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Abstract

We use an endogenous growth model calibrated to the Spanish economy to evaluate the effects of a rapid doubling of international prices of brown energy inputs. In the baseline calibration of the model, which resembles the current state of the Spanish economy, this results in a 0.30% drop in GDP on impact. After increasing the share of renewables in the energy mix from 26% to 85%, in line with the 2050 targets for the Spanish economy, the same shock results in a 0.24% fall in GDP on impact, and the recovery is faster: the present discounted value of the full GDP response is reduced by 65%. The three main conclusions that we draw from this exercise are: i) an increase in the share of renewables makes the economy less vulnerable to shocks in international prices of brown energy inputs; ii) this vulnerability reduction is less than proportional: dividing the share of brown energy by approximately five only reduceds the size of the effects on GDP by between 21% and 65%; and iii) the main statistic that determines how much the vulnerability is reduced is not the share of brown energy inputs, but the degree to which final energy prices respond to the shock to brown energy prices.

Keywords: energy prices, green transition, external shocks, carbon tax.

JEL classification: O38, O52, O44, E32.

Resumen

Utilizamos un modelo de crecimiento endógeno calibrado a la medida de la economía española para evaluar los efectos de una rápida duplicación del precio internacional de los insumos de energía marrón. En la calibración de referencia del modelo, que se asemeja al estado actual de la economía española, esto se traduce en una caída del 0,30 % del PIB. Tras el aumento del porcentaje de energías renovables en el mix energético del 26 % al 85 %, de acuerdo con los objetivos de la economía española para 2050, la misma perturbación provoca una caída del PIB del 0,24 %, y la recuperación es más rápida: el valor actualizado de la respuesta total del PIB se reduce en un 65 %. Las tres conclusiones principales que extraemos de este ejercicio son las siguientes: i) un aumento de la cuota de renovables hace que la economía sea menos vulnerable a las perturbaciones externas en el precio internacional de los insumos de energía marrón; ii) esta reducción de la vulnerabilidad es menos que proporcional: dividir la cuota de energía marrón por aproximadamente cinco solo reduce entre un 21 % y un 65 % la magnitud de los efectos sobre el PIB, y iii) la principal estadística que determina cuánto se reduce la vulnerabilidad no es la cuota de insumos de energía marrón, sino el grado en el que los precios finales de la energía responden a la sacudida de los precios de la energía marrón.

Palabras clave: precios de la energía, transición verde, perturbaciones externas, impuesto sobre el carbono.

Códigos JEL: O38, O52, O44, E32.

1 Introduction

First and foremost, the green transition should be aimed at preventing the most negative climate change scenarios, minimizing physical risks in the long run while balancing them versus short-term transition risks. But even for people not convinced by the benefits of mitigating physical risks, an argument can be made that reducing the dependence on brown energy inputs can reduce the vulnerability of an economy to external shocks. In this paper, we look at the Spanish economy and analyze how the current targets for renewable energy production in 2050 can reduce the negative effects of a shock to brown energy prices.

In particular, we use an endogenous growth model to evaluate the effects of a shock to the international price of brown energy inputs, under a calibration that resembles the current situation in Spain, and also in a version of that same economy where the transition to a green economy is solidly underway.

Our simulated shock is a fast doubling of the international price of brown energy inputs. In the baseline calibration, with which the model resembles the current state of the Spanish economy, this results in a 0.30% drop in GDP on impact. The alternative calibration matches the 2050 targets for the Spanish economy: the situation before the shock happens is now one where renewables represent 85% of the energy mix, instead of the current 26%. In this version of the model, the same shock results in a 0.24% fall in GDP on impact, and the recovery of the economy is faster.

The three main conclusions that we draw from this exercise are:

- The planned increase in the share of renewables should make the economy less vulnerable to shocks in the international price of brown energy inputs.
- This vulnerability reduction is less-than-proportional: dividing the share of brown energy by approximately five only halved the simulated effect on GDP.
- The main statistic that determines how much the vulnerability is reduced is not the share of brown energy inputs, but the degree to which final energy prices respond to the shock to brown energy input prices.

The remainder of the paper is structured as follows. We set our results in relation to the existing literature in section 2. We describe the model in section 3 and present our calibration strategy in section 4. We present the results of the simulation exercises in section 5 . Finally, section 6 concludes.

2 Related Literature

The main contribution of this paper is to study how the green transition can reduce the vulnerability of the economy to external shocks. In doing so, it contributes and bridges two strands of the literature.

First, we contribute to the literature exploring the macroeconomic effects of policies that induce a green transition. At the general level, this literature has mainly focused on the long-run and transition benefits and costs of implementing these policies. We, instead, focus on the potential benefits at the business-cycle frequency that a green transition could bring. For example, Golosov et al. (2014) studies optimal carbon taxes in an economy where fossil fuel is a scarce resource, and Acemoglu et al. (2012) explore optimal policy in an endogenous growth model with environmental constraints. The model that we present features endogenous too, but instead of deriving what the optimal policy is we take the target energy mix as given (European Council, 2020), and focus on the transmission of external shocks once the transition has been achieved. A number of recent papers have incorporated climate-related features in models incorporating nominal rigidities. For example, Airaudo et al. (2023) study the consequences of different climate policies for output and inflation along the transition path in a small open economy calibrated to Chile. Nakov and Thomas (2023) extend the framework of Golosov et al. (2014) with sticky prices and derive the optimal monetary policy response to energy transition and Del Negro et al. (2023) focus on the inflationary consequences of climate policies in a multi-sector New Keynesian model. We share with these papers the interest on the short-run consequences of climate policies and energy transition, but we focus on the real effects through reduced external vulnerability rather than on their inflationary consequences.

Second, we contribute to the literature assessing the macroeconomic consequences of fluctuations in energy prices. The current paper complements this literature by offering a new perspective on how an energy transition could shape the effects of these shocks. Bachmann et al. (2022) study the macroeconomic consequences for Germany of a cut-off from Russian energy imports. Pieroni (2023) focuses on the distributional consequences of energy prices in heterogeneous agents model with nominal rigidities. Auclert et al. (2023) study the propagation of energy price increases and the role played by monetary policy in open economies with household heterogeneity, while Bayer et al. (2023) focuses on the fiscal response to the energy crisis through energy subsidies and transfers to households. Closer to us, Blanchard and Gali (2007) explore the determinants over time of the effects of oil shocks, focusing on the role played by labor markets, monetary policy, and the share of oil in production. We instead highlight the importance of the decoupling of green and brown energy prices once the green transition has been completed.

3 Model

We consider and extend the endogenous growth model of Atkeson and Burstein (2019), also used in Domínguez-Díaz et al. (2024). The framework is a real model of a closed economy, with the exception of imported dirty energy. Firms use labor, capital, and an energy good to produce. The energy good itself is a mix of imported energy and domestically produced clean energy. Furthermore, we allow firms to engage in innovative investment to improve the efficiency with which they use energy goods and non-energy inputs (Aghion and Howitt, 1992; Romer, 1990). We describe next the main ingredients of the model and problems faced by the different agents in the economy, and relegate to Appendix A a detailed description of the first-order conditions.

3.1 Households

The economy is populated by an infinitely lived representative household with time-separable preferences over per capita consumption C_t/H_t and hours worked:

$$\max_{C_t,K_{t+1},B_{t+1},L_t^p,L_{x,t}^r,L_{e,t}^r} \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t H_t \left(\log\left(\frac{C_t}{H_t}\right) - \kappa \frac{\left(\frac{L_{x,t}^r + L_{r,e}^r + L_t^p}{H_t}\right)^{1+\varphi}}{1+\varphi} \right) \quad \text{s.t.} \tag{1}$$

$$C_t + I_t + B_{t+1} = W_t^p L_t^p + W_{x,t}^r L_{x,t}^r + W_{e,t}^r L_{e,t}^r + r_t^k K_t + (1 + R_{t-1}) B_t \tag{2}$$
$$+ D_t - \Xi^L(L_t^p, L_{x,t}^r, L_{e,t}^r, L_{t-1}^p, L_{x,t-1}^r, L_{e,t-1}^r),$$

$$K_{t+1} = (1-\delta_K)K_t + I_t - \Xi^I(I_t, K_t), \tag{3}$$

where $\beta \in (0,1)$ and H_t denotes population, which grows at an exogenous rate g_H. The household can save in physical capital K_t , which rents to firms at rental rate r_t^k , and in government bonds B_t, with risk-free return R_t. Additionally, the household derives labor income from supplying production working hours L_t^p, paid at wage rate W_t^p, and research working hours in energy and non-energy research goods, $L_{e,t}^r$ and $L_{x,t}^r$, with wage rates $W_{e,t}^r$ and $W_{x,t}^r$. We assume that labor is subject to adjustment costs $\Xi^L(L_t^p, L_{x,t}^r, L_{e,t}^r, L_{t-1}^p, L_{x,t-1}^r, L_{e,t-1}^r)$. Finally, economy-wide firms' profits D_t are rebated lump-sum to the household.

The capital accumulation equation is given by (3), where δ_K marks the depreciation rate of private physical capital, $\Xi^I(I_t, K_t)$ denotes capital adjustment costs, and I_t denotes household's investment.

3.2 Production Sector

The supply side of the economy consists of multiple layers of production. A final good producer combines energy and non-energy inputs to produce a final good that can be used for consumption and investment. The energy and non-energy inputs are themselves bundles of intermediate energy and non-energy goods. Intermediate non-energy goods are produced by combining physical capital and production labor. The energy intermediate good producers combine dirty energy inputs, imported from abroad, and clean energy inputs, produced domestically. Both types of intermediate good producers engage in innovative investment. Finally, there are a energy research good producer and a non-energy research good producer that use research labor as factor input.

3.2.1 Final Good Producer

A competitive final good producer combines a bundle of differentiated energy and non-energy intermediate goods, denoted by $Y_{X,t}$ and $Y_{E,t}$ respectively, using a constant elasticity of substitution (CES) production function to produce a final good Y_t:

$$\max_{Y_{X,t},Y_{E,t}} \quad Y_t - P_{X,t}Y_{X,t} - P_{E,t}Y_{E,t} \quad \text{s.t.} \quad Y_t = \left[\theta^{\frac{1}{\sigma}} Y_{X,t}^{\frac{\sigma-1}{\sigma}} + (1-\theta)^{\frac{1}{\sigma}} Y_{E,t}^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{4}$$

with $\sigma > 0$. Above, $P_{X,t}$ and $P_{E,t}$ denote the price indexes of the non-energy and energy bundles. $Y_{X,t}$ and $Y_{E,t}$ are bundles of intermediate non-energy, $y_{x,t}(z_x)$, and energy, $y_{e,t}(z_e)$, goods given by:

$$Y_{X,t} = \left[\sum_{z_x} M_{x,t}(z_x) y_{x,t}(z_x)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}}, \tag{5}$$

$$Y_{E,t} = \left[\sum_{z_e} M_{e,t}(z_e) y_{e,t}(z_e)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}}, \tag{6}$$

with $\rho > 1$. Above, $y_{x,t}(z_x)$ denotes the output of a non-energy intermediate producer with productivity index z_x, which has a price $p_{x,t}(z_x)$. $M_{x,t}(z_x)$ denotes the mass of non-energy intermediate goods with productivity index z_x at time t. The variables of the energy intermediate goods, with price $p_{e,t}(z_e)$, are defined analogously.

3.2.2 Non-energy Intermediate Good Producers

Non-energy intermediate good producers produce differentiated goods y_x using production labor l^p and physical capital k. We summarize the technology that is used in the production of an intermediate good at time t by its productivity index z_x:

$$y_{x,t}(z_x) = z_x k_t(z_x)^{\alpha} l_t^p(z_x)^{1-\alpha}, \tag{7}$$

with $\alpha \in (0,1)$. As in Atkeson and Burstein (2019), we assume that z_x has a countable support with grid elements $z_{x,n}$, and refer to the highest element in the grid for each intermediate good as the frontier technology for that good. Since capital and labor are flexible at the firm level, the optimal allocation of production inputs maximizes per-period firms' variable profits, defined as:

$$\pi_{x,t}(z_x) \equiv p_{x,t}(z_x)y_{x,t}(z_x) - W_t^p l_t^p(z_x) - r_t^k k_t(z_x). \tag{8}$$

Non-energy intermediate good producers can engage in innovative investment, which requires the purchase of a research good. Innovative investment results in the creation of a new product in the economy, as in Romer (1990), or in efficiency improvements of already existing products. As we show later, this leads to changes in aggregate productivity.

