and receives a subsidy s proportional to purchases of green energy $P^G_t e^G_t$.

The firm's optimization problem, in nominal terms, is the following:

$$\max \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[P_{H,t}\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon} a_{H,t} - P^G_t e^G_{i,t}(1-s) - P^B_t e^B_{i,t}\left(1+\tau^e\right) - W_t \bar{h}_i - P_{H,t} - R^k_t k_t - \right.\right.$$
$$\left.\left. \frac{\kappa_{PH}}{2}\left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H\right)^2 a_{H,t} + MC_t\left(F(e_{i,t}, h_{i,t}) - \left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon} a_{H,t}\right)\right]\right\}.$$

Here, λ_t is the discount factor of the firm that coincides with the Lagrange multiplier of the consumer's problem. We solve for a symmetric equilibrium, where all intermediate firms take the same decisions.

The optimal decision for $n_{i,t}$ is given by:

$$\left(A_{i,t}k_t^{\alpha}h^{1-\alpha}\right)^{\frac{\epsilon-1}{\epsilon}}\frac{A_{i,t-1}}{A_{i,t}}B\phi n_{i,t}^{\phi-1}=e^{\frac{\epsilon-1}{\epsilon}}\frac{A_{i,e,t-1}}{A_{i,e,t}}B_e\phi\left(1-n_{i,t}\right)^{\phi-1},$$

and the optimal pricing decision results to:

$$\pi_{H,t}\left(\pi_{H,t}-\bar{\pi}_H\right)=\beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{H,t+1}\left(\pi_{H,t+1}-\bar{\pi}_H\right)\frac{a_{H,t+1}}{a_{H,t}}\right]+\frac{\varepsilon}{\kappa_{PH}}\left(\frac{mc_t}{p_{H,t}}-\frac{\varepsilon-1}{\varepsilon}\right), \tag{7}$$

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 with respect to the price level in the economy and real marginal cost is $mc_t=\frac{MC_t}{P_t}$. Real profits are given by:

$$\Gamma_t^I=p_{H,t}a_{H,t}-P_t^Ge_{i,t}^G(1-s)-P_t^Be_{i,t}^B\left(1+\tau^e\right)-w_t\bar{h}-R_t^kk_t-\frac{\kappa_{PH}}{2}\left(\frac{P_{H,i,t}}{P_{H,i,t-1}}-\bar{\pi}_H\right)^2a_{H,t}.$$

The rest of the optimality conditions are described in the Appendix.

3.4 Energy sectors

3.4.1 Green energy production

Green energy is produced domestically by combining specific green technology capital stock, s_t^G, the stock of public green capital $s_t^{G,P}$, that firms take as given, and a factor that is in fixed limited supply, L, according to the following production function:

$$e_t^G=\Omega L^{1-\mu}[(1-\gamma)(s_t^G)^{\omega}+\gamma(s_t^{G,P})^{\omega}]^{(\mu/\omega)}. \tag{8}$$

Ω denotes the level of productivity in clean energy production. Parameters ω and γ determine the elasticity of substitution between private and public stocks of green capital and the share of each in green energy production.

This sector solves a static optimization problem consisting in choosing how much green capital to rent s_t^G to maximize the period profits, taking prices P_t^G, R_t^G, and technology as given. For simplicity, we assume the return on the fixed factor L is equal to zero:

$$\Gamma_t^G = P_t^G e_t^G - R_t^G s_t^G$$

We think about the public and private green capital as complements rather than substitutes. Our intuition for this assumption is that public green capital is mainly infrastructure for the development of the green energy sector, while private green capital is mostly capital goods.

3.4.2 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, $e_t^{B,d}$, that we assume is traded internationally and can be exported or imported at the international price $P_t^{B,*}$. Since e_t^B is the domestic demand for brown energy, the imports of brown energy, $e_t^{B,*}$, are given by:

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

We assume the law of one price holds for the brown energy market, and thus, the domestic price of brown energy is the following:

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

From the previous expression, note that

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

and

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

hold. The international price $p_t^{B,*}$ is assumed to follow an exogenous process.

3.5 Final goods imports

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

$$p_{F,t} = rer_t = FX_t \frac{P_t^*}{P_t}, \tag{9}$$

and the growth rate of the real exchange rate can be written as a function of the nominal exchange rate depreciation and domestic and foreign inflation rates:

$$g_t^{rer} = \frac{rer_t}{rer_{t-1}} = \frac{FX_t}{FX_{t-1}} \frac{\pi_t^*}{\pi_t}, \tag{10}$$

where we assume that the foreign inflation rate π_t^* follows an AR(1) process.

3.6 Final goods exports

The foreign demand for domestically produced goods is given by the following expression:

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

where λ is the elasticity of substitution of foreign and domestic goods in the foreign economy, and it could be different from θ. As for the case of foreign inflation, π^*_t, the process for foreign output y^*_t is exogenous from the point of view of the small open economy.

3.7 Monetary Authority

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

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R}. \tag{11}$$

3.8 Fiscal Authority

The fiscal authority satisfies the following period budget constraint:

$$\tau_t + \tau^e p^B_t e^B_t + b_{t+1} = s p^G_t e^G_t + \frac{b_t}{\pi_t} R_{t-1} + i^{pub}_t, \tag{12}$$

where b_{t+1} is real debt with one-period maturity purchased by domestic households and τ_t are lump-sum taxes to the households that follow a fiscal rule:

$$\tau_t - \tau^* = \phi_\tau \left(b_t - \bar{b}\right) + \sigma^\tau \epsilon^\tau_t.$$

Here τ^* is the steady state value of this tax, ϵ^τ_t is a fiscal shock, and ϕ_τ is the elasticity of taxes to debt deviations from the steady state. When this elasticity is high enough, the fiscal authority adjusts taxes to ensure debt sustainability. i^{pub}_t is public investment in green capital that enhances the accumulation of green public capital $s_t^{G,P}$, which we assume follows an exogenous process.

3.9 Aggregation

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

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

Then,

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

Transfers to households are given by:

$$
\Gamma_t = \Gamma_t^I + \Gamma_t^G.
$$

3.10 Balance growth path assumptions

As mentioned earlier, the directed technical change affects the long-run energy share and growth in the economy (See also Hassler et al. (2021)). In particular, define X_{t-1} as the output trend at period t, at which $y_{H,t}$ grows. We define:

$$
X_t = A_t k_t^{\alpha} \tag{13}
$$

such that

$$g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^{\alpha}}{X_{t-1}^{1-\alpha} X_{t-1}^{\alpha}} = \tilde{A}_t \tilde{k}_t^{\alpha}, \tag{14}$$

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.

To have a balance growth path, given the functional form of the production function, we need the two additive parts of it to grow at the same rate. It means that we need:

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

and from equation (6)

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

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

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

Hence,

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

and

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

Finally, from the first order condition of intermediate producers with respect to energy inputs, we get that prices p_t^G and p_t^B grow at $X_{t-1}^{1-\mu}$. In the appendix, we present the complete set of stationarized equations.