We allow both incumbent firms, those that produce at time t and were also producing at time $t-1$, and new entrants (that did not produce at time $t-1$) to invest in innovation. Innovative investment by entrants can only lead to the creation of products that are new to society.[1] Incumbent firms, additionally, can also improve the efficiency of the products that they already own. Furthermore, we assume that an exogenous fraction δ_0 of goods produced by incumbent firms exits the market each period. We describe the innovation process of incumbents and entering firms next.

Innovative investment by entering firms We denote by $M^n_{x,t+1}$ the measure of non-energy intermediate good enters that invest in innovation at time t. Each of these firms obtains at $t+1$ a frontier technology to produce a new intermediate good with productivity index z'_x. As in Atkeson and Burstein (2019), and similar to Luttmer (2007), we assume that z'_x is drawn from a distribution such that $\mathbb{E}_t z'^{\rho-1}_x = \eta_{n,x} Z^{\rho-1}_{x,t}/M_{x,t}$, where $Z_{x,t}$ denotes aggregate productivity of non-energy intermediate good produces and $M_{x,t}$ marks the total measure of non-energy products available. More precisely, these are defined as:

$$Z_{x,t} = \left(\sum_{z_x} z_x^{\rho-1} M_{x,t}(z_x) \right)^{\frac{1}{\rho-1}} \tag{9}$$

$$M_{x,t} = \sum_{z_x} M_{x,t}(z_x). \tag{10}$$

[1]The model could also be also easily adapted to include business stealing as is standard in quality ladder models (Klette and Kortum, 2004). See, for example, Atkeson and Burstein (2019).

Finally, we assume that an entering firm has to purchase $1/M_{x,t}$ units of the research good at time t to create a new firm with one product at time $t+1$. We denote by $x^n_{x,t}$ the total amount of research goods purchased by M^n_{t+1} entering firms at time t. Note that this implies that $x^n_{x,t} = M^n_{x,t+1}/M_{x,t}$.

Denoting by $V_{x,t}(z_x)$ the value of a non-energy intermediate-good firm with productivity index z_x at time t, the free-entry condition is given by:

$$\frac{1}{M_{x,t}} P^r_{x,t} = \mathbb{E}_t \frac{1}{1+R_t} V_{x,t+1}(z'_x), \tag{11}$$

where $P^r_{x,t}$ marks the price of the research good at time t. The left-hand side in (11) is the marginal cost of investing one additional unit in innovation $x^n_{x,t}(z_x)$, since this has a cost $P^r_{x,t} M^{-1}_{x,t}$ for an entering firm. The right-hand side is the expected discounted value of obtaining a product with productivity z'_x at time $t+1$ as a result of that innovative investment decision.

Innovative investment by incumbent firms. Incumbent non-energy firms can purchase research goods to create products that are new to society, as entering firms, or to improve the efficiency of the products that they already own.

First, consider the former case. An incumbent firm has the opportunity to invest $x^m_{x,t}(z_x)$ units of the research good at time t to create a new product at time $t+1$ with probability $h\left(x^m_{x,t}(z_x)/s_{x,t}(z_x)\right)$, where $s_{x,t}(z_x)$ is given by:

$$s_{x,t}(z_x) \equiv \left(\frac{z_x}{Z_{x,t}}\right)^{\rho-1}. \tag{12}$$

Similar to the case of entering firms, we assume that the productivity index of the new product created by non-energy incumbent firms is drawn from a distribution such that $\mathbb{E} z'^{\rho-1}_x = \eta_{x,m} z^{\rho-1}_x$. Similarly, the aggregate quantity of research goods purchased by incumbent firms to create new products is given by $x^m_{x,t} = \sum_{z_x} M_{x,t}(z_x) x^m_{x,t}(z_x)$.

Second, consider the case of a non-energy incumbent firm that wishes to improve the productivity of a product with productivity index z_x that it already produces. Such firm purchases $x^c_{x,t}(z_x)$ units of the research good at time t and draws a new productivity index z'_x for its existing product – conditional on not exiting the market – from a distribution such that $\mathbb{E}z'^{\rho-1}_x = \zeta_x\left(x^c_{x,t}(z_x)/s_{x,t}(z_x)\right)z^{\rho-1}_x$. In a similar fashion to the previous cases, we define the aggregate quantity of this class of innovative investment $x^c_{x,t} = \sum_{z_x} M_{x,t}(z_x)x^c_{x,t}(z_x)$.

Under the previous assumptions, we can write the intertemporal problem of an incumbent firm with productivity index z_x as:

$$V_{x,t}(z_x) = \max_{x^c_{x,t}(z_x),x^m_{x,t}(z_x)} (1-\tau^{\text{Corp}}_t)\pi_{x,t}(z_x) - P^r_{x,t}\left(x^m_{x,t}(z_x) + x^c_{x,t}(z_x)\right) + \mathbb{E}_t\frac{1}{1+R_t}V_{x,t+1}(z'_x), \tag{13}$$

where $\pi_{x,t}(z_x)$ are per period variable profits of non-energy producers as defined in (8) and τ^{Corp}_t is a corporate tax rate.

3.2.3 Energy Intermediate Good Producers

In order to produce, an energy intermediate producer with productivity index z_e combines imported energy goods, $\mathcal{D}_t(z_e)$, and clean energy goods $\mathcal{C}_t(z_e)$ according to the following CES production function:

$$y_{e,t}(z_e) = z_e\left[\theta_e^{\frac{1}{\sigma_e}}\mathcal{D}_t(z_e)^{\frac{\sigma_e-1}{\sigma_e}} + (1-\theta_e)^{\frac{1}{\sigma_e}}\mathcal{C}_t(z_e)^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}}, \tag{14}$$

with $\sigma_e > 0$.

Energy intermediate producers purchase clean inputs at price $P_{\mathcal{C},t}$. The price paid by firms for dirty energy inputs has two components. First, there is an international price of dirty inputs, $P^*_{\mathcal{D},t}$. This price is exogenous from the perspective of the domestic economy, which we later model as following an $AR(1)$ process in logs. Second, we let the domestic government impose a per-unit carbon tax on dirty energy imports, denoted by $\tau^{\mathcal{D}}_t$. Hence, the post-tax price paid by domestic firms on dirty energy imports, $P_{\mathcal{D},t}$, is given by:

$$P_{\mathcal{D},t} = P^*_{\mathcal{D},t} + \tau^{\mathcal{D}}_t \tag{15}$$

Per-period firms' variable profits are given by:

$$\pi_{e,t}(z_e) \equiv p_{e,t}(z_e)y_{e,t}(z_e) - P_{\mathcal{C},t}\mathcal{C}_t(z_e) - P_{\mathcal{D},t}\mathcal{D}_t(z_e). \tag{16}$$

Similarly to the case of non-energy intermediate producers, we let energy good producers engage in innovative investment. Products exit the market at the same exogenous rate, δ_0. In this case, for simplicity, we consider only innovation by new entrants, which is modelled in an analogous manner to the innovation of entering non-energy producers.

More precisely, we denote by $M^n_{e,t+1}$ the measure of energy intermediate good enters that invest in innovation at time t. These firms draw a productivity z'_e from a distribution such that $\mathbb{E}_t z'^{\rho-1}_e = \eta_{n,e} Z^{\rho-1}_{e,t}/M_{e,t}$. The aggregate productivity of energy goods, $Z_{e,t}$, and the total measure of energy products available, $M_{e,t}$, are defined as:

$$Z_{e,t} = \left(\sum_{z_e} z_e^{\rho-1} M_{e,t}(z_e) \right)^{\frac{1}{\rho-1}} \tag{17}$$

$$M_{e,t} = \sum_{z_e} M_{e,t}(z_e). \tag{18}$$

An entering energy good producer has to purchase $1/M_{e,t}$ units of an energy research good at time t to create a new firm with one product at time $t+1$. Denoting by $x^n_{e,t}$ the total amount of research goods purchased by $M^n_{e,t+1}$ entering firms at time t, we have that $x^n_{e,t} = M^n_{e,t+1}/M_{e,t}$.

Denoting by $V_{x,t}(z_x)$ the value of an intermediate-good firm with productivity index z_x at time t, The free-entry condition for energy intermediate good producers is given by:

$$\frac{1}{M_{e,t}} P^r_{e,t} = \mathbb{E}_t \frac{1}{1+R_t} V_{e,t+1}(z'_e), \tag{19}$$

where $P^r_{e,t}$ is the price of the energy research good, and $V_{e,t+1}(z_e)$ the value of a energy intermediate-good firm with productivity index z_e at time $t+1$, given by:

$$V_{e,t}(z_e) = (1 - \tau^{\text{Corp}}_t) \pi_{e,t}(z_e) + \mathbb{E}_t \frac{1}{1+R_t} V_{e,t+1}(z'_e), \tag{20}$$

3.2.4 Clean energy production

Clean energy is produced domestically, contrary to dirty energy which is imported from abroad. We assume that clean energy is produced using only physical capital, according to:

$$\mathcal{C}_t = \left(K_t^{\mathcal{C}}\right)^{\alpha_e}, \tag{21}$$

with $\alpha_e \in (0,1)$.

We assume that the capital used in the production of clean energy is directly decided by the government. Therefore, one could think of $K_t^{\mathcal{C}}$ as a fixed factor of production (e.g., land), whose use is limited by the number of permits issued by the government. In section 5 we discuss the realism and adequacy of this assumption in relation to the purpose of the simulations presented in this article.

3.2.5 Research Good Producers

Non-energy research good. A representative producer of non-energy research goods hires research labor $L_{x,t}^r$ to produce the research good used in the innovation process of non-energy intermediates according to:

$$Y_{x,t}^r = A_{x,t}^r Z_{x,t}^{\phi-1} L_{x,t}^r. \tag{22}$$

Above, $A_{x,t}^r$ can be interpreted as a stock of freely available scientific progress, which we assume to grow at an exogenous rate $g_{A_{r,x}}$. The term $Z_{x,t}^{\phi-1}$, with $\phi \leq 1$, follows Jones (2002). It represents intertemporal knowledge spillovers. Namely, since $\phi \leq 1$, increases in aggregate productivity of non-energy goods $Z_{x,t}$ reduce the efficiency of research labor, capturing the notion outlined in Bloom et al. (2020) that "ideas are getting harder to find".

The research good is sold at price $P_{x,t}^r$ to non-energy intermediate good producers engaging in innovative investment, such that the research good producer solves the following problem:

$$\max_{L_{x,t}^r} \quad P_{x,t}^r Y_{x,t}^r - W_{x,t}^r L_{x,t}^r \quad \text{s.t.} \quad Y_{x,t}^r = A_{x,t}^r Z_{x,t}^{\phi-1} L_{x,t}^r \tag{23}$$

Energy research good. The energy research good is produced analogously to the non-energy research good. Namely, the production function of the energy research good is given by:

$$Y^r_{e,t} = A^r_{e,t} Z^{\phi-1}_{e,t} L^r_{e,t}, \tag{24}$$

where $L^r_{e,t}$ is research labor hired by the representative energy research good producer. As before, we allow for intertemporal knowledge spillovers, with $\phi \leq 1$.

The price of the research good, purchased by energy intermediate good producers, is $P^r_{e,t}$, leading to the following maximization problem:

$$\max_{L^r_{e,t}} \quad P^r_{e,t} Y^r_{e,t} - W^r_{e,t} L^r_{e,t} \quad \text{s.t.} \quad Y^r_{e,t} = A^r_{e,t} Z^{\phi-1}_{e,t} L^r_{e,t} \tag{25}$$

3.3 Government

The government consists of a fiscal authority. The government raises revenue from corporate taxes, carbon taxes on imported dirty energy, and lump-sum taxes levied on households. It uses the revenue and government debt B_{t+1} to finance interest payments on public debt and expenditures, which consist of clean energy capital investment $I^{\mathcal{C}}_t$. Therefore, the budget constraint of the government is given by:

$$I^{\mathcal{C}}_t + B_t(1 + R_{t-1}) = B_{t+1} + \tau^{\text{Corp}}_t \left(\sum_{z_x} M_t(z_x)\pi_t(z_x) \sum_{z_e} M_t(z_e)\pi_t(z_e) \right) + \tau^{\mathcal{D}}_t \mathcal{D}_t + T_t,$$

$$\text{with} \quad I^{\mathcal{C}}_t = K^{\mathcal{C}}_{t+1} - (1 - \delta^{\mathcal{C}}) K^{\mathcal{C}}_t,$$

where $\delta^{\mathcal{C}}$ marks the depreciation rate of clean energy capital.