4 Calibration and solution

4.1 Numerical implementation

We solve the model using perfect foresight. Our calibration strategy intends to target business cycle first and second-order moments on national accounts and energy production and use for Chile.

4.2 Functional forms

Utility function:

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

Capital adjustment costs:

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

We assume a similar form for the adjustment costs for green capital:

$$\Phi\left(\frac{s_{t+1}^G}{s_t^G}\right) = \frac{\kappa_S}{2}\left(\frac{s_{t+1}^G}{s_t^G} - \bar{g}\right)^2.$$

4.3 Calibration

We calibrate the model matching the first moments for Chile for the period 1960 to 2019. The frequency is annual, and Table 1 reports the parameter values we use in our numerical exercise. We set the intertemporal elasticity of substitution to one, the average growth rate is 1.025 according to the data, the average inflation rate equals 4 percent, and the average nominal risk-free rate is set to 3 percent. $\beta = 0.995$ which is consistent with a slightly positive real interest rate in the steady state. Following Justiniano and Preston (2010), we set the elasticity of substitution between domestic and foreign goods equal to

0.85 and the share of foreign goods in consumption to 0.24. The elasticity between domestic varieties is set so that the steady-state markup is 11 percent. We assume equal depreciation rates for both types of capital and target an annual depreciation rate of 12%. The physical adjustment costs are set to match the volatility of investment over output in the data. We set the capital share at 0.26.

We set the elasticity of substitution between physical capital and energy to 0.35, which implies that the two inputs are complements in production and the share of brown energy in the total energy production to 0.53. The substitution of energy inputs in energy production is set to 0.67 according to the estimates of Papageorgiou et al. (2017), assuming that the two energy inputs are substitutes. We also assume that the share of green capital in the production of green energy is 30% and normalize land in the production to equal 0.1, which is compatible with having the share of the green investment to capital in the steady state equal to the data average of 0.1 percent. The coefficients of the production of technical change of researchers are similar to the ones assumed by Hassler et al. (2021). Finally, the adjustment costs of prices are set equal to 30. The value of κ_P determines the degree of nominal rigidity. One can relate this value to the average price contract length by exploiting the relationship between the log-linearized NK Phillips curve in the Calvo model and the one implied by the Rotemberg model. In particular, the slope of the Phillips curve with respect to real marginal costs is equal to ϵ/κ_P, while the corresponding value in the Calvo model is $[(1-\Psi)(1-\Psi\beta)/\Psi]$ where $1/(1-\Psi)$ is the average contract length. According to this relationship, the value of κ_P we chose corresponds roughly to an average contract length of one year.

The parametrization of the Taylor coefficients is standard. Besides the calibration of the monetary policy rule, in the baseline calibration, all other policy parameters are set to zero apart from the tax response to the debt we set equal to 0.39 to match the debt-to-GDP ratio in the steady state which is set to 60 percent. Matching the data for Chile, we assume

Table 1: Parameter Values

β	Discount factor	0.995
σ	CES elasticity in utility	1.00
g	Average growth rate	1.025
π	Average inflation	1.04
R^*	Average risk free rate	1.03
θ	Substitution between home and foreign goods in consumption	0.85
λ	Foreign demand coefficient	0.85
χ	Share foreign goods in consumption	0.24
ϵ_p	Elasticity between varieties	10.0
δ	Depreciation rate of physical and green stock of capital	0.12
κ_K,κ_S	Adj. cost of physical and green capital	0.005
α_A	Capital share	0.26
ϵ	Substitution between Energy and other factors	0.35
ζ	Share of brown energy	0.53
ξ	Substitution between energy inputs	0.67
Ω	Average Productivity of green technology $e_G/e = 11\%$	0.71
μ	Share of effective green capital in production of green energy	0.42
L	Land (Fixed factor)	0.10
ϕ_A	Spread coefficient, spread$= 3\%$	0.005
B	Production function coefficient for researchers	0.030
ϕ_N	Production function coefficient for researchers	0.880
κ_P	Adj. cost of prices	30.00
ϕ_π	Interest rate response to inflation	1.500
ϕ_Y	Interest rate response to output	0.250
ρ_R	Interest rate smoothing parameter	0.85
τ^*	Average tax	0.39
ϕ_τ	Tax response to debt	0.003
$\frac{nx}{y}$	Target for net exports to GDP	0.012
$\frac{d}{y}$	Target debt to GDP ratio	0.60
γ	Share of Public investment in green energy production	0.40
ω	Elasticity of green public and private capital	0.1

that the country is in a steady state with positive net exports. We set the parameters for the production of green energy so that the share of public investment in green energy production is 40 percent and the elasticity of public and private green capital equals 0.1. Finally, we set the steady state level of the brown energy endowment so that the small open economy is a net importer of brown energy.

5 Transitional Dynamics

For the transitional dynamics, we focus on a perfect foresight model as our interest is in the long-run dynamics for which short-run uncertainty is irrelevant. We assume the economy is in equilibrium (in the equilibrium consistent with a steady state) before period 1. Starting at this initial condition we simulate a Green Transition where the economy is moving from low use of green energy to extensive use of it. Given that the economy is a perfect foresight one, the whole transition is known by the agents in the model since period 1.

Numerically, the solution of the model implies solving a set of nonlinear equations given by

$$
\begin{aligned}
f(y_2, y_1, y_0, u_1) &= 0 \\
&\vdots \\
f(y_{t+1}, y_t, y_{t-1}, u_t) &= 0 \\
&\vdots \\
f(y_{T+1}, y_T, y_{T-1}, u_T) &= 0
\end{aligned}
$$

for each endogenous variable for each period t. Here, $f(y_{t+1}, y_t, y_{t-1}, u_t)$ denotes the set of equations that characterizes the equilibrium, y_t is the vector of endogenous variables, and u_t a vector of innovations that is perfectly known. The initial conditions are y_0 (initial steady state), and the terminal conditions are y_{T+1} (final steady state).

5.1 A transition induced by increases in brown energy prices

We first assume that the secular dynamics around the green transition are driven by increases in brown energy prices determined in the rest of the world ($P^*_{B,t}$). To be precise, starting from the initial steady state, we assume a 60-year transition that ends with a 30% increase in brown energy prices. Figure 4 presents the transitional dynamics for the small open economy.

The increase in the international price of brown energy accelerates the use of green energy and reduces the use of brown energy, and the economy ends up in a new equilibrium where the use of brown energy is permanently reduced in favor of green energy usage. In the new steady state, the ratio of green to brown energy increases by 40%. In the shorter run, the increase in the international price of brown energy drives up domestic brown energy prices and, given the relatively low substitutability between brown and green energy in production, also the price of green energy. This results in a surge in inflation in the short and medium run that smooths out gradually as the firms allocate more researchers to efficient energy usage increasing its productivity.