3.4 Equilibrium, Market Clearing, and Productivity Dynamics

A *competitive equilibrium* is a sequence of consumption and hours $\{C_t, L^r_{e,t}, L^r_{x,t}, L^p_t\}_t$, private and innovative investment $\{I_t, x^n_{x,t}, x^m_{x,t}, x^c_{x,t}, x^n_{e,t}\}_t$, such that given prices and a sequence for clean capital $\{K^{\mathcal{C}}_t\}_t$ and for the international price of dirty energy inputs and the carbon tax $\{P^*_{\mathcal{D},t}, \tau_{\mathcal{D},t}\}$ such that households and firms optimize and markets clear:

1. The labor market clears if $L^p_t = \sum_{z_x} M_t(z_x) l^p_t(z_x)$ and the amount of research hours supplied by the household equals the research hours demanded by the research good producers.

2. The capital market clears if $K_t = \sum_{z_x} M_t(z_x) k_t(z_x)$

3. The market for research goods clears if the innovative investment by entering firms and incumbent firms equal the production of the research good:

$$Y^r_{x,t} = x^n_{x,t} + x^m_{x,t} + x^c_{x,t} \tag{26}$$

$$Y^r_{e,t} = x^n_{e,t} \tag{27}$$

4. The final good is used for consumption, investment in physical capital of non-energy goods, investment in clean energy capital, and as to pay for purchases of imported dirty energy goods:

$$C_t + I_t + I_t^{\mathcal{C}_t} = Y_t - P^*_{\mathcal{D},t}\mathcal{D}_t \tag{28}$$

Similarly, we define a *Balanced Growth Path* (BGP) as a competitive equilibrium where all variables grow at constant rates. In appendix A.3 we provide a detailed description of detrended variables and associated equilibrium conditions in terms of stationary variables.

3.5 Aggregation and Productivity Dynamics

Under the assumptions made on the innovation process of firms together with constant markups, aggregate output of non-energy goods can be written as:

$$Y_{x,t} = Z_{x,t}\left(K_t\right)^{\alpha}\left(L^p_t\right)^{1-\alpha}, \tag{29}$$

where aggregate productivity $Z_{x,t}$ is defined in (9).

Similarly, for the aggregate production of energy goods, we have that:

$$Y_{e,t} = Z_{e,t}\left[\theta_e^{\frac{1}{\sigma_e}}\mathcal{D}_t^{\frac{\sigma_e-1}{\sigma_e}} + (1-\theta_e)^{\frac{1}{\sigma_e}}\mathcal{C}_t^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}}, \tag{30}$$

where $Z_{e,t}$ is defined in (17) and $\mathcal{C}_t$ and $\mathcal{D}_t$ denote the aggregate use of clean and dirty energy, respectively.

The expression for aggregate output provided above, together with expression for $Z_{e,t}$ and $Z_{x,t}$, makes clear that firm-level innovative investment – and policies that affect it – lead to endogenous changes into aggregate productivity of non-energy goods, $Z_{x,t}$, and energy goods $Z_{e,t}$, which can be understood as a measure of energy efficiency in the economy.

We can see this point more clearly by deriving an expression for the dynamics of aggregate productivity following Atkeson and Burstein (2019). First, we consider the dynamics for the total measure of non-energy and energy products available, $M_{x,t}$ and $M_{e,t}$, given by:

$$M_{x,t+1} = (1-\delta_0)M_{x,t} + x^n_{x,t}M_{x,t} + h\left(x^m_{x,t}\right)M_{x,t}. \tag{31}$$

$$M_{e,t+1} = (1-\delta_0)M_{e,t} + x^n_{e,t}M_{e,t}. \tag{32}$$

The above expressions state that the total measure of products available in $t+1$ is governed by the following forces. The first one corresponds to the exogenous exit of products from the market. That is, only a fraction $1-\delta_0$ of existing products in t survive to the next period. The second force corresponds to the mass of entering firms, $M^n_{x,t+1} = x^n_{x,t}M_{x,t}$ and $M^n_{e,t+1} = x^n_{e,t}M_{e,t}$, which engage in innovative investment at time t to create a new product at time $t+1$. Finally, the last term if the law of motion for $M_{x,t+1}$ corresponds to the fraction of incumbent non-energy firms that engage in innovative investment to create new non-energy products.

Following a similar logic, we can derive the dynamics of aggregate productivity non-energy and energy goods, given by:

$$Z^{\rho-1}_{x,t+1} = (1-\delta_0)\zeta(x^c_{x,t})M_{x,t}\frac{Z^{\rho-1}_{x,t}}{M_{x,t}} + \eta_{n,x}x^n_{x,t}M_{x,t}\frac{Z^{\rho-1}_{x,t}}{M_{x,t}} + \eta_{m,x}h(x^m_{x,t})M_{x,t}\frac{Z^{\rho-1}_{x,t}}{M_{x,t}} \tag{33}$$

$$Z^{\rho-1}_{e,t+1} = (1-\delta_0)M_{e,t}\frac{Z^{\rho-1}_{e,t}}{M_{e,t}} + \eta_{n,e}x^n_{e,t}M_{e,t}\frac{Z^{\rho-1}_{e,t}}{M_{e,t}} \tag{34}$$

The level of productivity next period depends on the following terms determined by the innovative investment of firms. The first term on the right-hand side of both equations is the average productivity $t+1$ of products that were already produced at time t by incumbent firms that did not exit the market. The second term is the average productivity of new products in the economy resulting from innovative investment of entering firms. Finally, the last term determining the evolution of the productivity of non-energy goods corresponds to the average productivity of new products at time $t+1$ that results from innovative investment incurred by incumbent non-energy firms at time t.

Taking logs in equation (33) and rearranging we can then express productivity growth, $g_{Z,x,t} \equiv \log Z_{x,t+1} - \log Z_{x,t}$ and $g_{Z,e,t} \equiv \log Z_{e,t+1} - \log Z_{e,t}$, as:

$$g_{Z,x,t} = \frac{1}{\rho - 1} \log \left((1-\delta_0)\zeta(x^c_{x,t}) + \eta_{m,x} h(x^m_{x,t}) + \eta_{n,x} x^n_{x,t} \right), \tag{35}$$

$$g_{Z,e,t} = \frac{1}{\rho - 1} \log \left((1-\delta_0) + \eta_{n,e} x^n_{e,t} \right), \tag{36}$$

which makes explicit the dependence of productivity growth on innovative investment decisions of incumbent and entering firms.

4 Calibration

We calibrate the model to the Spanish economy. The calibration sample is 2000-2019, starting shortly after the creation of Euro area and ending right before the COVID-19 crisis. One period in the model corresponds to one year. We draw from two main data sources to calibrate the model. First, we obtain aggregate data from the National Statistical Office of Spain (Instituto Nacional de Estadística, INE). Second, we rely on Central Balance Sheet Data Office (Central de Balances), maintained by Banco de España, to obtain the firm-level data used in the calibration of the innovation process of firms.

4.1 Household Sector

We set the inverse of the Frish elasticity φ to be equal to one, in the range of the estimates provided in Chetty et al. (2011). We set the time-discount factor, β, to target an annualized interest rate of 2.5% at the steady state. The population growth, g_H, is set to 0.6%, in line with the average population growth in Spain over the sample period.

As regards the parameters affecting the capital accumulation process, we first assume a functional form for the capital adjustment costs $\Xi^I(I_t, I_{t-1}, K_t)$ similar to Christiano et al. (2011):

$$\Xi^I(I_t,K_t) = \frac{\sigma_I}{2}\left(\frac{I_t}{K_t} - (\delta_K + \exp(g_Y) - 1)\right)^2 K_t, \tag{37}$$

where g_Y marks the constant growth rate of output at the BGP. We set σ_I equal to 17, in line with the estimates of Eberly et al. (2008), and the depreciation rate of private physical capital, δ_K, to be 5.5% annually, in line with the estimates of Arencibia Pareja et al. (2018).

We assume that labor adjustment costs have a similar functional form:

$$\Xi^L(L^p,L^r) = \frac{\sigma_L}{2}\left(\log(\frac{L^r_{x,t}/H_t}{L^r_{x,t-1}/H_{t-1}})^2 + \log(\frac{L^r_{e,t}/H_t}{L^r_{e,t-1}/H_{t-1}})^2 + \log(\frac{L^p_t/H_t}{L^p_{t-1}/H_{t-1}})^2\right). \tag{38}$$

We calibrate the parameter governing the labor adjustment costs, σ_L, such that it is equal to 4.5% of the quarterly wage rate at the BGP, which is in line with the vacancy-posting costs estimates of Silva and Toledo (2009). This results in $\sigma_L = 0.35$.

4.2 Government

We set the corporate tax rate to target a ratio of firms' tax payments to profits equal to 9.2%, which is achieved with $\tau^{\text{Corp}} = 0.42$. As regards the carbon tax, we set it equal to zero in our current calibration for 2019. In our counterfactual simulation exercises, we will increase the carbon tax to levels similar to those projected by the European Commission.

4.3 Production and Innovation

We set the elasticity of substitution across intermediate goods equal to 4, in line with the estimates of Broda and Weinstein (2006). The parameter governing the intertemporal externality of technological progress in (22) and (24), ϕ, is set to -1.6 following Fernald and Jones (2014). Next, we set exogenous growth rate of A_x equal to 0.96% to target an annual growth rate of output of 1.6% at the BGP, the average growth rate GDP in our sample period. Given this, the implied growth rate of A_e at the BGP is -0.17. The capital share α in the model is set to target a capital-to-GDP ratio of 4.2, as in Arencibia Pareja et al. (2018).

The quasi-share on non-energy goods in production, θ, is set to target a ratio of total energy expenses to output of 5%, following the OECD Inter-Country Input-Output (ICIO) data tables. The elasticity of substitution between energy and non-energy goods, σ, is set

Parameter	Description	Value	Target / Source
Households			
φ	Frisch elasticity	1	Chetty et al. (2011)
β	Discount factor	0.99	$R = 2.5\%$
g_H	Growth rate Pop.	0.6%	INE
δ_K	Depreciation capital	5.5%	Arencibia Pareja et al. (2018)
$\delta^{\mathcal{C}}$	Depreciation clean capital	5.5%	Same as δ_K
σ_I	Capital adj. cost	17	Eberly et al. (2008)
σ_L	Labor adj. cost	0.35	Silva and Toledo (2009)
Government			
τ^{Corp}	Corporate profit tax rate	0.42	Firms' taxes / profits = 9.18%
$\tau^{\mathcal{C}}$	Carbon tax	0	Assumption
Production			
ρ	Elasticity Substitution	4	Broda and Weinstein (2006)
ϕ	Intertemp. Externatility	-1.6	Fernald and Jones (2014)
α	Capital share	0.43	$K/Y = 4.2$
α_e	Capital share clean energy	0.90	EUKLEMS
θ	Quasi-share non energy	0.95	Engery-to-output = 5%
θ_e	Quasi-share non energy	0.74	Clean-to-dirty = 26%
σ	Elast. subst. Y_x-Y_e	0.14	Labandeira et al. (2017)
σ_e	Elast. subst. $\mathcal{C}$-$\mathcal{D}$	3	Papageorgiou et al. (2017)
$g_{Ar,x}$	Non-energy exogenous Prod. Growth	0.96%	$g_Y = 1.6\%$
Innovation			
δ_0	Exit rate	0.05	
$\eta_{n,x}, \eta_{n,e}$	Prod. step entrant	1.6	
$\eta_{m,x}$	Prod. step incumb.	0.74	See text for a discussion
$\{h_0, h_1\}$	Fct. innov. new prod. incumb.	$\{0.4, 0.5\}$	
$\{\zeta_0, \zeta_1, \zeta_2\}$	Fct. innov. exist. prod. incumb.	$\{0.9, 0.6, 0.5\}$	

Table 1: Calibration

Notes: List of calibrated parameters. See text for a discussion on targets, values, and data used.

to 0.14, in line with the median estimates of Labandeira et al. (2017). Next, we set quasi-share of dirty energy inputs in the production of the energy good, θ_e, to target a green energy share in the energy mix, $\frac{\mathcal{C}}{\mathcal{C}+\mathcal{D}}$, of 26%, in line with the estimates of the European

Commission (European Commission, 2024). The elasticity of substitution between dirty and clean energy inputs is set to 3, following the estimates of Papageorgiou et al. (2017). The exponent of clean energy capital in (21), α_e, is set to 0.9, as to target the capital share of energy sectors observed in EUKLEMS.