Given the reallocation of researchers along the transition, the productivity of traditional inputs slows down shortly, and this discourages physical capital accumulation, but as green energy becomes more efficiently used, its path reverses in the medium run, and the productivity of traditional factors increases as well in the medium run.[6] However, the complementarity between energy and traditional inputs in the short run, coupled with the slow dynamics in the energy accumulation and the increase in the price of brown energy, render the green transition recessionary. In other words, since firms perfectly

[6]Note that the picture depicts detrended productivity, A. Given its definition, productivity cannot fall below one.

foresee long-term increases in brown prices, they adjust their production by decreasing traditional factors and, in particular, investment demand generating a recession in the short run. Actually, the dynamics of the economy resemble those of a sudden stop, with output falling and net exports reverting in the short run.

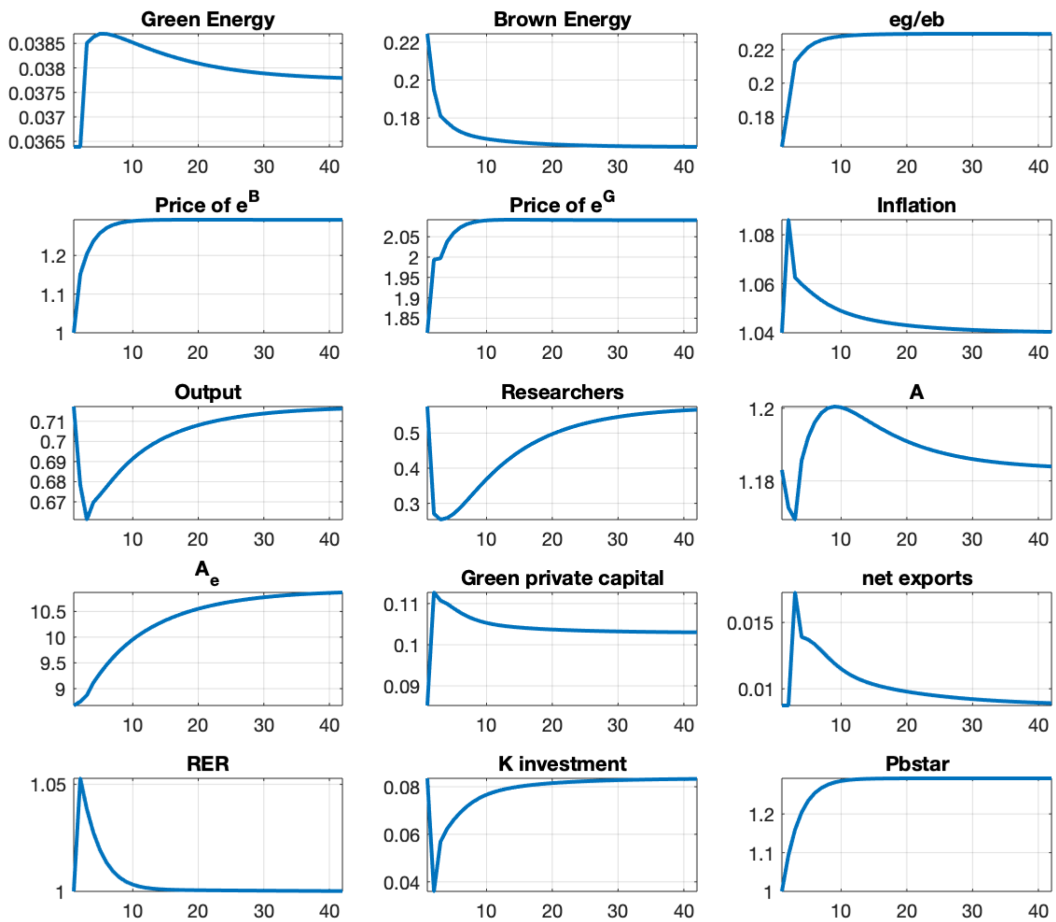

Figure 4: Transitional Dynamics: Increases in Brown Energy Prices

Quantitatively for a 40% increase in the ratio of green to brown energy, inflation increases at maximum in the second year from 4 to 8.6 percent, and the maximum output fall is considerable (7.8% in the third year) and persistent. Hence, our analysis suggests that such a transition induces ”greenflation” in the first few years and significant and persistent output losses. The effects of the shock on inflation are moderate because the negative demand effect from the fall in private investment moderates the inflationary consequences of the shock.

5.2 The role of supply and demand frictions

The macroeconomic dynamics of the green transition depend crucially on the frictions we have assumed in the demand and the supply side of the economy. Given that the model is one with sticky prices, demand frictions in the short run will affect the transition, while supply frictions also have a role in shaping firms' responses in face of relative energy price changes. We investigate here how the assumed major frictions affect the macroeconomic dynamics.

From the demand side, we consider the role of price stickiness in shaping the transitional dynamics. Figure 5 plots the transitional dynamics for our benchmark economy in blue continuous lines, and the dashed yellow lines correspond to the dynamics that would result in an economy that is otherwise identical to the benchmark economy except for a higher degree of price stickiness. Notice that changing the degree of price stickiness in the economy does not alter the two steady states relative to the benchmark economy, but it affects the transitional dynamics. In the hypothetical economy, prices take, on average more than two years to adjust. As a result, the demand channel in this economy is stronger. When agents foresee increases in carbon prices, they would like to increase consumption today in view of higher prices in the future, at the same the foreseeable increase of brown energy prices pushes up marginal costs. However, when prices become very costly to adjust, firms do not react immediately to the rise in marginal costs and, as a result, the inflation responses are somewhat smaller, and so are the maximum output losses along the transition.

From the supply side, we have assumed various frictions that could significantly affect the transitional dynamics but also the initial and terminal steady states.