Our calibration strategy for the innovation process of firms is based on Domínguez-Díaz et al. (2024), which closely follows Atkeson and Burstein (2019) whenever possible. We borrow the calibrated parameters for the Spanish economy from Domínguez-Díaz et al. (2024), who consider a similar model to the one outlined here but without energy inputs in production. We then assume that the parameter values governing the innovation process of energy firms are the same as those governing the innovation process of non-energy firms.

We outline next the calibration procedure followed in Domínguez-Díaz et al. (2024). First, we posit the following functional forms for the innovation functions of incumbents for new products, $h(x^m_{x,t})$, and for existing products, $\zeta(x^c_{x,t})$, of non-energy good producers:

$$h(x^m_{x,t}) = h_0(x^m_{x,t})^{h_1} \tag{39}$$

$$\zeta(x^c_{x,t}) = \zeta_0 + \zeta_1(x^c_{x,t})^{\zeta_2}. \tag{40}$$

Therefore, there are eight remaining parameters to be calibrated related to non-energy good producers. We need to calibrate the productivity steps of new products for entrants and incumbents, $\eta_{n,x}$ and $\eta_{m,x}$; the exogenous exit rate of products from the economy, δ_0; and the parameters governing the innovation function for new products (h_0 and h_1) and for continuing products (ζ_0, ζ_1, and ζ_2). We calibrate these parameters following the same strategy derived in Atkeson and Burstein (2019). Namely, we start by setting ζ_2 equal to 0.5, which is the midpoint of admissible values for this parameter according to Atkeson and Burstein (2019). Next, we set the remaining seven parameters to target the following firm-level moments obtained from Central Balance Sheet Data Office: the growth rate of the number of firms (1%); the share of production that corresponds to new firms (0.02), to the growth of incumbent firms (0.04), and to previous levels of production of incumbent firms (0.94); the share of employment that corresponds to new firms (0.03), to the growth of incumbent firms (0.03), and to previous levels of employment of incumbent firms (0.94). [2] Given these parameters, there are two remaining parameters related to the innovation process of energy-good firms. These are the exit rate δ_0, assumed to be the same for non-energy firms, and the productivity step for entrants $\eta_{n,e}$. As mentioned above, and lacking better evidence, we assume that $\eta_{n,e} = \eta_{x,e}$.

5 Simulation Exercises

5.1 Baseline simulations

We next use the model to evaluate the effects of a shock to the international price of brown energy inputs. We consider two scenarios: one based on the baseline 2019 calibration (which we call 'low share') and another reflecting a high-share configuration aligned with Spain's 2050 renewable energy production targets. In particular, in the high-share scenario, the situation before the shock happens is now one where renewables represent 85% of the energy mix, instead of the current 26%. This five-fold reduction in the share of brown energy can be expected to create big differences in the way the economy responds to an exogenous shock to international energy input prices. By simulating this shock within our model, we can quantitatively analyze these differences and identify the critical factors driving them.

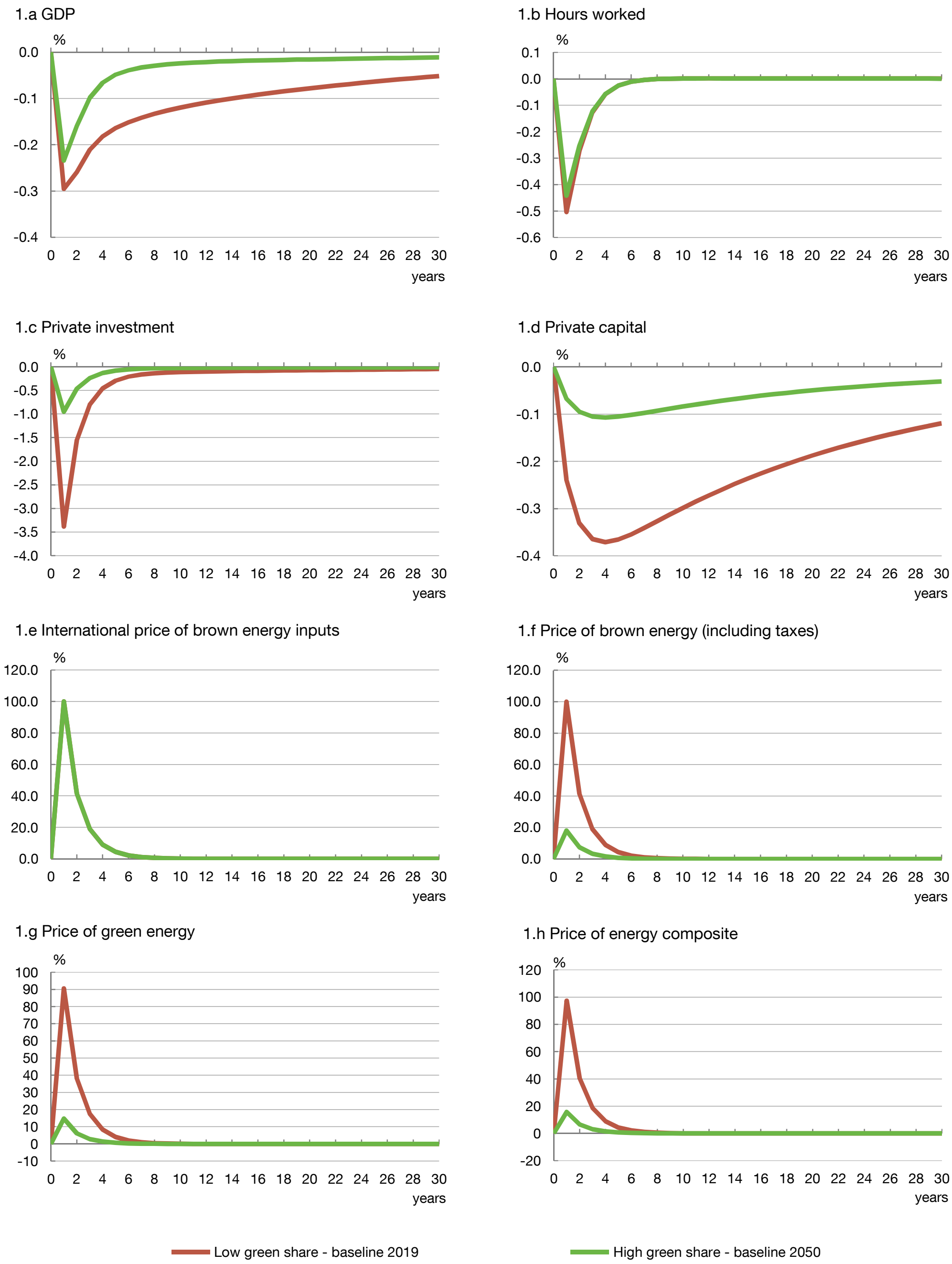
Our simulated shock is a fast doubling of the international price of brown energy inputs. As shown in Figure 1, it is a temporary shock, that's progressively undone in the following years, with an autorregressive coefficient of 0.5. In the baseline calibration, with which the model resembles the current state of the Spanish economy, this shock results in a 0.30% drop in GDP[3]. On the one hand, the increased international price of dirty energy

[2]Atkeson and Burstein (2019) use data on employment and the number of establishments. Since our data set only contains information at the firm level but not at the establishment level, we instead use production. Yet, we obtain data moments are close to the moments computed by these authors, as presented in Table 3 of the online appendix of that paper.

[3]We acknowledge that this overall effect is relatively small compared with other estimations in the literature. A big factor explaining this is that EGGEM is a real model and excludes e.g. the effects of an eventual reaction of monetary policy. Given the main role we find for the translation of the brown energy price shock to green energy prices, this lack of monetary channels may be muting our results, in the sense that the real-world importance of the green transition for the vulnerability to external shocks may be larger than what we find.

reduces households' disposable income, driving down the demand for goods produced domestically. On the other hand, higher energy prices result in an increase of firms' production costs. Both channels induce firms to reduce the amount of labor that they hire and their demand for investment, explaining the fall in aggregate GDP. Given capital adjustment costs, the short-term effect is driven mostly by the response of hours worked, whereas the medium-term effect is determined by the persistent fall in private capital brought by the short-lived reduction in private investment.

Figure 1
Impulse response functions for an exogenous shock to the price of brown energy inputs



The second simulation looks at the same shock, when it happens in an alternative calibration of the model where the green transition is approaching completion. The brown energy input, which in this model is the only intermediate consumption good that is imported from abroad, now represents a much smaller share of the energy mix (15% instead of 74%), and renewables have taken over. This is achieved in the model through a combination of a pair of stick-and-carrot policies.

The stick is a carbon tax, $\tau_{\mathcal{D},t}$, that mimics the economic effects of the European Emissions Trading System (ETS). Recall from section 3.2.3 that this enters the model as a per-unit wedge between the international price of brown energy inputs, $P^*_{\mathcal{D},t}$, and the net price that producers have to pay in order to use this input: $P_{\mathcal{D},t} = P^*_{\mathcal{D},t} + \tau_{\mathcal{D},t}$. The revenue from this tax is given back to households in the form of lump-sum transfers.[4] The technological simplifying assumptions behind this specification are: that emissions are linked to the use of this brown energy input, and that investment in energy efficiency affects both linearly.[5] An even bigger simplification is on the economic assumptions behind the carbon tax: in this model, policymakers set the price of carbon, whereas in the European ETS they set the amount of emission allowances, and market clearing sets the corresponding price. For our results, this implies that one channel is left out of the simulations: in the real world, an increase in energy prices can reduce energy use, and in turn this can bring down the price of emission allowances.[6] In future work we could try to implement this in the model, maybe incorporating the micro-founded market structure from Quintana (2024), but for now this falls outside the scope of the current analysis. In any case, we will later discuss, in section 5.2, how the omission of this channel constitutes a conservative element for our results, in the sense that the reduction in vulnerability that we find would be even more pronounced if we considered this additional channel.

The carrot is an expansion of the regulatory limits to the production of clean energy. In the model, clean energy production is predetermined, in the sense that it cannot respond

[4]Alternative ways to recycle the revenue from the carbon tax could be implemented. They would alter the simulated effects of the green transition, but not so much the marginal impact of a shock at different points of that path, which is the main focus of this paper.

[5]By this we mean that technologies that reduce the amount of energy needed per unit of production will reduce emissions by the same factor, but it is not possible within the model to invest in technologies that reduce the amount of emissions per unit of brown energy used in production.

[6]This was observed in Europe when natural gas prices skyrocketed in 2022, but not during the initial rise of late 2021.

to economic conditions in the short term: clean energy production always happens at full available capacity, and dirty energy production is the one clearing the market. Additionally, green energy production capacity is a choice variable for policymakers: reflecting the current situation of investment into solar plants in Spain, projects by firms are assumed to permanently outstrip administrative authorizations for their construction. The model ignores the fact that this situation may change in the future, e.g. if energy prices fall faster than the price of constructing a new solar plant. It also ignores small-scale investment by households and firms for self-consumption. There could be doubts about whether these assumptions could hinder the ability of the model to assess the long-term effects of the green transition, but because installation of new renewable energy capacity is relatively slow, they shouldn't decisively affect our results inasmuch as we look at the short-term response to a shock to brown energy input prices under different scenarios.