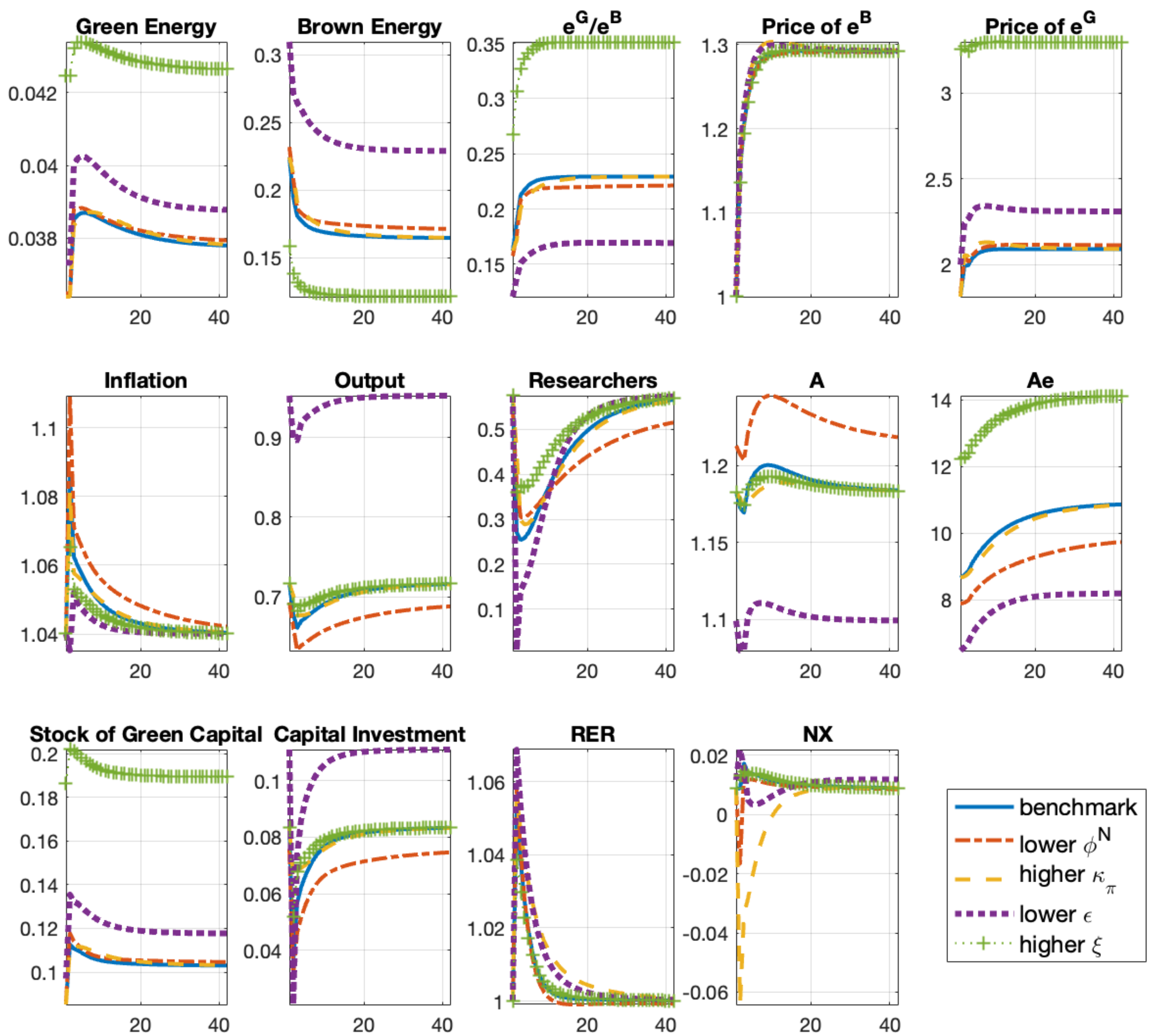

Figure 5: Transitional Dynamics: The role of frictions

We start by considering how rigidities in allocating researchers for improving traditional inputs' or energy efficiency shape the transitional dynamics we have described in the benchmark economy. We consider a lower ability of firms to move researchers in order to increase energy efficiency by decreasing parameter ϕ^N (we reduce ϕ^N to 0.8 in this case). The transitional dynamics of the economy with lower ϕ^N are depicted with red dashed-dotted lines in Figure 5. Supply frictions play a crucial role in determining steady states and transitional dynamics. When firms cannot switch researchers through directed search easily, the economy reaches a steady state with a lower ratio of green to brown energy usage relative to the benchmark since the difficulty in reallocating researchers translates into productivity differences that persist in the new steady state as it is clearly shown in the dynamic path of A_e. Moreover, the increase in marginal costs from the higher brown energy prices becomes more costly in terms of both inflation and output losses. Not being able to increase energy efficiency deprives the firms of an extra margin of adjustment and leads to elevated marginal costs in the short run that translate into huge increases in inflation. Inflation increases from 4 to almost 12 percent in the short run and remains above 5 percent for almost 17 years, and output falls by almost eight percent in the short run and remains persistently low.

We next investigate how the assumed elasticity between traditional factors and energy affects the macroeconomic dynamics of the green transition. In the benchmark calibration, we have assumed that $\epsilon = 0.35$, we now set $\epsilon = 0.1$.[7] The case of lower ϵ is depicted with dotted purple lines in Figure 5. In the benchmark economy, we assume traditional factors and energy to be complements in production with setting $\epsilon = 0.35$, by decreasing ϵ, we increase the complementarity between traditional factors and energy. The value of ϵ affects the steady states and the transitional dynamics. Lower values of ϵ imply a higher initial steady state value for output and brown energy and a lower initial steady state value of productivity A and A_e. Moreover, the fact that energy becomes a stronger complement to traditional factors implies that firms have to move much more resources towards R&D when the news of permanent increases in brown energy prices arrives in order to

[7] Hassler et al. (2021) assume $\epsilon = 0.02$. Given the change in the steady state values that this calibration implies, for ease of comparison with our benchmark calibration, we do not show the results of this alternative calibration in Figure 5. The intuition behind the results for lower values of ϵ holds even for very low values of this parameter.

maintain production capacity. Although comparing is really hard given the changes in the steady states, the inflationary costs of the green transition in this economy are clearly lower. Firms' behavior complies with the intuition for the benchmark economy, they substitute for brown energy, increasing the efficiency of energy usage as in the previous case, and the consumption of brown energy is reduced. However, the higher complementarity between traditional factors and energy reduces the surge in a firm's marginal costs as the change in resources to R&D is more abrupt and dictates a faster reversal in production costs. Finally, we investigate how changes in the substitutability between green and brown energy in production affect the transitional dynamics (green crossed lines in the figure). Again changing ξ also alters the steady state values of green energy and prices. A lower value of ξ (here, we assume that $\xi = 0.1$) positively affects the trade-off between output losses and inflation along the green transition.

Overall our sensitivity analysis suggests that it is important to take into account the idiosyncrasies of every economy when designing possible green transitions, as supply and demand frictions are important for shaping the transitional dynamics.

5.3 The role of monetary policy

Figure 4 clearly illustrates that along the transition, monetary policy might face a tradeoff between inflation and output stabilization. Nowadays, the role of the monetary policy stance during the green transition is at the center of academic and policy debates. In Figure 6, we repeat the baseline exercise by changing the stance of monetary policy.

In the benchmark economy, we have assumed a Taylor coefficient for inflation of 1.5 we reduce now this value to 1.05 (dashed yellow lines in Figure 6) and increase it to 5 (red dashed-dotted lines in Figure 6). Olivier Blanchard has recently put forward the idea that central banks should raise the inflation target.[8] We also investigate how a change in the

[8]Financial Times, November 28, 2022

inflation target from 4 to 6 percent along the transition affects the transitional dynamics (purple dashed lines in Figure 6).