The combination in practice of this increase in the carbon tax and the expansion of clean capacity works as follows. We first introduce an increase in the carbon tax, following calculations from the European Commission about the ETS prices that would be compatible with the current targets. In particular, this implies a price that goes from 25 euros per tonne of CO2 equivalent in 2020 to 390 euros in 2050.[7] This is reinforced by an expansion of the ETS, to cover all emissions from all sectors, instead of the current 37%. If we keep international brown energy input prices constant at their 2019 level, we calculate that this path implies a carbon tax of close to 11% in 2019, and 452% in 2050 (i.e. if the price of brown energy inputs in international markets is always 1, firms in the model would have to pay 1.11 euros per unit of brown energy in 2019, and 5.52 euros in 2050). According to the model, this generates a fall in the use of brown energy that is not enough to hit the current targets for the Spanish economy, so it is then combined with an expansion of green energy capacity, calibrated so that the model matches the target of 85% green energy in 2050.

In the long run, GDP falls as the carbon tax drives up the effective price of dirty imported energy and revenue recycling through lump-sum transfers fails to provide enough compensation. However, the increase in the supply of clean energy has a positive contri-

[7] See European Commission (2024)

bution to GDP, as this is domestic production that serves as substitute of imported dirty energy. Additionally, as a response to higher post-tax prices, innovative investment by energy good firms increases, driving up energy efficiency through cost-saving technologies. This increase in energy efficiency allows firms – for a given level of output – to reduce their purchases of energy inputs. This channel effectively reduces the exposure of firms to the increase in the carbon tax, mitigating to some extent its negative consequences. Some of the quantitative effects of the energy transition on GDP would change if the use of the revenue from the carbon tax was different (e.g. if a distortionary tax was reduced, instead of just increasing lump sum transfers), and also if the mitigation of physical costs from climate change was taken into consideration. Because the model abstracts from these issues, we don't stress the results of the simulation of the transition, leaving it to future work, and instead focus here on the impulse response functions of a temporary shock at the initial and final calibration of the model.

As shown in Figure 1 , under the alternative calibration that matches the 2050 targets for the Spanish economy, the same shock that resulted in a 0.30% fall in GDP in the baseline now results in a 0.24% fall in GDP, but more importantly, the recovery from this initial fall is much faster, because the effects on private investment are much more modest (a 1% fall instead of a 3.4% fall) and private capital suffers a much smaller decline. As a result, at the end of the first year GDP is 0.07% below its initial level, when the baseline still showed a fall of 0.18%. The present discounted value of the GDP fall is -2.6% in the low green share economy, and just -0.9% in the high green share economy (a 65% reduction). In this sense, the green transition can reduce the vulnerability of the economy to external shocks to the price of brown energy inputs.

The significance of these results is showcased in the simulation exercise that Figure 2 presents. In this case, instead of a response function to a singular shock, we run a simulation of a long series of shocks that replicates indefinitely the cycle in oil prices observed in 1990-2019. The starting point for this exercise is the data series for the international oil price in euros, in relative terms vs the GDP deflator for Spain, in percentage deviations from its sample average. This 30-year-long series starts slightly below zero, and ends slightly above zero (and it would cross again to negative territory in 2020), so it can be stitched to itself continuously to generate an infinitely repeating cycle. With that evolution as a target for the price of the brown energy input in the model, we find the appropriate series of shocks to replicate the data and simulate it to obtain an infinitely repeating series for GDP. Repeating the exercise with the model with low green share and with high green share, we quantify the reduction in external vulnerability as a contribution of international brown price shocks to the standard deviation (variance) of Spanish GDP that is 33% (55%) lower in the high green share economy than in the low green share economy[8]. As expected from the IRF results, peaks are smaller (in both directions) and recovery is faster.

In any case, all of these results point to a vulnerability reduction is less-than-proportional: dividing the share of brown energy by approximately five (an 80% fall in what a priori could be considered an important statistic for the exposure of the economy to these external shocks) produced a reduction in the effect of brown energy price shocks on GDP; but this reduction in the effects of external shocks was, in relative terms, smaller, ranging from a 16% reduction if we look at the short-term GDP response, to 65% if we look at the present discounted value of the whole impulse response function, with figures like 33% (standard deviation) or 55% (variance) if we look at the reduction in the volatility of the contribution of energy shocks to GDP over a full cycle.

5.2 Additional simulations: looking for the role of different channels

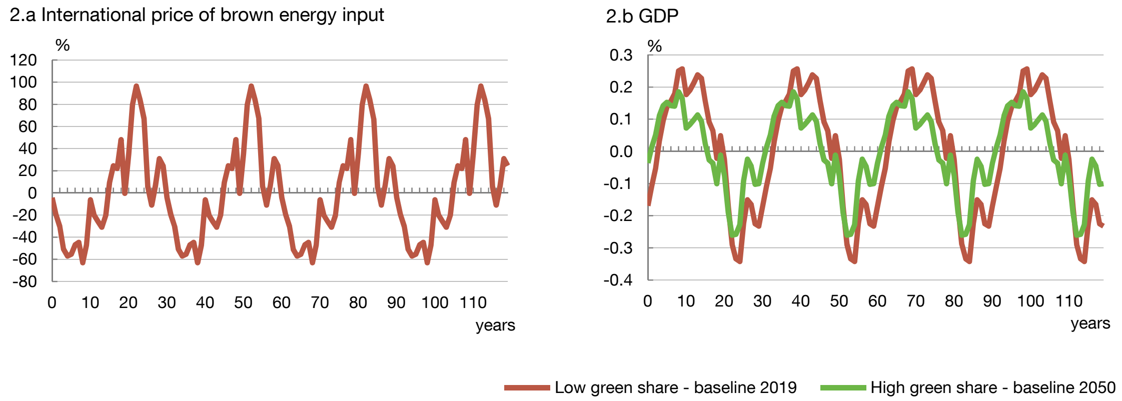
This subsection discusses additional simulations with the model, that are designed to shed light on the role of different factors in this change in the impulse response functions. We consider them less realistic than the baseline simulation presented in the previous subsection, but because they highlight the elements that can alter those results, they are useful for understanding the role and relative weight of the different channels at play.

Figure 3 adds to the previous results (shown again for easier comparison) an additional simulation of the same shock, this time in an economy that has achieved the high green share (85% share of renewables in the energy mix) without imposing a carbon tax, just through a vast expansion of the capacity of clean electricity generation. This kind of transition, with the carrot but without the stick, generates in the model a green transi-

[8] The average GDP level, because of the design of the exercise, does not change

Figure 2

Simulation of a series of brown energy price shocks that indefinitely repeats the 1990-2019 cycle in oil prices



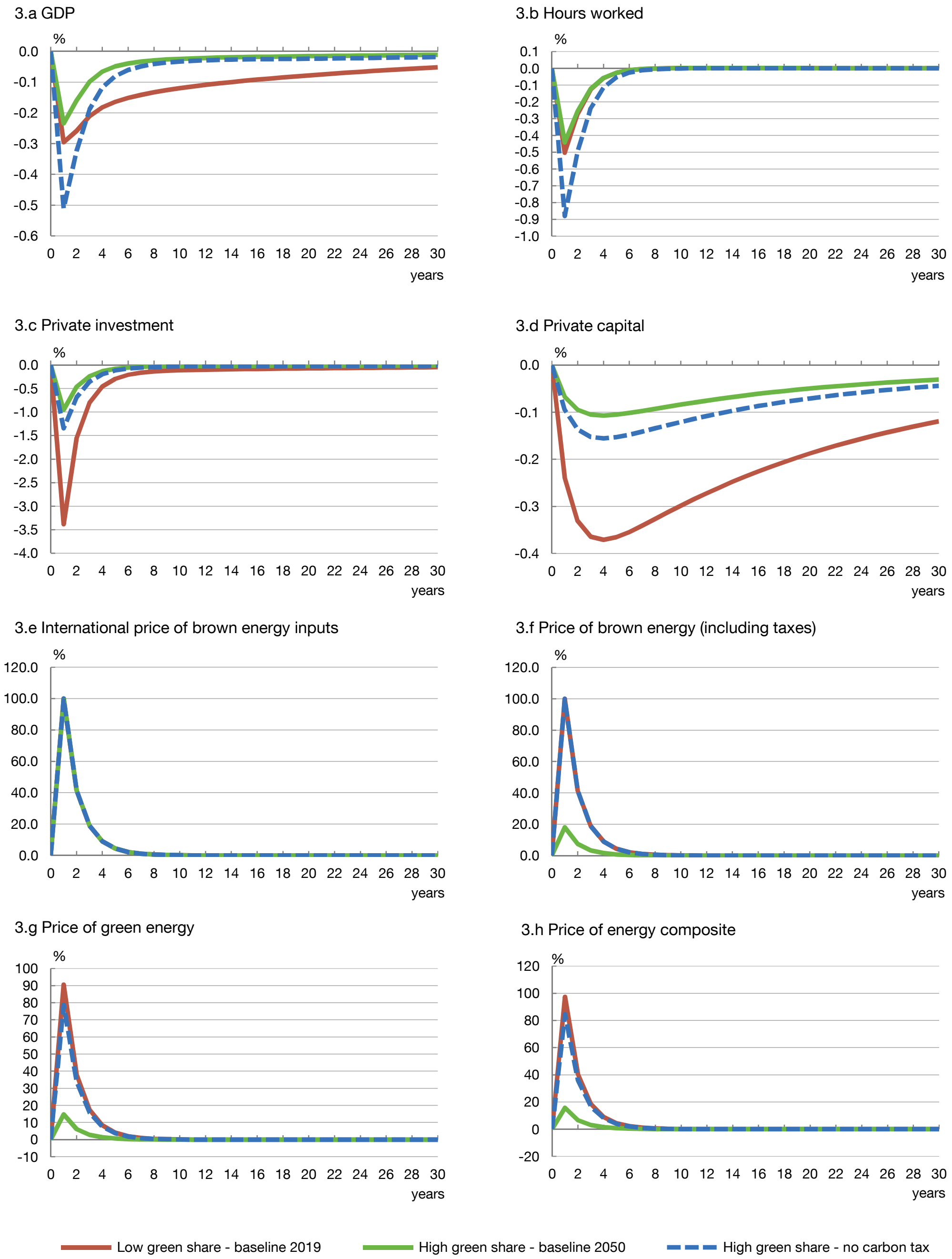
tion that is now characterized by a big fall in the price of renewables, and subsequently a weaker investment in energy efficiency, and a strong increase in energy intensity of production. When the increase in the international price of brown energy inputs happens in this economy, it generates an even bigger fall in GDP, compared with the initial calibration that represents the Spanish economy in 2019, even though the share of brown energy in the total energy mix has been reduced five-fold.

Two main factors could explain this result[9]:

- High weight of brown energy in absolute terms: this sort of green transition, where total energy intensity grows so much as a response to the fall in the price of electricity from renewables, implies that the big fall in brown energy sources in relative terms is compatible with a modest reduction in absolute terms. The share of brown energy in real GDP is 3.8% in the 2019 calibration, 0.6% in the baseline 2050 calibration, and 1.2% in this calibration where a high green share is achieved without a carbon tax. For total energy, the corresponding shares are 5.2%, 4.3%, and 7.9%.

[9] Additionally, a third channel is at play. With a high elasticity of substitution between energy sources (σ_E=3) the fall in the price of renewables that accompanies this sort of green transition is so dramatic that, even though the energy intensity of production is increased, in nominal terms the share of income that firms and consumers have to devote to purchasing energy actually falls. In the baseline 2050 simulation, when the shock hits, firms reduce their demand for both capital and labor, but at the same time consumers become poorer and get a stronger incentive to work, which actually mitigates the sharp reduction in hours worked. When the green transition is achieved without a carbon tax, this lower share of energy expenses on households' income in turn subdues this mitigating channel, and as a result the fall in hours worked becomes markedly bigger. This explains why the fall in GDP and hours worked under the 'high green share - no carbon tax' scenario is bigger than in the 'high green share - baseline 2050' scenario, even though this is not the case for investment and capital. This channel is relegated to a footnote because, even if it explains behaviors that can be seen in the graphs, it is not particularly relevant for our main arguments above.