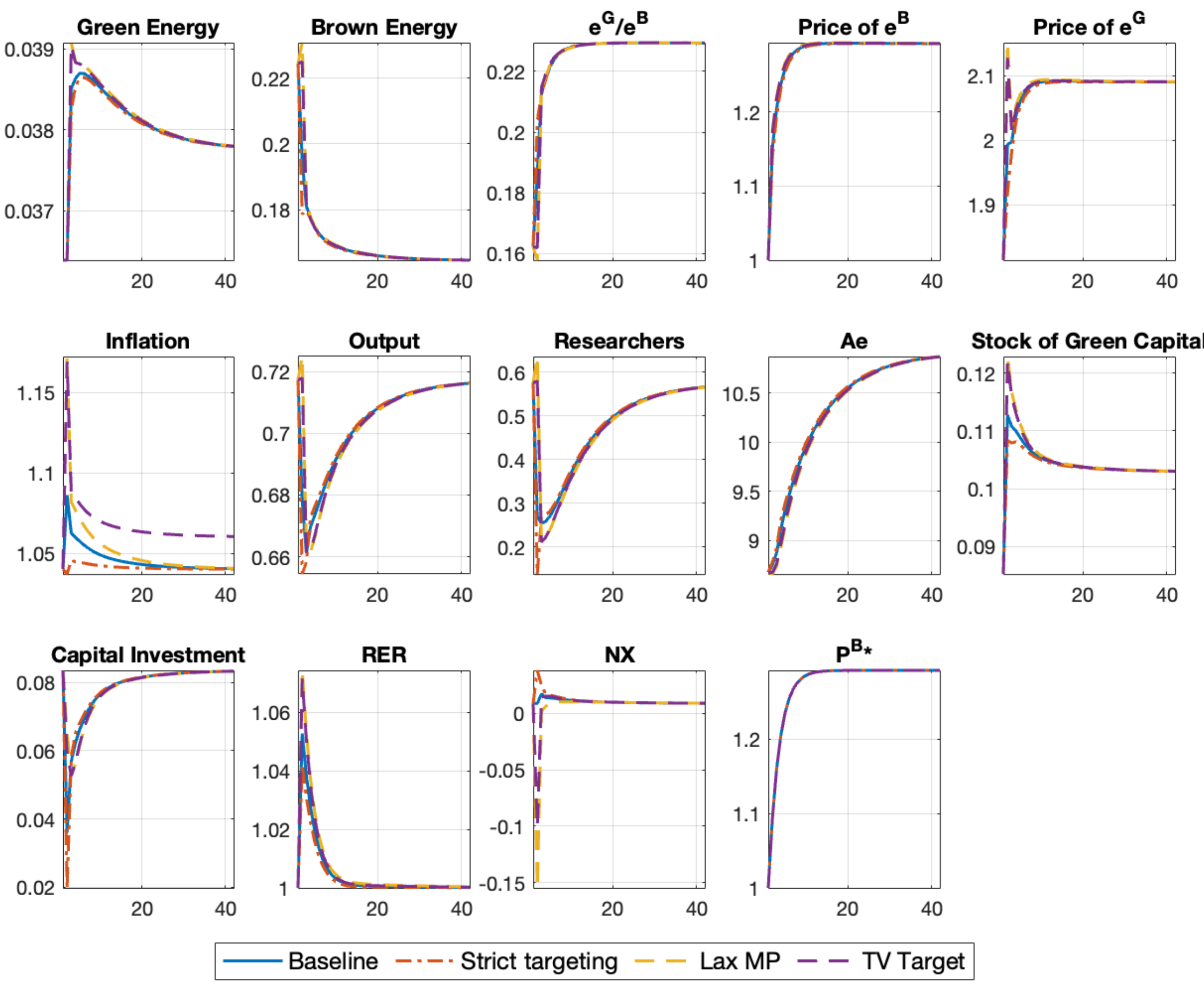

Figure 6: Transitional Dynamics: The role of monetary policy

Obviously, the monetary policy stance affects the transitional dynamics of inflation. That is, a stricter monetary policy stance shields the economy against inflation. However, this comes at a cost of higher short-run losses for output. Relative to standard NK models in our model economy, monetary policy also affects the incentives to accumulate green capital in the short run, and monetary policy choices seem to be crucial for determining the external balance along the green transition. Finally, a relaxation of the inflation target does not seem to bring gains in terms of output losses along the transition and contributes to further greenflation.

Hence, we would conclude that in our small open economy targeting inflation could be beneficial for moderating greenflation. On the other hand, a loose monetary policy stance would affect little real output losses bringing about further inflationary pressures. We will return to the evaluation of monetary policy options using welfare metrics in Section 6.

5.4 The role of fiscal policy

We now present how fiscal policy can affect the green transition. To grasp a better understanding of the effects of fiscal policy we investigate each fiscal instrument separately and induce policy changes that result in a new steady state with the same increase in the green-to-brown energy ratio as the one induced by changes in brown energy prices. Hence, in the exercises that follow, we keep the level of international brown energy prices fixed and change the fiscal instrument to induce a transition that resembles, in terms of the new steady-state ratio of green to brown energy, the transition that results from permanent changes in the international brown energy prices.[9]

5.4.1 Taxing the Brown Energy

In Figure 3, we have presented evidence pointing to substantial heterogeneity in the level of effective carbon taxes in emerging and developed economies. Since carbon taxes affect the price of brown energy one would expect that they should equally affect the green transition. The red dotted lines in Figure 7 present the transition of the economy when

[9]Notice that if we set the fiscal instruments so that in the new steady state we match the share of green to total energy use results are identical. As it is apparent in Figure 7, the changes in taxes, subsidies, and green public investment to achieve this alternative target are similar to the ones presented in the exercise where we match the relative usage of energy

brown taxes change from 10 in the initial steady state to 40 percent in the new steady state during a 60-year transition, while brown energy prices remain fixed at their initial level.

Naturally, when the taxation of brown energy increases, this translates into increases in the intermediate firms' marginal costs that tend to push up inflation. At the same time, increases in taxation should generate a negative wealth effect that decreases demand. On the supply side, firms try to move researchers in order to improve the efficiency of energy usage and substitute brown for green energy faster. This behavior decreases the demand for capital but increases the demand for green capital. Overall, domestic demand falls short of domestic supply, and in order for the international markets to clear, the real exchange rate depreciates, also raising the price of brown energy, accelerating further the transition. Yet, the policy has a substantial output and inflationary costs. Inflation increases along the transition in the short run from 4 to 7 percent while output falls persistently with a maximum fall of 5.3%.

5.4.2 Subsidies for Green Production

An alternative way to accelerate the green transition is through a subsidy for the production of green energy. We investigate such a transition by considering that subsidies increase along a 60-year transition from zero in the initial steady state to 70% in the new steady state. The transition is depicted in Figure 7 with yellow dashed lines.

The increase in subsidies generates very distinct transitional dynamics compared to the case of the increase in carbon taxes. First, the pace of the green transition resulting from increases in subsidies is much slower relative to the case of carbon taxes. Second, raising subsidies does not compel the firms to substitute brown for green energy, and little effort is placed into increasing the energy efficiency in production. Firms change very little the amount of researchers in efficient energy use R&D. Given that green investments are subsidized, the level of the green capital stock increases in the economy. However, the price of green energy increases since no significant advances occur in energy production, and the increase in subsidies simply drives up green energy prices by stimulating demand for green energy.

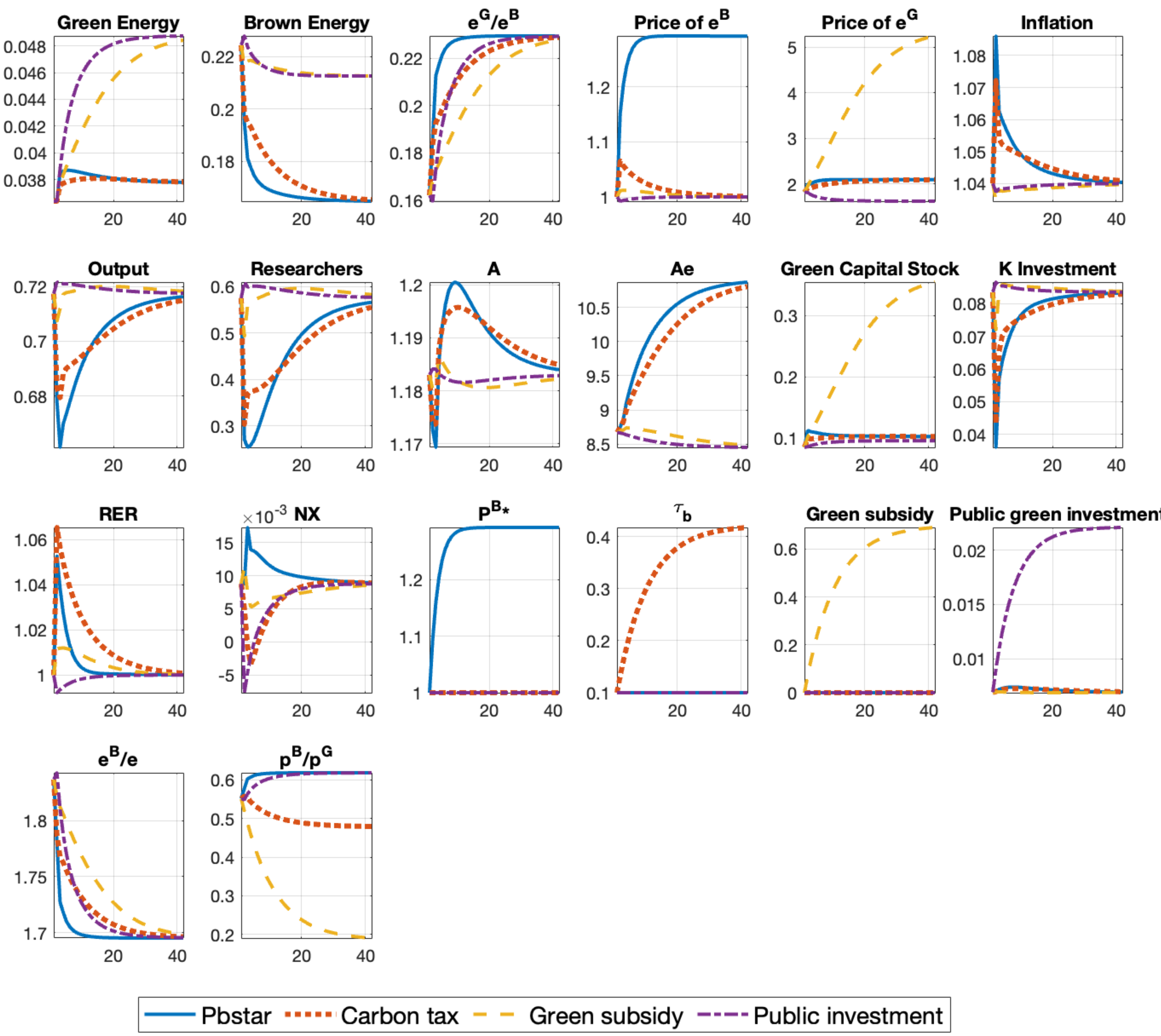

Figure 7: Transition using different fiscal instruments

On the other hand, since agents are Ricardian in the model, they realize that the increase in subsidies will drive up future taxation, and this generates a negative wealth effect that shrinks domestic demand, this results in a depreciation of the real exchange rate that increases brown energy prices. Yet, the domestic demand effect is strong enough that it balances inflationary pressures, and the transition with subsidies implies small output costs and no greenflation.

5.4.3 Public green investment

The German finance minister, Christian Lindner, recently announced the launching of 200 billion euros to fund industrial transformation between March 2022 and 2026, including climate protection, hydrogen technology, and expansion of the electric vehicle charging network. At the same time, Germany is planning to boost investment in renewables for energy production. The German government, thus, intends to accelerate the green transition through public investment infrastructure. In Figure 7, we plot with purple dashed-dotted lines a green transition in which public investment in green infrastructure increases by 220 percent from the initial to the new steady state to achieve a similar green-to-brown energy ratio in the new steady state as in the previous three cases.

The boost in green public investment stimulates green private investment, although it provides disincentives for firms to improve energy efficiency usage (as in the case of subsidies). Firms actually allocate resources to increase the productivity of traditional factors, as the price of green energy falls in the long run due to the increase in the productivity of green energy production from government intervention. Overall, public investment encourages the usage of green energy at a lower cost without crowding out the usage of brown energy sources substantially, affecting insignificantly output and inflation dynamics. Relative to subsidies, green public investment policies imply output gains as the increase in the productivity of the green sector induces a positive wealth effect and a reduction in firms' marginal costs. Moreover, such a policy can achieve the goals of the transition at a fast pace with no inflationary costs. Of course, the beneficial effects of green public investment depend crucially on the substitution between private and public green capital. In experiments we do not present here for the economy of space, we show that when private and public green capital are substitutes, the increase in public green investment crowds out private green investment, and the transition becomes more sluggish. However, for reasonable values of the elasticity of substitution, the transitional dynamics for inflation and output do not change substantially.

Several comments are in order after completing this exercise: First, transitions due to increases in energy prices and taxes on brown energy are the most painful ones in terms of inflation and output losses, but at the same time, increases in brown energy prices are the ones that achieve faster the desired transformation. Second, green public investment can effectively and timely bring about the green transition by reducing the price of green energy in the long run. Third, subsidies take longer to reach environmental objectives and disproportionately push the price of green energy and green capital stock. Forth, green public investment and subsidies increase more effectively green energy use but do not crowd out the usage of brown energy, and they do not lead to higher efficient energy use. Finally, when greenflation results, it is very difficult to be counteracted with subsidies or green investment, and inflation deviations persist for several years along the transition.

5.4.4 Public debt and spreads

Given that we are interested in analyzing small open economies that are often subject to sovereign debt crises, we analyze in Figure 8 how the public debt to GDP ratio and the spreads behave along the green transition when using the different fiscal instruments. The color codes for the different transitional dynamics are the same as in the previous graph.