Figure 3
IRFs for an exogenous shock to the price of brown energy inputs, adding the scenario without carbon tax



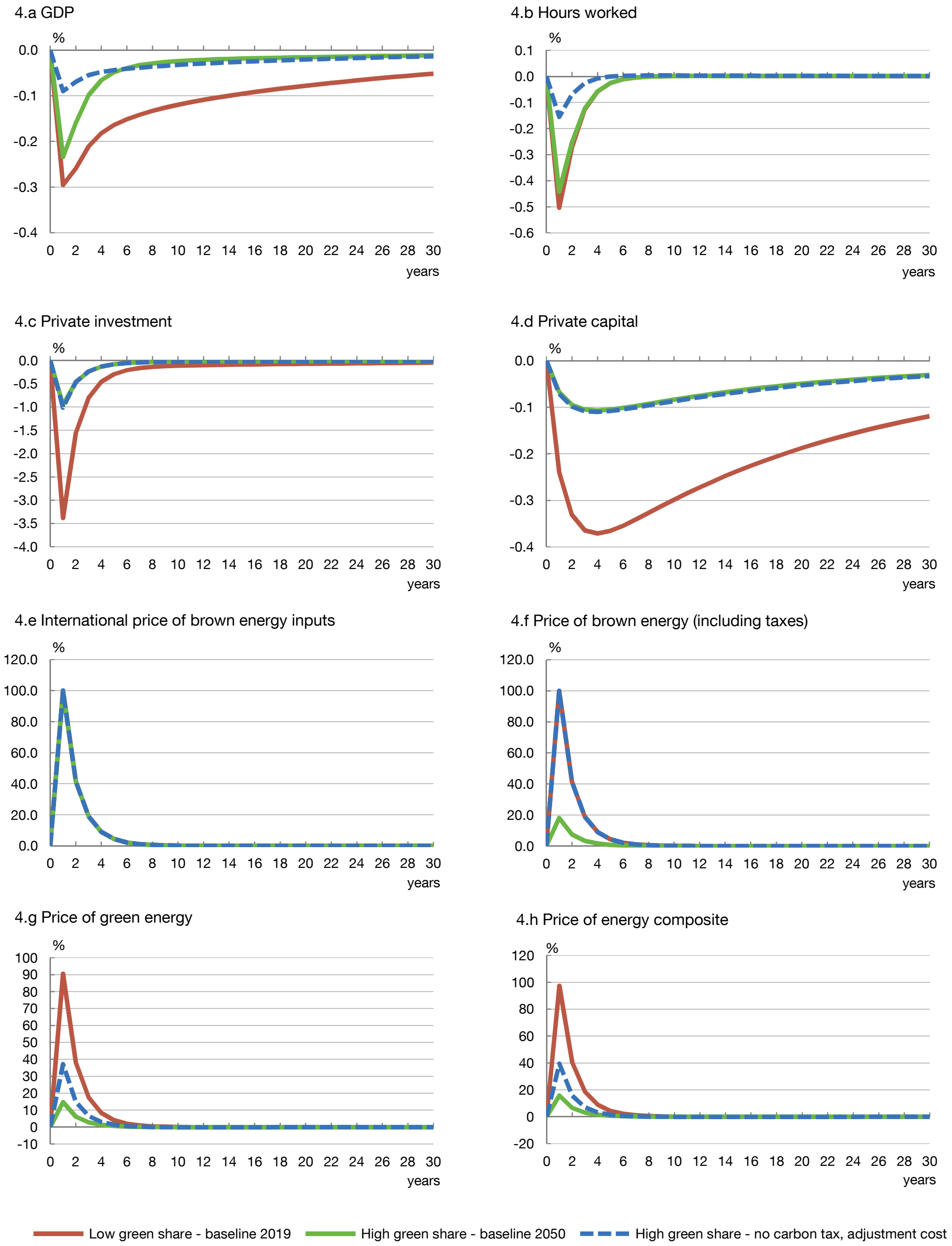
Even if most of the increase in energy intensity is in renewables, it still means that the fall in brown energy use in absolute terms is only three-fold, far from the five-fold reduction that we target in relative terms. Because of this, the direct impact of the shock is comparatively high.

- Big passthrough to final energy prices: without the carbon tax acting as a wedge between international input prices and final brown energy prices, the shock appears bigger to consumers and producers in the model in percentage terms. Additionally, the CES structure of the production function generates an almost full passthrough to the price of green energy. As a result, the price of the aggregate final energy good responds almost one-to-one to the initial shock. The carbon tax, specified as a monetary sum per unit of emissions, i.e. (with the assumptions of the model) per unit of energy used, mitigated this response of the price of the aggregate final energy good in the baseline 2050 simulation.

In order to discern which of these possible explanations is likely to have the most weight, Figure 4 introduces an additional simulation, where the same shock is simulated, this time on an economy that has undergone the green transition (achieving a share of green energy of 85%) without a carbon tax (i.e. only with the carrot, so the price of renewables falls strongly, energy intensity grows, and the element of the high weight of brown energy in absolute terms still applies) but where adjustment costs reduce the passthrough of brown energy prices to green energy prices. This results in an even bigger mitigation of the effect of the shock on Spanish GDP: investment and capital show basically the same response as in the baseline 2050 calibration, but hours worked fall by less, and the short-run response of GDP becomes much more muted.

The main conclusion from these simulations is that a reduction in the share of brown energy only generates a subsequent mitigation of external vulnerabilities (narrowly defined here as a smaller response of output for a specific exogenous shock) if it is accompanied by a lower transmission to green energy prices of the changes in brown energy prices. It is positive, therefore, that we can expect to see such a reduction in the importance of brown energy as a determinant of overall energy prices, in parallel to the decline in its share over total energy inputs. Recent data from electricity markets (in Spain and many other countries) already shows a decline in the number of hours in which fossil-fuel plants set the marginal price that is paid to all sources of electricity generation; that is, as a result of the increase in the production of renewables, overall electricity prices are already becoming progressively decoupled from the costs of production of fossil-fuel-based electricity generation. This decoupling process is expected to continue into the future. Quin-

Figure 4
IRFs for an exogenous shock to the price of brown energy inputs, adding the scenario with adjustment cost and no carbon tax



tana (2024) provides a micro-founded analysis of this process, through a model in which electricity prices are endogenously determined by the interaction between demand, generation available from renewable sources, and the costs of brown electricity generation. Our simulations show that this can be expected to be a major factor in reducing the vulnerability of the economy to external shocks in the price of brown energy inputs.

6 Conclusion

In this paper we have presented a model of endogenous growth with a reasonably detailed energy block, and used it to simulate the effects of shocks to the international price of brown energy inputs. We have done this under a calibration of the model that replicates the structure of the Spanish economy in 2019, and also in an alternative calibration defined by its green transition targets for 2050. The share of green energy is 26% in the former, and 85% in the latter. Additional scenarios were simulated in order to identify which channels and factors were most relevant in driving our results.

The three main conclusions that we draw from these simulations are:

- An increase in the share of renewables makes the economy less vulnerable to shocks in the international price of brown energy inputs.
- This vulnerability reduction can be less-than-proportional: dividing the share of brown energy by approximately five only reduced the peak effect on GDP by 21%, the present discounted value of the whole response by 65%, and the contribution of shocks to the price of brown energy inputs to the standard deviation of Spanish GDP by 33%.
- The main statistic that determines how much the vulnerability is reduced is not the share of brown energy inputs, but the degree to which final energy prices respond to the shock to brown energy input prices.

Our results highlight the importance of carbon taxes not only in introducing the necessary incentives to make the economy undergo the green transition, reducing the share of brown sources in the energy mix, but also as a means to affect final energy prices and control how they react to shocks. Besides that, it could be desirable to pursue reforms in the electricity markets that enhance the decoupling of the remuneration to renewable energy producers from the evolution of the international price of brown energy inputs. Even if the primary objective of reducing the negative effects of climate change is not taken into consideration, these policies can become attractive simply as a means of reducing the vulnerability of an economy to external shocks.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn and David Hemous. (2012). "The environment and directed technical change". *American Economic Review*, 102(1), pp. 131-166. https://doi.org/10.1257/aer.102.1.131

Aghion, Philippe, and Peter Howitt. (1992). "A model of growth through creative destruction". *Econometrica (1986-1998)*, 60(2), pp. 323-351. https://doi.org/10.2307/2951599

Airaudo, Florencia, Evi Pappa and Hernan Seoane. (2023). "The green metamorphosis of a small open economy". Discussion Paper Series, 17863, CEPR. https://cepr.org/publications/dp17863

Arencibia Pareja, Ana, Samuel Hurtado, Mercedes de Luis López and Eva Ortega. (2018). "New version of the Quarterly Model of Banco de España (MTBE)". Documentos Ocasionales, 1709, Banco de España. https://repositorio.bde.es/handle/123456789/6390

Atkeson, Andrew, and Ariel Burstein. (2019). "Aggregate implications of innovation policy". *Journal of Political Economy*, 127(6), pp. 2625-2683. https://doi.org/10.1086/701823

Auclert, Adrien, Hugo Monnery, Matthew Rognlie and Ludwig Straub. (2023). "Managing an energy shock: Fiscal and monetary policy". NBER Working Paper Series, 31543, National Bureau of Economic Research. https://doi.org/10.3386/w31543

Bachmann, Rüdiger, David Baqaee, Christian Bayer, Moritz Kuhn, Andreas Löschel, Benjamin Moll, Andreas Peichl, Karen Pittel and Moritz Schularick. (2022). "What if? The economic effects for Germany of a stop of energy imports from Russia". ECONtribute Policy Brief Series, 028, University of Bonn and University of Cologne. https://www.econstor.eu/bitstream/10419/268581/1/ECONtribute_PB_028_2022.pdf

Bayer, Christian, Alexander Kriwoluzky, Gernot Müller and Fabian Seyrich. (2023). "Hicks in hank: Fiscal responses to an energy shock". Discussion Paper Series, 18557, CEPR. https://cepr.org/publications/dp18557

Blanchard, Olivier J., and Jordi Gali. (2007). "The macroeconomic effects of oil shocks: Why are the 2000s so different from the 1970s?". NBER Working Paper Series, 13368, National Bureau of Economic Research. https://doi.org/10.3386/w13368

Bloom, Nicholas, Charles I. Jones, John Van Reenen and Michael Webb. (2020). "Are ideas getting harder to find?". *American Economic Review*, 110(4), pp. 1104-1144. https://doi.org/10.1257/aer.20180338

Broda, Christian, and David E. Weinstein. (2006). "Globalization and the Gains from Variety". *The Quarterly Journal of Economics*, 121(2), pp. 541-585. https://doi.org/10.1162/qjec.2006.121.2.541

Chetty, Raj, Adam Guren, Day Manoli and Andrea Weber. (2011). "Are micro and macro labor supply elasticities consistent? A review of evidence on the intensive and extensive margins". *American Economic Review*, 101(3), pp. 471-475. https://doi.org/10.1257/aer.101.3.471

Christiano, Lawrence, Martin Eichenbaum and Sergio Rebelo. (2011). "When is the government spending multiplier large?". *Journal of Political Economy*, 119(1), pp. 78-121. https://doi.org/10.1086/659312

Del Negro, Marco, Julian di Giovanni and Keshav Dogra. (2023). "Is the Green Transition Inflationary?". Staff Reports, 1053, Federal Reserve Bank of New York. https://www.newyorkfed.org/research/staff_reports/sr1053.html

Domínguez-Díaz, Rubén, Samuel Hurtado and Carolina Menéndez. (2024). "The medium-term effects of investment stimulus". Documentos de Trabajo, 2402, Banco de España. https://doi.org/10.53479/35913

Eberly, Janice, Sergio Rebelo and Nicolas Vincent. (2008). "Investment and value: A neoclassical benchmark". NBER Working Paper Series, 13866, National Bureau of Economic Research. https://doi.org/10.3386/w13866

European Commission. (2024). "Comission staff working document impact assessment report". Working Document, 52024SC0063, European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024SC0063

European Council. (2020). "European Council conclusions, 17-21 July 2020". https://www.consilium.europa.eu/en/press/press-releases/2020/07/21/european-council-conclusions-17-21-july-2020/

Fernald, John G., and Charles I. Jones. (2014). "The future of US economic growth". *American Economic Review,* 104(5), pp. 44-49. https://doi.org/10.1257/aer.104.5.44

Golosov, Mikhail, John Hassler, Per Krusell and Aleh Tsyvinski. (2014). "Optimal taxes on fossil fuel in general equilibrium". *Econometrica,* 82(1), pp. 41-88. https://doi.org/10.3982/ECTA10217

Jones, Charles I. (2002). "Sources of U.S. economic growth in a world of ideas". *American Economic Review,* 92(1), pp. 220-239. https://doi.org/10.1257/000282802760015685

Klette, Tor Jakob, and Samuel Kortum. (2004). "Innovating firms and aggregate innovation". *Journal of Political Economy,* 112(5), pp. 986-1018. https://doi.org/10.1086/422563

Labandeira, Xavier, José M. Labeaga and Xiral López-Otero. (2017). "A meta-analysis on the price elasticity of energy demand". *Energy Policy,* 102, pp. 549-568. https://doi.org/https://doi.org/10.1016/j.enpol.2017.01.002

Luttmer, Erzo G. J. (2007). "Selection, Growth, and the Size Distribution of Firms". *The Quarterly Journal of Economics,* 122(3), pp. 1103-1144. https://doi.org/10.1162/qjec.122.3.1103

Nakov, Anton, and Carlos Thomas. (2023). "Climate-conscious monetary policy". Documentos de Trabajo, 2334, Banco de España. https://doi.org/10.53479/34755

Papageorgiou, Chris, Marianne Saam and Patrick Schulte. (2017). "Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective". *The Review of Economics and Statistics,* 99(2), pp. 281-290. https://doi.org/10.1162/REST_a_00592

Pieroni, Valerio. (2023). "Energy shortages and aggregate demand: Output loss and unequal burden from HANK". *European Economic Review,* 154, p. 104428. https://doi.org/https://doi.org/10.1016/j.euroecorev.2023.104428

Quintana, Javier. (2024). "Green transition with renewable energy investments: a network approach". Forthcoming.