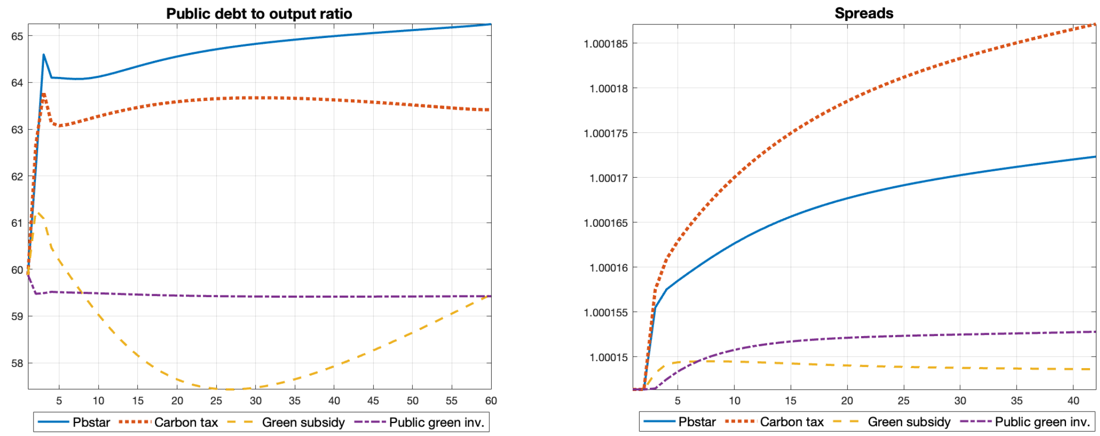

Figure 8: Fiscal burden and spreads along a transition

The left panel of figure 8 presents the debt-to-GDP dynamics when debt is allowed to change steady state value after the transition. The fiscal burden along the transition is relatively low, independent of the policy used. However, the debt-to-GDP ratio increases substantially when carbon taxes are used as the fiscal instrument to accelerate the transition. The simultaneous increase in the price of brown energy and carbon taxes increases fiscal revenues lowering debt, but on the other hand, the fall in GDP growth deteriorates output and decreases the denominator of the ratio. Although the other two policies imply increases in public spending and, hence, in public debt, their limited effects on output growth result in smaller increases in the debt-to-GDP ratio relative to the baseline case. Actually, both subsidies and public green investment tend to decrease the debt-to-GDP ratio in the medium run.

The behavior of spreads shows that the policy options have similar implications for external debt. Given the recessionary effects of carbon taxation, private debt increases more in the economy in transition with an increase in carbon taxes as international markets require higher sovereign spreads to borrow to domestic agents. Spreads increase less when the transition is accomplished through subsidies and public investment since, with these policies, output costs are small even when compared to the baseline scenario with no active fiscal policy (continuous blue line in Figure 8).

6 The welfare costs of the green transition

The analysis we have conducted so far reveals that the green transition will be painful as it will necessarily lead to increases in inflation and decelerate output growth for several periods. According to the last section, the role of fiscal policy in accelerating the transition is key, while the monetary policy does not seem adequate to smooth the transition as it faces a trade-off between correcting deviations of inflation and output. However, the adoption of different fiscal policy instruments entails different fiscal costs in terms of debt-to-GDP deviations and the evolution of spreads along the transition. Hence, it is very difficult to look at the inflationary, spread, and debt dynamics to conclude which policy option is the best for accomplishing the green transition. A natural measure to rank the different policy choices is to look at welfare. In this section, we calculate the welfare cost of the green transition under different transition scenarios. First, we recover the trend along the transitions using (13) and (14):

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

for a given initial condition X_0, common to all scenarios. Second, we recover the path of consumption in levels along the transition,

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

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

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

$$W_k = \sum_{t=1}^{\infty} \beta^t ln\left(c_{t,k} + \Lambda_k\right), \tag{15}$$

where k is the correspondent scenario: i) A 30% increase in brown energy prices, ii) an increase in carbon taxes from 10% to 42%, iii) an increase in green subsidies from 0% to 70%, iv) an increase in Green Public Infrastructure by 220%.

The value of Λ_k determines the welfare gains or losses with respect to the initial steady state. Positive values of Λ_k imply that consumers are worse off along the transition to the new steady state compared to the initial steady state, and negative values, instead, represent welfare improvements. The first column of Table 2 presents the Λ_ks for the different scenarios considered. The green transition is associated with welfare losses as we have not included any term in the utility function that could account for factors such as health or probability of survival that would have made the transition beneficial for the model economy. Anyhow, using fiscal policy to obtain the green transition is less harmful in terms of consumption, and the best fiscal instrument to obtain the green transition is clearly public infrastructure that actually delivers welfare gains, while the worst policy tool is carbon taxes. Of course, this result depends on the assumption we have adopted on the production of green energy, such as the substitutability between private and public green capital as well as the share of public green capital in total green energy production. In exercises we do not present here for the economy of space, we show that even when we assume that public and private green capital are complements or we assume a smaller share of the public sector in green production, it is still the case that investment in public infrastructure delivers the best welfare outcomes.

6.1 Negative Externality

Given that our analysis concerns a small open economy, we have considered that a possible externality from brown energy usage from the part of a small open economy should

Table 2: Welfare Comparisons

	No externality	**Externality** e^B	**Premium** $\frac{e^G}{e}$
Brown Energy price	0.079	0.206	-0.072
Carbon Tax	0.043	0.177	-0.107
Green Subsidy	0.026	0.273	-0.142
Public Infrastructure	-0.039	0.205	-0.209
Brown Energy price, ϕ_π**=5**	0.080	0.206	-0.071

be minimal with respect to the global economy and assumed that utility depends only on consumption in the previous section. In this section, we present an extension of the welfare calculations when we assume an externality derived from the utilization of brown energy in the production of domestic goods, e_t^B. Following Hassler et al. (2021), we assume there exists a damage function $D\left(e_t^B\right)$ that affects household consumption. The intuition for this externality is that the pollution generated by the utilization of brown energy as an input of production generates detrimental effects on households' health, and this is reflected, for simplicity, as a fall in consumption. The functional form for the damages function is given by:

$$D_t\left(e^B\right) = \tilde{\gamma}(e_t^B)^2.$$

The consumption net of the externality is given by:

$$\hat{c}_t = c_t - D\left(e_t^B\right).$$

Again, following Hassler et al. (2021), we calibrate $\tilde{\gamma}$ to get the total consumption loss due to the externality as a 20% loss of GDP in the initial steady state. This gives us a value of $\tilde{\gamma} = 2.8486$. The second column of Table 2 presents welfare calculations for this measure.

Assuming a negative externality from the utilization of brown energy in consumption significantly alters the welfare rankings of the different fiscal policy options. Now carbon taxes is the welfare-maximizing policy option for the green transition since when carbon taxes are in place, brown energy consumption is reduced considerably relative to the other two fiscal policy interventions. In fact, green subsidies have the highest negative impact on welfare since their adoption does not decelerate the consumption of brown energy. Of course, this heavily depends on the value of $\tilde{\gamma}$. In an exercise we do not present here for the economy of space, we show that if we calibrate $\tilde{\gamma}$ to get the total consumption loss due to the externality to 5% of GDP in the initial steady state, then public infrastructure remains the best policy alternative for attaining the green transition.