Romer, Paul M. (1990). "Endogenous technological change". *Journal of Political Economy*, 98(5), Part 2, pp. S71-S102. https://doi.org/10.1086/261725

Silva, José Ignacio, and Manuel Toledo. (2009). "Labor turnover costs and the cyclical behavior of vacancies and unemployment". *Macroeconomic Dynamics*, 13(S1), pp. 76-96. https://doi.org/10.1017/S1365100509080122

A Model Appendix

In this appendix we provide the details of the model outlined in the main text, including the first order conditions associated with the optimization problems of agents.

A.1 Households

The solution to the household problem outlined in the main text and described by equations (1), (2), and (3), satisfies the following optimality conditions:

$$\frac{1}{C_t/H_t} = \mathbb{E}_t \beta (1+R_t) \frac{1}{C_{t+1}/H_{t+1}}, \tag{41}$$

$$\frac{1}{C_t/H_t} = \mathbb{E}_t \beta \frac{1}{C_{t+1}/H_{t+1}} \frac{1}{q_t} \left(r^k_{t+1} + q_{t+1} \left(1 - \delta_K - \frac{\partial \Xi^I (I_{t+1}, K_{t+1})}{\partial K_{t+1}} \right) \right), \tag{42}$$

$$\frac{1}{q_t} = 1 - \frac{\partial \Xi^I (I_t, K_t)}{\partial I_t}, \tag{43}$$

$$\left(\frac{L^P_t + L^R_{x,t} + L^R_{e,t}}{H_t} \right)^{\varphi} \frac{C_t}{H_t} = W^R_{x,t} - \frac{\partial \Xi^L_t}{\partial L^R_{x,t}} - \mathbb{E}_t \frac{1}{1+R_t} \frac{\partial \partial \Xi^L_{t+1}}{\partial L^R_{x,t}}, \tag{44}$$

$$\left(\frac{L^P_t + L^R_{x,t} + L^R_{e,t}}{H_t} \right)^{\varphi} \frac{C_t}{H_t} = W^R_{e,t} - \frac{\partial \Xi^L_t}{\partial L^R_{e,t}} - \mathbb{E}_t \frac{1}{1+R_t} \frac{\partial \partial \Xi^L_{t+1}}{\partial L^R_{e,t}}, \tag{45}$$

$$\left(\frac{L^P_t + L^R_{x,t} + L^R_{e,t}}{H_t} \right)^{\varphi} \frac{C_t}{H_t} = W^P_t - \frac{\partial \Xi^L_t}{\partial L^P_t} - \mathbb{E}_t \frac{1}{1+R_t} \frac{\partial \partial \Xi^L_{t+1}}{\partial L^P_t}, \tag{46}$$

Equations (41) and (42) are the Euler equations for risk-free bonds and capital, respectively. q_t above marks Tobins's q – the marginal value of capital in terms of consumption units – and is given in equation (43). The final three equations summarize the labor supply of research and production labor of the household.

A.2 Firms

A.2.1 Final Good Producer

The solution to the final good producer's problem (4) delivers the following system of demand equations for intermediate goods:

$$P_{x,t} = \left(\frac{Y_t}{Y_{x,t}}\right)^{\frac{1}{\sigma}} \theta^{\frac{1}{\sigma}}, \tag{47}$$

$$P_{e,t} = \left(\frac{Y_t}{Y_{e,t}}\right)^{\frac{1}{\sigma}} (1-\theta)^{\frac{1}{\sigma}}, \tag{48}$$

$$y_{x,t}(z_x) = \left(\frac{p_{x,t}(z_x)}{P_{x,t}}\right)^{-\rho} Y_{x,t}, \tag{49}$$

$$y_{e,t}(z_e) = \left(\frac{p_{e,t}(z_e)}{P_{e,t}}\right)^{-\rho} Y_{e,t}, \tag{50}$$

A.2.2 Intermediate Good Producers

We divide the problem solved by intermediate good producers in two problems. A first one is a static problem where firms optimally choose production inputs and prices. The second problem is a dynamic problem where firms decide how much to invest in innovation.

Static Problem: Non-energy intermediate good producers. The static problem of a non-energy good firm with productivity index z_x consists on choosing labor $l^p(z_x)$, capital $k(z_x)$, and prices $p_x(z_x)$ to maximize variable profits (8), subject to the demand equation (47) and the production technology (7). The solution to that problem is characterized by the following equations:

$$\frac{k_t(z_x)}{l_t^p(z_x)} = \frac{\alpha}{1-\alpha}\frac{W_t^P}{r_t^k}, \tag{51}$$

$$\frac{W_t^P}{p_{x,t}(z_x)} = \lambda_{x,t}(z_x)(1-\alpha)\frac{y_{x,t}(z_x)}{l_t^p(z_x)}, \tag{52}$$

$$\lambda_{x,t}(z_x) = \max\left\{0, \frac{1}{z_x}\mathrm{MC}_{x,t}\right\}, \tag{53}$$

$$p_{x,t}(z_x) = \mu \frac{1}{z_x} MC_{x,t}, \tag{54}$$

$$\mu = \min\{\frac{\rho}{\rho - 1}, \bar{\mu}\}, \tag{55}$$

$$\text{MC}_{x,t} \equiv \left(\frac{W_t^P}{1-\alpha}\right)^{1-\alpha} \left(\frac{r_t^k}{\alpha}\right)^{\alpha} \tag{56}$$

Equation (51) shows that the capital-to-labor ratio chosen by intermediate good firms is independent of the idiosyncratic productivity index z_x, albeit the levels of this variables does not need to be. Equation (52) is the equation that defines labor demand for production work of a firms with productivity index z_x, where $\lambda_{x,t}(z_x)$ is the Lagrange multiplier as given by (53).[10]

Equation (54) states that intermediate good producers charge a constant markup μ over marginal costs MC_t/z, defined in (56). As in Atkeson and Burstein (2019), we assume that the markup is given by the minimum between the monopoly markup $\rho/\rho-1$ and the technology gap with respect to the second most productive firm producing the same product with productivity index $z/\bar{\mu}$.

Dynamic Problem: Non-energy intermediate good producers. The dynamic problem of an incumbent non-energy firms consists on choosing innovative investment to maximize:

$$\begin{aligned} V_{x,t}(z_x) = \max_{x^m_{x,t}(z_x), x^c_{x,t}(z_x)} & \pi_{x,t}(z_x)(1-\tau_t^{\text{Corp}}) - P^r_{x,t}(x^m_{x,t}(z_x) + x^c_{x,t}(z_x)) \\ & + \mathbb{E}_t \frac{V_{x,t+1}(z'_x)}{1+R_t} \left((1-\delta_0) + h\left(\frac{x^m_{x,t}(z_x)}{s_{x,t}(z_x)}\right)\right), \end{aligned} \tag{57}$$

where variable profits $\pi_{x,t}(z_x)$ are defined in (8). The continuation value of the firm $V_{x,t+1}(z'_x)$ is weighted by two terms. The first of them $1-\delta_0$ corresponds to the probability of keeping an existing product. The second term $h(x^m_{x,t}(z_x)/s_{x,t}(z_x))$ is the probability of having the opportunity to invest in a new product.

[10]The complementary slackness conditions is given by $\lambda_{x,t}(z_x)\left(y_{x,t}(z_x) - z_x k_t(z_x)^{\alpha} l_t^p(z_x)^{1-\alpha}\right) = 0$.

We solve the problem (57) following the same steps as in Atkeson and Burstein (2019). Namely, one first can easily show that variable profits scale with $s_{x,t}(z_x)$, that is $\pi_{x,t}(z_x) = s_{x,t}(z_x)(1-\tau_t^{\text{Corp}})\frac{\mu-1}{\mu}Y_{x,t}$. Second, one can show that innovative investment scales with $s_{x,t}(z_x)$ as well – $x^j_{x,t}(z_x) = s_{x,t}(z_x)x^m_{x,t}$ for $j \in \{c, m, n\}$. This leads to $V_{x,t}(z_x) = V_{x,t}s_{x,t}(z_x)$, where $V_{x,t}$ is given by:

$$V_{x,t} = \max_{x^m_{x,t}, x^c_{x,t}} (1-\tau_t^{\text{Corp}})\frac{\mu-1}{\mu}P_{x,t}Y_{x,t} - P^r_{x,t}(x^m_{x,t} + x^c_{x,t}) + \mathbb{E}_t\frac{V_{x,t+1}}{1+R_t}\left((1-\delta_0)\zeta(x^c_{x,t}) + \eta_{x,m}h(x^m_{x,t})\right)\frac{Z^{\rho-1}_{x,t}}{Z^{\rho-1}_{x,t+1}} \tag{58}$$

The first order conditions for innovative investment for incumbent firms and the free-entry conditions for new entrants are therefore given by:

$$x^m_{x,t}: \quad P^r_{x,t} = \frac{1}{1+R_t}V_{x,t+1}\eta_{m,x}h'(x^m_{x,t})\left(\frac{Z_{x,t}}{Z_{xt+1}}\right)^{\rho-1} \tag{59}$$

$$x^c_{x,t}: \quad P^r_{x,t} = \frac{1-\delta_0}{1+R_t}V_{x,t+1}\xi'(x^c_{x,t})\left(\frac{Z_{x,t}}{Z_{x,t+1}}\right)^{\rho-1} \tag{60}$$

$$\text{Free-entry}: \quad P^r_{x,t} = \frac{1}{1+R_t}V_{x,t+1}\eta_{n,x}\left(\frac{Z_{x,t}}{Z_{x,t+1}}\right)^{\rho-1} \tag{61}$$

Static Problem: Energy intermediate good producers. The static problem of a non-energy good firm with productivity index z_e consists on choosing dirty energy inputs $\mathcal{D}_t(z_e)$, clean energy inputs $\mathcal{C}_t(z_e)$, and prices $p_e(z_e)$ to maximize variable profits (16), subject to the demand equation (47) and the production technology (14). The solution to that problem is characterized by the following equations:

$$\frac{P_{\mathcal{D},t}}{P_{\mathcal{C},t}} = \left(\frac{\theta_e}{1-\theta_e}\right)^{\frac{1}{\sigma_e}}\left(\frac{\mathcal{C}_t(z_e)}{\mathcal{D}_t(z_e)}\right)^{\frac{1}{\sigma_e}}, \tag{62}$$

$$\frac{P_{\mathcal{D},t}}{p_{e,t}(z_e)} = \lambda_{e,t}(z_e)\theta_e^{\frac{1}{\sigma_e}}\left(\frac{\left[\theta_e^{\frac{1}{\sigma_e}}\mathcal{D}_t(z_e)^{\frac{\sigma_e-1}{\sigma_e}} + (1-\theta_e)^{\frac{1}{\sigma_e}}\mathcal{C}_t(z_e)^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}}}{\mathcal{D}_t(z_e)}\right)^{\frac{1}{\sigma_e}}, \tag{63}$$

$$\lambda_{e,t}(z_e) = \max\left\{0, \frac{1}{z_e}\text{MC}_{e,t}\right\}, \tag{64}$$

$$p_{e,t}(z_e) = \mu \frac{1}{z_e} MC_{e,t}, \tag{65}$$

$$\mu = \min\{\frac{\rho}{\rho - 1}, \bar{\mu}\}, \tag{66}$$

$$\mathrm{MC}_{e,t} \equiv \left[\theta_e P_{\mathcal{D},t}^{1-\sigma_e} + (1-\theta_e) P_{\mathcal{C},t}^{1-\sigma_e}\right]^{\frac{1}{1-\sigma_e}} \tag{67}$$

Dynamic Problem: Energy intermediate good producers. Recall that the problem of an incumbent energy firm is given by:

$$V_{e,t}(z_e) = (1 - \tau_t^{\mathrm{Corp}}) \pi_{e,t}(z_e) + \mathbb{E}_t \frac{1}{1+R_t} V_{e,t+1}(z'_e)(1 - \delta_0), \tag{68}$$

where variable profits $\pi_{e,t}(z_e)$ are defined in (16). The continuation value of the firm $V_{e,t+1}(z'_e)$ accounts for the $1 - \delta_0$ probability of keeping an existing product.

Following the same steps as in the case of the non-energy good firm it can be shown that $V_{e,t}(z_e)$ scales with $s_{e,t}(z_e)$, $V_{e,t}(z_e) = V_{e,t} s_{e,t}(z_e)$, where $V_{e,t}$ is given by:

$$V_{e,t} = (1 - \tau_t^{\mathrm{Corp}}) \frac{\mu - 1}{\mu} P_{e,t} Y_{e,t} + \mathbb{E}_t \frac{V_{e,t+1}}{1+R_t} (1 - \delta_0) \frac{Z_{e,t}^{\rho-1}}{Z_{e,t+1}^{\rho-1}} \tag{69}$$

In the case of intermediate energy good firms, innovation decesions are charectized only the free entry condition

$$\text{Free-entry}: \quad P_{e,t}^r = \frac{1}{1+R_t} V_{e,t+1} \eta_{n,e} \left(\frac{Z_{e,t}}{Z_{e,t+1}}\right)^{\rho-1} \tag{70}$$

A.2.3 Research Good Producer

The maximization problem of the research non-energy good producer (23) deliver the following first order conditions for demand of research labor:

$$P_{x,t}^R A_{x,t}^R Z_{x,t}^{\phi-1} = W_{x,t}^R \tag{71}$$

Similarly, the first order condition for the research energy good producer is given by:

$$P^R_{e,t} A^R_{e,t} Z^{\phi-1}_{e,t} = W^R_{e,t} \tag{72}$$

A.3 Balanced Growth Path

Our economy features endogenous growth. Therefore we detrend the equilibrium variables by their constant balanced-growth-path (BGP) growth rates to obtain an stationary equilibrium.

We denote by small-case letters detrended variables. That is, for Y_t we have that $y_t \equiv {}^{Y_t}/_{\exp(t g_y)}$, where g_x is the constant growth rate of output at the BGP. This variable is constant at the BGP. Following this notation we can write the system of equilibrium equations in terms of stationary variables as:

$$\frac{1}{c_t} = \mathbb{E}_t \beta (1 + R_t) \exp(g_Y - g_H) \frac{1}{c_{t+1}} \tag{73}$$

$$\frac{1}{c_t} = \mathbb{E}_t \exp(g_Y - g_H) \frac{1}{c_{t+1}} \frac{1}{q_t} \left(r^k_{t+1} + q_{t+1} \left(1 - \delta_K - \frac{\partial \Xi^I(i_{t+1}, k_{t+1})}{\partial k_{t+1}} \right) \right) \tag{74}$$

$$\frac{1}{q_t} = 1 - \frac{\partial \Xi^I(i_t, k_t)}{\partial i_t}, \tag{75}$$

$$\begin{aligned} \left(\frac{l^P_t + l^R_{x,t} + l^R_{e,t}}{h_t} \right)^{\varphi} \frac{c_t}{h_t} \exp(g_Y - g_H) = & w^R_{x,t} \exp(g_Y - g_H) - \frac{\partial \Xi^L_t}{\partial l^R_{x,t}} \\ & - \mathbb{E}_t \frac{1}{1 + R_t} \frac{\partial \xi^L_{t+1}}{\partial l^R_{x,t}}, \end{aligned} \tag{76}$$

$$\begin{aligned} \left(\frac{l^P_t + l^R_{x,t} + l^R_{e,t}}{h_t} \right)^{\varphi} \frac{c_t}{h_t} \exp(g_Y - g_H) = & w^R_{e,t} \exp(g_Y - g_H) - \frac{\partial \Xi^L_t}{\partial l^R_{e,t}} \\ & - \mathbb{E}_t \frac{1}{1 + R_t} \frac{\partial \xi^L_{t+1}}{\partial l^R_{e,t}}, \end{aligned} \tag{77}$$

$$\left(\frac{l_t^P + l_{x,t}^R + l_{e,t}^R}{h_t}\right)^{\varphi} \frac{c_t}{h_t} \exp(g_Y - g_H) = w_t^P \exp(g_Y - g_H) - \frac{\partial \Xi_t^L}{\partial l_t^P} - \mathbb{E}_t \frac{1}{1+R_t} \frac{\partial \zeta_{t+1}^L}{\partial l_t^P}, \tag{78}$$

$$y_t = \left[\theta^{\frac{1}{\sigma}} y_{x,t}^{\frac{\sigma-1}{\sigma}} (1-\theta)^{\frac{1}{\sigma}} y_{x,t}^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{79}$$

$$p_{x,t} = \theta^{\frac{1}{\sigma}} \left(\frac{y_t}{y_{x,t}}\right)^{\frac{1}{\sigma}} \tag{80}$$

$$p_{e,t} = (1-\theta)^{\frac{1}{\sigma}} \left(\frac{y_t}{y_{e,t}}\right)^{\frac{1}{\sigma}} \tag{81}$$

$$y_{e,t} = z_{e,t} \left[\theta_e^{\frac{1}{\sigma_e}} \ell_t^{\frac{\sigma_e-1}{\sigma_e}} + (1-\theta_e)^{\frac{1}{\sigma_e}} c_t^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}} \tag{82}$$

$$\frac{p_{\mathcal{D},t}}{p_{e,t}} = \frac{1}{\mu} z_{e,t} \theta_e^{\frac{1}{\sigma_e}} \left(\frac{\left[\theta_e^{\frac{1}{\sigma_e}} \ell_t^{\frac{\sigma_e-1}{\sigma_e}} + (1-\theta_e)^{\frac{1}{\sigma_e}} c_t^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}}}{\ell_t}\right)^{\frac{1}{\sigma_e}} \tag{83}$$

$$\frac{p_{\mathcal{C},t}}{p_{e,t}} = \frac{1}{\mu} z_{e,t} (1-\theta_e)^{\frac{1}{\sigma_e}} \left(\frac{\left[\theta_e^{\frac{1}{\sigma_e}} \ell_t^{\frac{\sigma_e-1}{\sigma_e}} + (1-\theta_e)^{\frac{1}{\sigma_e}} c_t^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}}}{c_t}\right)^{\frac{1}{\sigma_e}} \tag{84}$$

$$c_t = (k_t^c)^{\alpha_e} \tag{85}$$

$$y_{x,t} = z_{x,t} (k_t)^{\alpha} \left(l_t^p\right)^{1-\alpha}. \tag{86}$$

$$\frac{w_t^P}{p_{x,t}} = \frac{1-\alpha}{\mu}\frac{y_{x,t}}{l_t^p}, \tag{87}$$

$$\frac{r_t^K}{p_{x,t}} = \frac{\alpha}{\mu}\frac{y_{x,t}}{k_t}, \tag{88}$$

$$p_{x,t}^R Y_{x,t}^R = w_{x,t}^R l_{x,t}^R \tag{89}$$

$$p_{e,t}^R Y_{e,t}^R = w_{e,t}^R l_{e,t}^R \tag{90}$$

$$v_{x,t} = \max_{x_{x,t}^m, x_{x,t}^c} (1-\tau_t^{\text{Corp}})\frac{\mu-1}{\mu} - p_{x,t}^r(x_{x,t}^m + x_{x,t}^c)$$
$$+ \mathbb{E}_t \exp(g_Y - (\rho-1)g_{z,x})\frac{v_{x,t+1}}{1+R_t}\left((1-\delta_0)\zeta(x_{x,t}^c) + \eta_{m,x}h(x_{x,t}^m)\right)\frac{z_{x,t}^{\rho-1}}{z_{x,t+1}^{\rho-1}}\frac{p_{x,t+1}y_{x,t+1}}{p_{e,t}y_{e,t}} \tag{91}$$

$$p_{x,t}^r = \frac{\exp(g_Y - (\rho-1)g_{z,x})}{1+R_t} v_{x,t+1}\eta_{n,x}\left(\frac{z_{x,t}}{z_{x,t+1}}\right)^{\rho-1}\frac{p_{x,t+1}y_{x,t+1}}{p_{x,t}y_{x,t}} \tag{92}$$

$$p_{x,t}^r = \frac{\exp(g_Y - (\rho-1)g_{z,x})}{1+R_t} v_{x,t+1}(1-\delta_0)\zeta'(x_{x,t}^c)\left(\frac{z_{x,t}}{z_{x,t+1}}\right)^{\rho-1}\frac{p_{x,t+1}y_{x,t+1}}{p_{x,t}y_{x,t}} \tag{93}$$

$$p_{x,t}^r = \frac{\exp(g_Y - (\rho-1)g_{z,x})}{1+R_t} v_{x,t+1}\eta_m h'(x_{x,t}^m)\left(\frac{z_{x,t}}{z_{x,t+1}}\right)^{\rho-1} \tag{94}$$

$$v_{e,t} = (1-\tau_t^{\text{Corp}})\frac{\mu-1}{\mu}$$
$$+ \mathbb{E}_t \exp(g_Y - (\rho-1)g_{z,e})\frac{v_{x,t+1}}{1+R_t}(1-\delta_0)\frac{z_{e,t}^{\rho-1}}{z_{e,t+1}^{\rho-1}}\frac{p_{e,t+1}y_{e,t+1}}{p_{e,t}y_{e,t}} \tag{95}$$

$$p_{e,t}^r = \frac{\exp(g_Y - (\rho-1)g_{z,e})}{1+R_t} v_{e,t+1}\eta_{n,e}\left(\frac{z_{e,t}}{z_{e,t+1}}\right)^{\rho-1}\frac{p_{e,t+1}y_{e,t+1}}{p_{e,t}y_{e,t}} \tag{96}$$

$$Y^r_{x,t} = a_{x,t} z^{\phi-1}_{x,t} l^r_{x,t}. \tag{97}$$

$$Y^r_{e,t} = a_{e,t} z^{\phi-1}_{e,t} l^r_{e,t}. \tag{98}$$

$$\left(\frac{\exp(g_{z,x}) z_{x,t+1}}{z_{x,t}}\right)^{\rho-1} = (1-\delta_0)\zeta(x^c_{x,t}) + \eta_{m,x} h(x^m_{x,t}) + \eta_{n,x} x^n_{x,t} \tag{99}$$

$$\left(\frac{\exp(g_{z,x}) z_{x,t+1}}{z_{x,t}}\right)^{\rho-1} = (1-\delta_0) + \eta_{n,e} x^n_{e,t} \tag{100}$$

$$Y^r_{x,t} = x^n_{x,t} + x^m_{x,t} + x^c_{x,t} \tag{101}$$

$$Y^r_{e,t} = x^n_{e,t} \tag{102}$$

$$c_t + i_t + i^{\mathcal{C}}_t = y_t - p_{\mathcal{D},t} d_t \tag{103}$$

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