6.2 Sustainability premium

When choosing between two otherwise identical products some consumers are willing to pay a higher price for a product with a reduced environmental impact. The price premium paid is typically interpreted as an indication of demand for environmental quality. The Global Sustainability Study 2021 reveals significant global paradigm shifts in how consumers view sustainability.[10] The study was designed to measure consumer willingness to pay for sustainability. According to the study's results, the sustainability premium differs across countries. In the USA, for example, 42 percent of consumers would be willing to pay a premium of 37 percent on sustainable products, while in Italy, 38 percent of the consumers would be willing to pay, but the estimated premium they would accept is only 16 percent. On average, more than one-third (34 percent) of the population is willing to pay more for sustainable products or services, and those willing to pay more would accept a 25 percent premium on average. Li and Kallas (2021) using a meta-analysis study report a similar number. Inspired by this evidence, we now consider the sustainability premium in the welfare calculations. In particular, we assume that consumption, when

[10] The Global Sustainability Study 2021 survey was conducted in July 2021, fielding through panel data provided by Dynata, an independent market research agency. It was conducted by global strategy and pricing consultancy Simon-Kucher Partners. For more details, see: https://www.simon-kucher.com/sites/default/files/studies/Simon-Kucher$_Global_Sustainability_Study_2021.pdf$

incorporating this premium, is defined by:

$$\tilde{c}_t = c_t + \tilde{\gamma} \left(\frac{e_t^G}{e_t} \right) \tag{16}$$

Equation (16) captures the idea that consumers have concerns about sustainability that depend on the share of green energy in total energy usage. Hence, we now interpret parameter $\tilde{\gamma}$ as the sustainability premium that enters in the utility calculations of consumers in the economy. Using the previous references, we set $\tilde{\gamma} = 0.25$. The welfare comparisons for the different transitions appear in the last column of Table 2. The introduction of a positive externality from green energy usage in consumption renders the green transition beneficial under any scenario. All transitions imply welfare gains. All fiscal tools increase welfare relative to the case in which brown energy increases induce the transition, and again investment in public infrastructure outperforms the other fiscal measures as the best tool for inducing the green transformation.

Finally, in the last row of Table 2, we also present calculations of welfare when monetary policy reacts more strongly to inflation deviations along a transition induced by changes in energy prices. In the case of no externality and a positive premium on green energy usage, fighting inflation is actually costly for welfare and consumers are slightly better off in an economy where the central bank is not aggressive in fighting inflation.

7 Conclusions

We study the transitional dynamics of green transformation and how it interacts with fiscal and monetary policy in emerging markets. To move to a greener economy, we have alternative ways or a combination of them. Increases in brown energy prices and taxes decrease the usage of brown energy but do not expand the green sector, they simply improve energy efficiency use, leading to surges in inflation and output losses. Green subsidies increase the most the stock of green capital but imply a slower transition with no output and inflation costs, but higher prices for green energy. Green public investment does not enhance the stock of green capital substantially but does increase green energy usage and results in decreases in green energy prices in the long run. Monetary policy can play a role in shaping greenflation in the short-run, but at the cost of possible output and welfare losses. The specific characteristics of the economy and supply or demand frictions should be taken into account when designing transitional policies as they imply different transitional dynamics and wrong choices can be very costly. Finally, we have tried to provide the reader with different welfare metrics for assessing the various alternatives. If the goal is to reduce brown energy usage globally the appropriate instrument is carbon taxation and the costs to pay are greenflation and short-term output losses. If instead we assume no externality from brown energy usage or consider consumption gains from using relatively more green energy, then green public capital investments provide a transition with no inflation, more green energy usage, and little output and fiscal costs.

In a nutshell, our analysis suggests that there is no easy way towards the green metamorphosis of a small open economy and one has to decide which sacrifice to make for securing a greener planet.

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8 Online Appendix

8.1 Equilibrium equations

8.1.1 Household

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

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

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

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

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

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

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

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

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

8.1.2 Intermediate goods producers

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

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

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

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

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

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

$$\pi_{H,t} \left(\pi_{H,t} - \bar{\pi}_H \right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1} \left(\pi_{H,t+1} - \bar{\pi}_H \right) \frac{a_{H,t+1}}{a_{H,t}} \right] + \frac{\varepsilon_t}{\kappa_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_t - 1}{\varepsilon_t} \right)$$

$$\left(A_t k_t^{\alpha} \bar{h}^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} \frac{A_{t-1}}{A_t} B \phi n_t^{\phi-1} = e^{\frac{\epsilon-1}{\epsilon}} \frac{A_{t-1}^e}{A_t^e} B_e \phi \left(1 - n_t \right)^{\phi-1}$$

8.1.3 Green energy producer

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

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

8.1.4 Brown energy sector

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

8.1.5 Government

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

$$\tau_t + \tau^e e_t^b + b_t = s p_t^G e_t^G + \frac{b_t}{\pi_t} R_{t-1} + i_t^{pub}$$

$$\tau_t - \tau^* = \phi_\tau \left(b_t - \bar{b} \right) + \sigma^\tau \epsilon_t^\tau$$

$$i_t^{pub} = \bar{I^P}$$

8.1.6 Definitions

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

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

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

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

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

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

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

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

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

AR(1) processes for: p_t^{B*}, μ_t^s, π_t^*, y_t^*, Ω_t, $e_t^{B,d}$.

8.2 Stationarized equilibrium equations

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

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

In this section we present the stationarized equilibrium equations.

8.3 Equilibrium equations

8.3.1 Household

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

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

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

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

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

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

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

$$p_{H,t}\tilde{y}_{H,t} = \tilde{c}_t + \tilde{i}_t + \tilde{i}_t^G + \tilde{i}_t^{pub} + \frac{\kappa_P}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t}\tilde{y}_{H,t} + n\tilde{x}_t + \tilde{p}_t^B e_t^{B,*}$$

8.3.2 Intermediate goods producers

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

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

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

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

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

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

$$\pi_{H,t} \left(\pi_{H,t} - \bar{\pi}_H\right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1} \left(\pi_{H,t+1} - \bar{\pi}_H\right) \frac{a_{H,t+1}}{a_{H,t}}\right] + \frac{\varepsilon_t}{\kappa_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_t - 1}{\varepsilon_t}\right)$$

$$\left(\tilde{A}_t \tilde{k}^{\alpha}_t h^{1-\alpha}\right)^{\frac{\epsilon-1}{\epsilon}} \frac{\tilde{A}_{t-1}}{\tilde{A}_t} g^{\alpha-1}_{t-1} B \phi n^{\phi-1}_t = \tilde{e}^{\frac{\epsilon-1}{\epsilon}} \frac{\tilde{A}^e_{t-1}}{\tilde{A}^e_t} g^{\mu-1}_{t-1} B_e \phi \left(1-n_t\right)^{\phi-1}$$

8.3.3 Green energy producer

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

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

8.3.4 Brown energy sector

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

8.3.5 Government

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

$$\tilde{\tau}_t + \tau^e \tilde{e}^b_t + \tilde{b}_t g_t = s \tilde{p}^G_t \tilde{e}^G_t + \frac{\tilde{b}_t}{\pi_t} R_{t-1} + \tilde{i}^{pub}_t$$

$$\tau_t - \tau^* = \phi_\tau \left(b_t - \bar{b}\right) + \sigma^\tau \epsilon^\tau_t$$

8.3.6 Definitions

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

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

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

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

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

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

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

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

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

AR(1) processes for: p^{B*}_t, μ^s_t, π^*_t, y^*_t, Ω_t, $e^{B,d}_t$, and we set $\tilde{i}^{pub}_t = 0$.